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Innovations in Organic Food Systems for Sustainable Production and Enhanced Ecosystem Services

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American Society of Agronomy

ICROFS International Centre for Research in Organic Food Systems

USDA United States Department of Agriculture National Institute of Food and Agriculture

Contents

Contents

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Innovations in Organic Food Systems for Sustainable Production and Ecosystem Services: An Introduction to the Special Issue of *Sustainable Agriculture Research*

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Organic agriculture is one of the best developed multifunctional production strategies in agriculture, and yet is not widely understood in terms of its full potential for contributing to food security, economic development, and environmental health. This special edition of the journal Sustainable Agriculture Research explores the knowledge, innovations, potentials, and research needs that will strengthen the links between organic food systems, sustainable production, and enhanced ecosystem services. The following articles are from an international conference titled “Innovations in Organic Food Systems for Sustainable Production and Ecosystem Services,” held on 1-2 November 2014 in Long Beach, California. The conference was co-sponsored by the Organisation for Economic Co-operation and Development (OECD) Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems, the International Centre for Research in Organic Food Systems (ICROFS), the United Stated Department of Agriculture, National Institute of Food and Agriculture (USDA-NIFA), and the American Society of Agronomy (ASA).

The articles presented here provide concrete evidence of the capacity of organic agriculture to meet a diverse set of societal goals. The framework of ecosystem services as it relates to agriculture and the environment has emerged in recent years in scientific literature and international discussions, such as the *Millennium Ecosystem Assessment* (2005) and the *International Assessment of Agricultural Knowledge, Science and Technology for Development* (McIntyre et al., 2009). Organic agriculture has embodied this concept from its inception. As defined by the International Federation of Organic Agriculture Movements (IFOAM), “Organic agriculture is a production system that sustains the health of soils, ecosystems, and people.” The multifunctionality of organic agriculture is well illustrated in this issue with examples related to enhancing soil quality and farm profitability (Delate et al., 2015), reducing nitrate leaching and increasing nitrogen use efficiency (Cambardella et al., 2015), increasing phosphorus use efficiency (Lynch, 2015), enhancing food quality (Heckman, 2015), and improving food security for smallholder farmers (Halberg et al., 2015).

The papers in this issue are presented in the context of recent calls for ‘ecological intensification’ as a new pathway for sustainable agriculture to achieve global food security (FAO, 2011; UNCTAD, 2013). As outlined by Niggli et al. (2008), eco-functional intensification of organic agriculture involves improving our knowledge and application of biological principles and agro-ecological methods to optimize system processes and increase synergies among system components, with the aim of enhancing the health, productivity, and resilience of the agro-ecosystem, food system, and environment. Jensen et al. (2015) illustrate the synergistic effects of enhancing spatial crop diversity through intercropping grains and legumes. Hokkanen et al. (2015) provide an example of optimizing system processes by using crop pollinators to precision deliver biocontrol agents in small fruits. Lynch (2015) describes how organic pasture systems enhance phosphorus cycling such that forage yields are equivalent to conventionally managed pastures despite significantly lower soil test phosphorus levels. Heckman (2015) and Vaarst (2015), in separate papers, discuss the importance of integrating livestock, trees, and pasture for eco-functional intensification of organic agriculture.

The complexity of agro-ecological systems and the input restrictions imposed for organic certification have fostered a unique culture of farmer experimentation, innovation, and collaboration that has and will continue to be a key driver of advancements in organic agriculture. Vogl et al. (2015) argue that while farmer experimentation is intrinsic to all agricultural endeavors, it is uniquely important in organic systems because adapting organic practices to specific sites is inherently knowledge intensive. The author calls for explicit efforts to create environments that encourage creativity, open communication, and reflection on both the experimental process as well as outcomes. Vaarst (2015) explores the role of farmer groups in addressing the need for context specific knowledge generation in the development of complex integrated animal farming. Padel et al. (2015) discuss how the effective combination of experiential and experimental knowledge, via farmer-researcher collaboration and participatory research, can drive innovation, and can be encouraged through farmer research funds and innovation awards.

Despite significant advances, key challenges remain if organic agriculture is to develop its full potential as a sustainable food production strategy. Niggli (2015) outlines the main factors limiting yields and yield stability in organic agriculture, and argues for a research approach based in agro-ecological theory to address these factors. Such an approach, explain Abbott and Manning (2015), requires a better understanding of the complex soil system and the interactions between biological and mineral fractions and bio-physical and bio-chemical processes. From a management standpoint, cover crops and green manures offer multiple essential functions including fixing nitrogen, adding organic matter, and providing habitat for beneficials, and are thus critical to the success of organic systems. However, the development of best management practices and suitable germplasm are needed to assure that cover crops can reliably provide these functions. For instance, the method by which green manure are terminated can significantly impact nitrogen use efficiency, as discussed by Lynch (2015).

Reducing reliance on tillage in organic systems is being explored for the potential to enhance energy efficiency, soil quality, and water availability. Canali (2015) presents results from research on a no-till cover crop system for Mediterranean vegetable production. Köpke et al. (2015) provide evidence that periodic tillage in organic systems may be beneficial in terms of enhancing nutrient cycling between the subsoil and surface soil, and offers a glimpse into the unique role that subsoil processes play in nutrient dynamics.

Ensuring that organic agriculture will meet society's evolving expectations for sustainable production and ecosystem services is another challenge. Merfield et al. (2015) note that while research supports the assertion that organic can deliver better economic, social, and environmental outcomes than other production systems, organic standards still do not cover many of the broader dimensions of sustainability. The authors describe an ecosystem services benchmarking tool for farmers to compare their production system anonymously with others in their community as a means of fostering innovation and learning. Jensen et al. (2015) call for more widespread adoption of evaluation metrics that measure yields in relation to environmental and social impacts; and Vaarst (2015) advocates for including factors that are more difficult to measure, like fairness and humaneness, in organic evaluations. Bàrberi (2015) argues that developing solutions based on functional biodiversity, rather than input substitution, will result in systems that are more resilient to biotic and abiotic stresses, and products that are more easily differentiated by consumers.

Organic agriculture has yet to become a dominant production method in any region of the world yet it serves a much broader role than is suggested by figures for the land area under organic certification or proportion of market share. Organic agriculture offers a "protective space" that fosters agro-ecologically based solutions to difficult questions (Niggli, 2015). The constraints imposed on the system encourage innovations that address simultaneous goals of food security, economic development, and environmental health; and that advance our collective understanding of the complex ecological processes underlying all agricultural systems. We hope the articles in this issue serve as a unique resource of information and inspiration for further research, innovation, policy recommendations, and development of organic and sustainable agriculture.

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A Review of Long-Term Organic Comparison Trials in the U.S.

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Abstract

Long-term organic farming system trials were established across the U.S. to capture baseline agronomic, economic and environmental data related to organic conversion under varying climatic conditions. These sites have proven useful in providing supporting evidence for successful transition from conventional to organic practices. All experiments chosen for this review were transdisciplinary in nature; analyzed comprehensive system components (productivity, soil health, pest status, and economics); and contained all crops within each rotation and cropping system each year to ensure the most robust analysis. In addition to yield comparisons, necessary for determining the viability of organic operations, ecosystem services, such as soil carbon capture, nutrient cycling, pest suppression, and water quality enhancement, have been documented for organic systems in these trials. Outcomes from these long-term trials have been critical in elucidating factors underlying less than optimal yields in organic systems, which typically involved inadequate weed management and insufficient soil fertility at certain sites. Finally, these experiments serve as valuable demonstrations of the economic viability of organic systems for farmers and policymakers interested in viewing farm-scale organic operations and crop performance.

Keywords: agroecology, transdisciplinary research, organic transition

1. Introduction

As early as 1843 in Rothamsted, England, and 1876 in the Morrow Plots in Illinois, U.S.A., agricultural researchers recognized the importance of documenting the impacts of long-term farming systems on crop productivity, soil quality and economic performance. The link between soil quality and farm viability was well understood, as Andrew Sloan Draper, who was President of the University of Illinois when the Morrow Plots were established, stated prophetically that "The wealth of Illinois is in her soil, and her strength lies in its intelligent development" (University of Illinois [UI], 2015). More recently, long-term organic farming system trials across the U.S. have been established to capture similar information. These long-term crop rotation studies also enable more robust economic analyses of potential profit outcomes as compared to experiments of shorter duration (Delbridge, Coulter, King, Sheaffer, & Wyse, 2011).

This paper examines six of the oldest grain-crop-based organic comparison experiments in the U.S. (Table 1), the goal of which is to demonstrate the unique contributions of each site and the usefulness of these sites in communicating agronomic, as well as environmental and economic outcomes from organic agroecosystems, to both producers and policymakers. Of particular interest to producers is the transition period at these sites: the 36 months between the last application of prohibited synthetic inputs and certified organic status. Long-term cropping systems trials can provide baseline data, monitor trends over time, and evaluate new technology in each system, within the context of sustainability indices (Baldock, Hedtcke, Posner, & Hall, 2014). Each site is categorized based on location (weather), soil type, crops, and organic/conventional management practices, to allow comparisons across sites. Additionally, notations on whether the site is certified-organic or organic-compliant (using organic practices without certification) are included. Recently, organic farmers have argued for organic research that is conducted on certified organic sites to ensure a modicum of equivalency as compared to practitioners' experiences. Thus, rotation treatments that would not qualify for organic certification have been discouraged from future comparisons (e.g., one site described below has changed their 2-yr to a 3-yr organic rotation).

Table 1. Long-term organic comparison trials in the U.S.

Name of experiment	Date initiated	Comparisons	Main crops	Lead entity and location
Farming Systems Trial (FST)	1981	Conv[1] C-S vs. Org 3 and 4-yr rotations	Corn, soybean, wheat	Rodale Institute Kutztown, Pennsylvania
Sustainable Ag Farming Systems (SAFS)	1988	Conv C, W, S, B and T vs. Org C, W, S, B, T, O	Corn, tomato, wheat, bean, safflower, oat/vetch/pea	University of California Davis, California
Variable Input Crop Management Systems (VICMS)	1989	Conv C-S vs. Org 3 (dropped Org 2) and 4-yr rotations	Corn, soybean, oat, alfalfa	University of Minnesota Lamberton, Minnesota
Wisconsin Integrated Cropping Systems Trials (WICST)	1989	Conv C-S vs. Org 3 and 4-yr rotations	Corn, soybean, wheat, oat, alfalfa	University of Wisconsin-Madison Arlington, Wisconsin
Beltsville Farming Systems Project (FSP)	1996	Conv C-S vs. Org 2, 3 and 6-yr rotations	Corn, soybean, wheat	USDA-ARS Beltsville, MD
Long-Term Agroecological Research (LTAR)	1998	Conv C-S vs. Org 3 and 4-yr rotations	Corn, soybean, oat, alfalfa	Iowa State University Greenfield, Iowa

[1] Conv = following conventional practices; Org = following certified organic practices. C=corn; S=soybean; W=wheat; O=oat; B=dry bean; S= safflower; T=tomato.

Key among organic practices is the necessity of extended crop rotations and organic-compliant soil amendments to optimize production, with each of these practices affecting soil quality, carbon sequestration, nitrogen cycling, and other associated functions. Soil quality is the main driver of optimal organic crop yields. Management of soil organic matter (SOM) to enhance soil quality and supply nutrients is a key determinant of successful organic farming, which involves balancing two ecological processes: mineralization of carbon (C) and nitrogen (N) in SOM for short-term crop uptake, and sequestering C and N in SOM pools for long-term maintenance of soil quality. The latter has important implications for regional and global C and N budgets, including water quality and C storage in soils. The importance of yield comparisons in long-term studies cannot be overlooked, as Seufert, Ramankutty, and Foley (2012) in their meta-analysis of organic and conventional crop yields recognized that optimal yields are central to sustainable food security, in addition to the range of other ecological, social and economic benefits organic farming can deliver. For example, when reviewing the relative yield performance of organic and conventional farming systems worldwide from studies beginning in 1988, Seufert et al. (2012) documented a 5% to 34% lower yield under organic management, depending upon crop and soil type, along with experience related to effective nutrient and pest management practices.

Several commonalities exist among the long-term experiments selected for this review (Table 1). All are systems-level experiments with rotation treatments derived from organic crop rotations practiced in each specific area. With corn (*Zea mays* L.) and soybean (*Glycine max* L.) production comprising 56% of the major crops grown in the U.S. (USDA-NASS, 2011), and wheat (*Triticum aestivum* L.) the third largest crop, one to three of these major crops are present in the trials discussed, as representative of the U.S. agricultural landscape. Because organic systems are complex in nature, in systems-level experiments, the abiotic and biotic components (structure) of the system can be evaluated in terms of the effects on system function (Drinkwater, 2002). Resulting system function data is then used to elucidate factors underlying less than optimal yields (Seufert et al., 2012) and help fine-tune best management practices to improve organic systems.

2. The Farming Systems Trial (FST) Rodale Institute, Pennsylvania

The Farming Systems Trial (FST) at Rodale Institute (RI) is the longest-running comparison of organic and conventional agriculture systems in the U.S. Located near Kutztown, Pennsylvania, the soil type is a moderately well-drained Comly silt loam. Established in 1981, in the year following the release of the first comprehensive study of organic agriculture by the USDA, which advocated such comparisons (USDA, 1980; Youngberg & Demuth, 2013), the FST compares two organic systems with a conventional system, using 0.17-ha plots in eight replications, with each crop in the rotation grown every year (Rodale Institute [RI], 2011). The farming systems chosen were based on typical grain crops grown in Pennsylvania: in the conventional system, corn and soybean were grown for 23 years, then wheat was added to the rotation starting in 2004. The two organic systems consisted of corn, soybean, wheat, and red clover (*Trifolium pretense* L.)-alfalfa (*Medicago sativa* L.) hay in the rotation, and compared contrasting methods for maintaining soil fertility: 1) legume cover crops only, vs. 2) manure-based fertility with cover crops. The conventional system followed land-grant university recommendations for synthetic chemical nutrient and pest management inputs. The FST was one of the first research units to report on the "transition effect" (Liebhardt et al., 1989), where organic grain yields matched conventional yields after an initial yield decline during the transition years. In 2008, genetically modified (GM) crops and glyphosate-based no-till treatments were added to the conventional comparison, in response to public pressure to compare more current conventional systems. Although organic plots could not be certified organic due to inadequate distance from GM crops, the organic systems always adhered to organic-compliant practices. While many in the organic community were opposed to RI adding GM crops in the FST, it has been interesting to note that, even with this advanced technology, conventional yields have not improved over non-GM conventional crops, contrary to what proponents believed would occur (RI, 2011). In addition, organic systems have demonstrated greater resiliency during drought, when organic corn yielded 8,411 kg ha^{-1} compared to 6,403 kg ha^{-1} in the conventional system (Lotter, Seidel, & Liebhardt, 2003).

The FST was one of the first comparison experiments that monitored water quality, through an underground lysimeter system, and found that leachate from the conventional system more frequently exceeded the NO_3-N drinking water standard of 10 ppm than the organic systems (Pimentel, Hepperly, Hanson, Douds, & Sidel, 2005). The RI also conducted a detailed energy analysis, which included the energy used in the manufacture, transportation and application of fertilizers and pesticides in each FST system. Their analysis identified that FST organic systems consumed 45% less energy than the conventional systems, with N fertilizer composing the largest conventional system energy input at 41% of total energy consumption. Thus, production efficiency was 28% higher in the organic system, with the conventional no-till system having the lowest efficiency, based on high-energy requirements for input manufacturing. In a concomitant analysis, greenhouse gas (GHG) emissions associated with the conventional systems were 40% greater per volume of production than the organic systems (RI, 2011).

Soil health, one of the key attributes in agriculture promoted by RI research, was shown to be greatest in the organic system where manure fertilization was employed, followed by the organic legume system. Annual carbon (C) increases were 981 kg C ha^{-1} in the organic/manure system, 574 kg C ha^{-1} in the organic/legume system, and 293 kg C ha^{-1} in the conventional system (Pimentel et al., 2005). Based on the higher soil quality promoting similar yields to the conventional system, the organic system has proven to be economically competitive, with an analysis conducted by Hanson and Musser (2003) showing only a 10% organic premium price was needed to ensure parity with the conventional system. When prevailing organic price premiums were added, the organic system returns averaged 2.9 to 3.8 times the conventional system (Moyer, 2013). Organic price premiums should be included in economic analyses, as they represent the reward organic farmers reap when practicing organic farming—a premium organic consumers are willing to pay in support of farmers who utilize less environmentally harmful methods of farming (Lin, Smith, & Huang, 2008).

3. The Sustainable Agriculture Farming Systems Project (SAFS), Davis, California

The Sustainable Agriculture Farming Systems project (SAFS) was established in 1988 at the University of California, Davis, to study the transition from conventional to low-input and organic crop production practices (University of California [UC], 2015). The experiment was unique in its study of Mediterranean crops, growing on Reiff loams (coarse-loamy, mixed, non-acid thermic Mollic Xerofluvents) and Yolo silt loams (fine-silty, mixed, non-acid, thermic Typic Xerothents). The SAFS site was located in the state with the highest number of organic farmers in the U.S., which led to the integral role of farmers and farm advisors in the planning, execution, and interpretation of results for greater dissemination to the organic farming community. In addition, organic plots were certified organic by California Certified Organic Farmers (CCOF), a critical factor in the site's applicability for regional farmers. Treatments included two conventional systems: a 2-yr (conv-2) and 4-yr (conv-4) crop rotation; and two 4-yr low-input and organic crop rotations (Poudel et al., 2001). The three 4-yr rotations included tomato, safflower, bean, and corn, while the conv-2 system was a tomato-wheat rotation. In the low-input and organic treatments, an oat/vetch/pea mixture was also part of the rotation. Four replications of each treatment and all crop rotation entry points were planted in 0.12 ha–plots, arranged in a randomized block, split-plot design. Furrow irrigation was used for all systems, typical of farming operations in California. Animal manure and winter cover crops provided fertility in the organic system, while the conventional systems received synthetic fertilizer inputs. The inclusion of a low-input system in long-term organic comparison trials can be problematic (unless it is the sole conventional comparator), because few, if any, of the “low-input” systems follow an equivalent pattern of input applications to allow comparisons across regions. For example, the SAFS low-input system used cover crops and animal manure during the first 3 years, then switched to cover crops and synthetic fertilizer, which would render it as essentially a conventional treatment.

Soils research at SAFS resulted in significant gain in our understanding of the processes involved in enhanced soil quality resulting from organic practices, including increased storage of plant nutrients and C, a reduction in soil-borne diseases, increased pools of P and K, higher microbial biomass and activity, an increase in mobile humic acids and soil water-holding capacity (Clark, Horwath, Shennan, & Scow, 1998). The SAFS site was one of the first experiments to examine soil microbial abundance and activity and determine the importance of cover crops and fall irrigations in promoting bacterial-feeding nematode populations and N mineralization (Jaffee, Ferris, & Scow, 1998), which led to improved organic tomato yields. Additionally, adjustments of grass/legume cover crop mixtures according to soil fertility conditions, along with rotating cover crops, helped prevent stem and foliar diseases. The inclusion of winter cover crops in the low-input and organic systems was a key factor in the success of these systems by supplying soil nutrients and aiding in water infiltration, which proved problematic under conventional management. Suppression of the root-knot nematode, *Meloidogyne javanica*, was associated with high levels of microbial biomass observed in the systems using cover crops (Bossio, Scow, Gunapala, & Graham, 1998). The conventional systems were the least efficient at storing N inputs, which are critical for long-term fertility maintenance (Clark et al., 1998). Microbial community variables were positively correlated with mineral N in the organic system, while the opposite was observed in the conv-4 system (Gunapala & Scow, 1998).

Under California’s often challenging climate, organic crops with high N demands, such as tomato and corn, were more susceptible to yield losses compared to conventional and low-input systems receiving annual applications of synthetic N fertilizer, while organic bean and safflower crops produced comparable yields (UC, 2015). As with the FST economic analysis, the importance of premium prices for economic viability was demonstrated, where, among the 4-yr rotations in the SAFS study, the organic system with premium prices was the most profitable (Clark, Klonsky, Livingston, & Temple, 1999). Interestingly, while the low-input system outperformed the organic system agronomically, because of the conventional prices received for low-input crops, this system fell below the two conventional systems in profitability.

In 2002–2003, SAFS began a second phase to examine the interaction of tillage effects on the three historical systems, and explore off-farm environmental quality by joining the Long Term Research on Agricultural Systems (LTRAS) project (UC, 2015). Many in the academic community were disappointed about the loss of such a valuable, long-term certified organic site as SAFS. The history of the SAFS site illustrates the fragility of long-term comparisons absent a strong and enduring institutional commitment. While important information may be derived from the LTRAS site, the LTRAS site does not have the same history of organic farmer involvement and oversight that the SAFS site invited, and many feel is critical for the success of long-term organic sites. As stated on the SAFS website: “Ideas that were once considered to be impractical or even radical are now gaining in popularity. As consumer demand for organic foods increases more growers are considering the transition to organic farming systems and seek out the SAFS project to get information and advice” (UC, 2015).

4. The Wisconsin Integrated Cropping Systems Trial (WICST), Arlington, Wisconsin

The WICST was established in 1989 but, because of a staggered start, every crop phase was not present every year for all the crop rotations until 1992 (Posner, Casler, & Baldock, 1995). Four replications of each crop phase were planted on 0.3–ha plots. The main soil type is a well-drained Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudoll). The treatments include six cropping systems (CS): 1) conventional continuous corn (CS1: CC); 2) conventional corn–soybean (CS2: C-S); 3) organic corn–soybean–winter wheat with frost-seeded red clover (CS3: C-S-W/RC); 4) conventional corn–alfalfa (CS4: C-A); 5) organic corn–alfalfa–oat (*Avena sativa* L.) plus field pea (*Pisum sativum* L.) mix, followed by a year of alfalfa hay (CS5: C-A/O/P-A); and a rotationally grazed pasture (CS6: RC/T/BG/OG) seeded to a mixture of red clover, timothy (*Phleum pratense* L.), brome grass (*Bromus inermis* L.) and orchardgrass (*Dactylis glomerata* L.). Soil changes at this site have not been as consistent as other long-term sites, primarily because of a history of a dairy–forage cropping system of corn and alfalfa with manure returned to the land for 20 years before establishing the trial, leading to high organic matter levels (47 kg g^{-1} at 0–15 cm) prior to the start of the experiment. The most salient observation from the WICST has been the correlation between weather, weeds and organic crop yields (Posner, Baldcock, &

Hedtcke, 2008). Because mechanical weed cultivation in organic systems is dependent on dry weather, in the years when wet weather prevented timely weed management, organic corn yields ranged from 72 to 84% of conventional corn yields, and organic soybean yields ranged from 64 to 79% of conventional soybean yields. Gaining experience and more advanced equipment for organic operations may have also impacted yield differences, as systems nearly equalized when better technology was introduced in the organic systems, and all cropping systems produced positive, average corn yield trends ranging from 0.1 to 0.2 Mg ha^{-1} yr^{-1} (Baldock et al. 2014). Similar to the FST results, adding GM crops did not improve yields. This was the first long-term trial to demonstrate that organic forage crop yields were equal or greater than conventional counterparts, with quality sufficient to produce an equivalent volume of milk as the conventional systems (Posner, Baldock & Hedtcke, 2008).

5. The Variable Input Crop Management Systems (VICMS) Trial, Lamberton, Minnesota

The Variable Input Crop Management Systems (VICMS) trial was established in 1989 at the University of Minnesota Southwest Research and Outreach Center near Lamberton, MN. Soil types at the site include Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Revere clay loam (fine-loamy, mixed, superactive, mesic Typic Calciaquolls), Ves clay loam (fine-loamy, mixed, superactive, mesic Calcic Hapludolls), and Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoquolls) (Porter et al. 2003). Two crop rotations and four management strategies are included in the trial, resulting in eight distinct crop management systems. The original crop rotations were a 2-yr corn-soybean rotation, and a 4-yr corn–soybean-oat/alfalfa–alfalfa rotation. The management strategies are zero-external-input (ZEI), low-external-input (LEI), high-external-input (HEI), and organic-inputs (OI). Liquid swine or beef manure was the external nutrient source in the 2- and 4-yr OI systems (applied at 129-138 kg N ha^{-1}). Treatments were replicated three times in a split-plot arrangement, with main plots as crop rotation, and all phases of each rotation present in each year. Split plots, constituting management systems, are 0.16–ha. As previously mentioned, the original 2-yr organic rotation has been replaced with a 3-yr rotation of corn-soybean-wheat/red clover to align the study more closely with predominant organic crop rotations in the region. From 1992 to 2007, corn grain yield was not reduced in LEI and OI 4-yr rotations compared to the HEI 2-year rotation (Coulter, Delbridge, King, Allan & Schaeffer, 2013). Highest organic corn yields, as observed in other long-term sites, were associated with timely weed management. The benefit of the longer organic rotation was observed with soybean yield response, as the relative soybean yield as a percentage of the HEI 2-yr rotation was greatest in the OI 4-yr rotation from 1992 to 2003 (65%) and in the OI 2- and 4-yr rotations from 2004 to 2007 (38 and 41%, respectively) (Coulter et al., 2013).

Soil quality increased in the organic systems in a similar pattern as other long-term sites. The OI system contained the greatest amount of particulate organic matter and potentially mineralizable C compared to the other systems in both rotations (Coulter et al., 2013). Total soil organic C and microbial biomass was higher in the 4-yr OI system than the 4-yr HEI system. Some of the most important contributions from the VICMS site included a detailed economic analysis of the organic systems, including risk analysis. Delbridge et al. (2011) found that when organic price premiums were applied, the average net return of the organic rotation was considerably larger than that of both conventional rotations (\$1329 ha^{-1} vs. an average of \$761 ha^{-1}). Across years and crops, net return was 88% greater with the OI 4-yr rotation than the HEI 2-yr rotation. Organic systems also were found to be stochastically dominant to conventional rotations at all levels of risk aversion (Delbridge, Fernholz, King, & Lazarus, 2013).

6. USDA-ARS (Agricultural Research Service)-Farming Systems Project (FSP)

The FSP was established in 1996 at the USDA-ARS Henry A. Wallace Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland. In contrast to other sites, the FSP was designed to evaluate the sustainability of organic rotations, using typical tillage regimes, compared to conventional cropping systems using both tilled and no-till operations (Cavigelli, Teasdale & Spargo, 2013). Farmers, extension agents, agribusiness professionals, and agricultural researchers were involved in system design. The FSP is comprised of five cropping systems: 1) conventional no-till (NT) corn–soybean–wheat/double-crop soybean rotation: NT: C–S–W/S; 2) a conventional chisel-till (CT) corn–soybean–wheat/soybean rotation: CT: C–S–W/S; 3) a 2-year organic corn–soybean rotation (Org2: C–S); 4) a 3-yr organic corn–soybean–wheat rotation (Org3: C–S–W); and 5) a 6-yr organic corn–soybean–wheat– alfalfa (3 years) rotation (Org6: C–S–W–A–A–A). All plots are 0.1 ha in size and all are managed using full-sized farming equipment. Soils at the site range from poorly-drained to well-drained Ultisols. Results observed at the FSP support the association between system stability and diversity, with lengthening rotations improving agronomic, economic and environmental performance. Specifically, N availability was greater in the 6-yr organic rotation and yields were greater than the 3-yr organic rotation and 2-yr conventional

C-S yields.

Regarding other aspects of soil quality, POMN and SOC in all organic systems were greater than in the conventional NT, which signaled the first report of this phenomenon. Conventional no-till farming, which relies on petroleum-based glyphosate herbicide, is advocated throughout the U.S. for its soil quality enhancement, but the N mineralization potential of the organic system at the FSP was, on average, 34% greater than conventional NT after 14 years. Total potentially mineralizable N in organic systems (average 315 kg N ha^{-1}) was significantly greater than the conventional systems (average 235 kg N ha^{-1}) (Spargo, Cavigelli, Mirsky, Maul & Meisinger, 2011). The SOC was greater in the 6-yr organic rotation compared to NT at all depths except 0 to 2 inches. Despite the use of tillage in organic systems, soil combustible C and N were higher after 9 years in an organic system that included cover crops compared with the three conventional no-till systems, two of which included cover crops, suggesting that organic practices can potentially provide greater long-term soil benefits than conventional no-till (Teasdale, Coffman & Mangum, 2007). Weed pressure decreased with longer rotations (Teasdale & Cavigelli, 2010), suggesting an allelopathic or competitive effect from multiple years of alfalfa–a solid-seeded crop that was cut regularly, which inhibited weed growth. Economic risk also decreased as rotation length increased, and organic returns averaged \$706 ha^{-1} compared to \$193 ha^{-1} (Cavigelli, Hima, Hanson, Teasdale, Conklin, & Lu, 2009). Throughout the mid-Atlantic states, rising concerns regarding nitrate and phosphate fertilization pollution into fragile waterways, like the Chesapeake Bay, has led to increasing restrictions and research on pollution-mitigation methods. A beneficial outcome of the 6-yr organic rotation in this regard was that less poultry manure was needed for optimal yields compared to shorter rotations, thus decreasing nitrate and phosphate pollution potential.

7. The Long-Term Agroecological Research (LTAR) Experiment, Iowa

The LTAR experiment was established in 1998 at the Iowa State University Neely-Kinyon Farm in Greenfield, Iowa, with funding from the Leopold Center for Sustainable Agriculture. This support allowed focus groups of conventional and organic farmers to help determine the appropriate design and purpose of the LTAR experiment (Delate & DeWitt, 2004). Farmers requested a long-term comparison of the ecological and economic outcomes of conventional and organic cropping systems. The research was then constructed to evaluate alternatives to the traditional corn–soybean rotation in Iowa, and investigate production processes based on agroecological principles, designed to reduce off-farm energy demand and to increase the internal resilience of agroecosystems, which consequently increases their adaptability to potential climate change. Unlike purely research-based experiments, the goal of the LTAR site is to encourage transition to organic production, by documenting the environmental services in organic systems that contribute to climate change mitigation and enhancement of soil quality, crop health, productivity, and food quality. Objectives include identifying cropping systems within the LTAR experiment that maximize yields and soil quality, by fostering carbon sequestration and minimizing nutrient loss; promoting supporting and provisioning ecosystem services of biodiversity, pest suppression, water quality, and soil health through the integration of C-stabilizing components; increasing economic returns by reducing costs of production in field operations and labor, decreasing dependence on external sources of applied fertility, lowering energy costs, and gaining carbon credits. Finally, educational objectives include field days, workshops and pasture walks for farmers, students, and agricultural professionals to increase understanding and facilitation of the transition to organic production.

The LTAR experiment is located on a 7-ha ridge top with a uniform slope of 0 to 2% with the predominant soil type a moderately well-drained Macksburg silty clay loam (fine, smectitic, mesic Aquic Argiudolls). The cropping system treatments at the LTAR site were designed based on local farmer input with the goal of organic certification 36 months after establishment. Each crop in each rotation is replicated four times in 0.1–ha plots. Rotations include: 1) conventional corn-soybean (C–S); 2) organic corn-soybean-oats/alfalfa (C–S–O/A); and 3) organic corn-soybean-oats/alfalfa-alfalfa (C–S–O/A–A). Conventional crops are maintained with synthetic fertilization and pesticides, while certified organic fertilization and pest management methods are used in organic plots, using typical farming equipment for the area. Effects of system and rotation treatments are determined for crop productivity and yields; weed, insect, disease, and nematode pest management; soil quality and fertility; nutrient retention and balance; and grain quality. Economic analyses, determined for each treatment, include costs of inputs, subsequent yields, and selling price of organic and conventional crops.

Over 13 years, LTAR organic corn and soybean yields were equivalent or greater than conventional counterparts. Unlike many studies where organic yields suffer during the transition phase, the first LTAR transitioning-to-organic phase demonstrated corn yields in the organic system that were 92% of conventional corn yields while organic soybean yields were 99.6% of conventional soybean yield (Delate & Cambardella, 2004). The advantage of the longer, 4-year organic rotation, which included two years of a perennial legume crop, was exhibited by organic corn yields that averaged 99% of the average conventional corn yield in the post-transitioning phase (Delate, Cambardella, Chase, Johanns, & Turnbull, 2013). Organic soybean yields were 5% greater in the organic rotations than conventional soybean yields. Soil quality results from the LTAR showed that overall soil quality, and especially soil N mineralization potential, was highest in the 4-year organic crop rotation. The organic soils had more soil organic carbon, total N, microbial biomass C, labile organic N, higher P, K, Mg and Ca concentrations, and lower soil acidity than conventional soils. A particularly interesting soils result was obtained in 2012, when an extended drought period was experienced, with 22 cm below normal rainfall during the growing season, and an average of 3 °C above normal temperatures in July. At the end of the 2012-growing season, particulate organic matter C (POM-C) was higher in the organic soils than the conventional, likely because of altered rates of decomposition of new residue C inputs during this especially dry year (Table 2). Soil quality enhancement was particularly evident for labile soil C and N pools, which are critical for maintenance of N fertility in organic systems, and for basic cation concentrations, which control nutrient availability through the relationship with cation exchange capacity (CEC). Despite the serious drought conditions during the growing season in 2012, organic management enhanced agroecosystem resilience and maintained a critical soil function, the capacity to supply nutrients to the crops. Carbon budgets developed after 10 years of organic production showed that the 4-yr organic cropping system can potentially sequester as much soil organic carbon (SOC) in the top 15 cm as obtained when converting from plowing to no-tillage, which is considered the best management practice in conventional farming.

Table 2. Neely-Kinyon Long-Term Agroecological Research (LTAR) experiment soil quality–Fall 2012

	SOC gkg^{-1}	TN gkg^{-1}	POM-C gkg^{-1}	POM-N gkg^{-1}	MBC $mgkg^{-1}$	PMIN-N $mgkg^{-1}$	NO_3-N $mgkg^{-1}$	P $mgkg^{-1}$	K $mgkg^{-1}$	Mg $mgkg^{-1}$	Ca $mgkg^{-1}$	pH	Aggs %	BD gcm^{-3}
ConvC-S[1]	23.1	2.4	3.0	0.31	275	40.1	21.4	21.2	185	366	3487	6.09	34.9	1.27
OrgC-S-O/A	25.7	2.6	4.5	0.33	270	51.9	20.5	57.5	283	413	3870	6.51	35.0	1.22
OrgC-S-O/A-A	24.8	2.5	3.8	0.23	296	52.1	19.7	34.0	251	407	3831	6.41	41.2	1.21
OrgC-S-C-O/A	24.7	2.5	4.3	0.28	362	52.2	16.7	27.4	203	479	3866	6.34	45.4	1.13
$LSD_{0.05}$	1.4	0.1	1.1	NS	42	7.1	NS	12.7	50.9	50.1	161	0.19	7.4	0.08

[1]Results from five randomly-located soil cores (0-15 cm), composited, and removed from each plot after fall harvest, prior to any tillage. Conv = conventional; Org = certified organic; C = corn; S = soybean; O = oats; and A = alfalfa. SOC = soil organic carbon; TN = total nitrogen; POM-C = particulate organic matter-carbon; POM-N = particulate organic matter-nitrogen; MBC = microbial biomass carbon; NO_3-N = nitrate-nitrogen; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; Aggs = aggregate stability; BD = bulk density; LSD = Least Significant Difference at $p<0.05$; NS = not significant.

Economic returns mirrored those previously reported at other sites, with the organic rotations garnering, on average, twice the returns of the conventional rotation (Delate et al., 2013), and lower costs than conventional crops during transition (Delate, Duffy, Chase, Holste, Friedrich, & Wantate, 2003; Delate, Chase, Duffy, & Turnbull, 2006). Results from the LTAR experiment have been similar to other long-term trials, although LTAR organic yields have often exceeded those reported in the literature. Higher than usual yields during the transition phase could be attributed to the overall fertility of the Mollisols at the site and the high level of weed management experience, which has been a key aspect of success. Despite the equivalence in net C input, the soil under organic management holds significantly more C than the soil under conventional management, and over the coming decade, we will continue to monitor resulting changes in soil edaphic and biotic characteristics including soil microbial community structure and function under the various cropping systems.

8. Conclusions

The six long-term organic comparison sites examined in this review have contributed to an invaluable understanding of the mechanisms underpinning higher soil quality in organic systems, particularly enhanced C and N storage, leading to competitive economic returns. All experiments were transdisciplinary in nature; analyzed comprehensive system components (productivity, soil health, pest status, and economics); and contained all crops within each rotation and cropping system each year, a critical factor for analysis across years. Plot size ranged from 0.1 to 0.3 ha–an area of sufficient size to utilize farm-scale machinery and provide an accurate portrayal of typical farmer experience–often lacking in research station plot research. While, ideally, on-farm sites with larger fields should be employed as comparators to field station experiments to allow a minimum comparison of 5 to 10 years since conversion from conventional farming, as promulgated by Sir Albert Howard (1946), oftentimes, long-term on-farm sites are difficult to obtain and manage. Comparisons with organic grain yields reported from organic farmer surveys in Iowa showed a reduction of 17-20% in organic corn and soybean yields, but returns comparable to the 2X results demonstrated in the long-term trials (Chase, Delate, Liebman, & Leibold, 2008). Organic yield performance was improved in four of the six sites with increased experience and timely weed management, while two sites (FSP and LTAR) with experienced farm managers reported adequate weed control and concomitant equivalent organic and conventional yields early in the long-term site's history. The addition of manure, along with legume forages/cover crops, in the organic fertility scheme has proven essential for sufficient soil quality to support optimal yields across all sites. The scientific rigor under which these sites were operated has provided strong evidence supporting the viability of organic cropping systems for farmers and policymakers alike. Wherever organic farmer involvement in experimental design and feedback was explicit, and organic certification was obtained, organic comparison sites appeared to be more successful in terms of engagement and dissemination of results.

With organic product supply lagging behind the expanding market demand, partially owing to the perceived obstacles to successful transition to organic production (Dimitri & Oberholtzer, 2009), these sites provided sufficient evidence of the potential for successful organic transition. Adoption of land management strategies that foster C sequestration in agricultural soils will be important over the next several decades as we develop new mitigation strategies and technologies to reduce C emissions (Smith, 2004). Agricultural land management options currently recommended to foster C sequestration nearly always include some reduction in tillage intensity, which has been the on-going, or second-phase research, of four of the long-term sites (FST, SAFS, FSP; now VICMS), and implementation of integrated, multifunctional cropping rotations that include cover crops/forage legumes, small grains, and animal manure/compost soil amendments, as demonstrated by all long-term sites. Water quality enhancement, by reducing NO_3-N loss through the adoption of organically managed extended rotations that include small grains, forage legumes and pasture (see Cambardella & Delate, this issue), is considered an integral part of the next phase of many of the long-term trials. These results suggest that organic farming practices have the potential to reduce nitrate leaching, foster carbon sequestration, and allow farmers to remain competitive in the marketplace. Institutional support for these long-term comparisons is critical for successful organic farming demonstrations for area farmers and policymakers.

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Optimising Cropping Techniques for Nutrient and Environmental Management in Organic Agriculture

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Abstract

Depth and architecture of root systems play a prominent role in crop productivity under conditions of low water and nutrient availability. The subsoil contains high amounts of nutrients that may potentially serve for nutrient uptake by crops including finite resources such as phosphorus that have to be used in moderation to delay their exhaustion. Biopores are tubular shaped continuous soil pores formed by plant roots and earthworms. Taproot systems especially those of perennial legumes can make soil nutrients plant available from the solid phase and increase the density of vertical biopores in the subsoil thus making subsoil layers more accessible for succeeding crops. Density of larger sized biopores is further enhanced by increased abundance and activity of anecic earthworms resulting from soil rest and amount of provided feed. Nutrient rich drilospheres can provide a favorable environment for roots and nutrient uptake of subsequent crops. Future efficient nutrient management and crop rotation design in organic agriculture should entail these strategies of soil fertility building and biopore services in subsoil layers site specifically. Elements of these concepts are suggested to be used also in mainstream agriculture headlands, e.g. as 'Ecological Focus Areas', in order to improve soil structure as well as to establish a web of biodiversity while avoiding constraints for agricultural production.

Keywords: root system, biopore, drilosphere, endoscopy, subsoil

1. Introduction

In organic agriculture, high quality crop production and ecosystem health are strongly affected by soil quality. Soil quality can be distinguished at least as having two components. Firstly, the production functions that enable efficient sustainable net production of crops with optimised process and product qualities. Secondly, the ecological functions like filter and buffer functions, biodiversity, self-regulation and soil resilience.

In mainstream agriculture nutrient management has focused on directly increasing the nutrient concentration of the soil solution of the Ap horizon by fertilization with soluble nutrients. High rooting density meets a nutrient rich topsoil as a result of high fertilization.

Highly soluble mineral fertilisers are not permitted to be used in organic agriculture. In contrast to mainstream agriculture, organic agriculture typically has to deal with a scarcity of nutrients. Strategies making the nutrients in the system internally available, e.g. via biological nitrogen fixation or weathering, or keeping the nutrients potentially available in the long-term as a function of cycling, have to be used efficiently. Instead of directly increasing nutrient intensity and capacity of the soil via fertiliser inputs from outside, the farm nutrient management in organic agriculture relies on using and enhancing biological and microbiological processes primarily driven by agronomic measures like crop rotation design and tillage managing stationary nutrient flows. A larger part of the plant nutrients in the soil may derive from the solid phase that consists of mineral particles and different sources of soil organic matter. Consequently, nutrient management has to be considered as the optimised combination of resources that are restricted or have to be made plant available by achieving an optimised utilization, e.g. via increased rooting density and efficiency of nutrient absorption (Köpke, 1995).

For a long time research has neglected the capacity of nutrients bound in the subsoil, although for instance between 25 and 70% of total soil P may be allocated in subsoil layers (Godlinski et al., 2004; Kautz et al., 2013a). Thus, in the case of P the subsoil may provide supply with a finite resource that has to be used in moderation to delay its exhaustion. Also, weathering in the subsoil and the release of potassium, magnesium and other nutrient elements from clay minerals have not been sufficiently investigated so far. Nevertheless, compared with the Ap horizon, only a relatively small proportion of the soil volume is considered as actively contributing to plant nutrient uptake in the bulk subsoil.

In natural ecosystems not directly affected by anthropogenic activities, nutrient uptake of the vegetation is almost completely performed by the solid phase. Thus, mimicking nature, as requested by Sir Albert Howard, a pioneer of organic agriculture (Howard, 1943) should entail the mobilisation of nutrients from the solid phase in the subsoil. In general, the spatial accessibility of less mobile nutrients like P and K is lower in the untilled subsoil compared with the tilled topsoil. Hence, any strategy of nutrient acquisition from the subsoil has to consider the size and architecture of the root systems and the extension of the rhizosphere as well as various biochemical strategies of the crop as essential measures. Subsoil accessibility by crop roots is enabled by channeling the bulk soil with larger sized biopores formed by taproot systems and earthworms. Recently in a comprehensive review, Kautz (2014) reported the current state of knowledge on the functions of biopores in agricultural soils and outlines consequences for organic management. Less is known about biopores' services that may provide additional environmental off-site benefits, i.e. biodiversity that may result in higher resilience of the agroecosystem. By identifying and managing the functions of biopores, they may provide ecological and environmental services for vital and sustainable agroecosystems.

This paper deals with an overview on our recent research on developing cropping systems that enable better use of water and nutrients from the subsoil. The overall aim is to create and manage large sized biopores in order to enable better access to deeper soil layers, to enhance water and nutrient uptake via biopores formed by roots and earthworms and to deliver also above ground ecological services. We end our journey with a conclusions and outlook section.

2. Accessing the Subsoil

2.1 Creating Biopores

Biopores are round-shaped channels formed by roots after their decay as well as those designed by earthworms which often use and widen biopores that were preformed by roots. Allorhizal root systems of dicots (taproots) leave larger sized biopores than fibrous more homogeneously distributed root systems of monocots. Our research on biopores is grounded in the early observations of Albert Schulz-Lupitz who developed his commercial farm on very poor sandy soils in the midst of the 19th century. He reported higher tuber yields after cultivating lupin as a preceding green manure crop to potatoes. This effect was not based on residual nitrogen of the legume only but on biopores created by lupin taproots that could penetrate and cross dry and iron-cemented subsoil layers and which enabled access of potato roots to water holding subsoil layers beneath (Schultz-Lupitz, 1895).

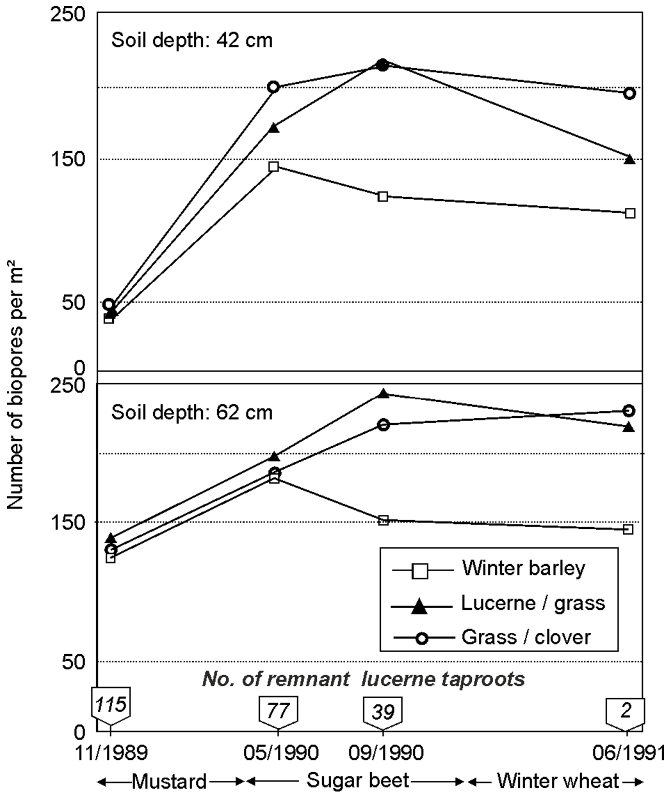


Figure 1. Density of biopores in the subsoil as a function of different precrops, soil depth and time

Source: Dreesmann (1993). Pflanzenbauliche Untersuchungen zu Rotklee-und Luzernegras-Grünbrachen in der modifizierten Fruchtfolge Zuckerrüben -Winterweizen - Wintergerste.

Figure 1 shows the effect of a modified sugar beet-winter wheat-winter barley crop rotation where winter barley was substituted by green fallows consisting of either lucerne/grass or grass/red clover. Green fallows and barley were sown in autumn 1988 and the green fallows mulched twice during the summer season of 1989. After ploughing all treatments in autumn 1989 mustard was grown as a catch crop over winter followed by sugar beet in spring 1990 (Dreesmann, 1993). Compared with the barley precrop the density of biopores at 42 and 62 cm soil depth was clearly higher after the grass/legume fallows. This effect lasted on the loessial soil during the following seasons of the first and second subsequent main crops, i.e. sugar beet and winter wheat. Thus, the higher number of biopores after lucerne/grass and grass/clover compared to barley precrop is attributable to the taproot systems of the legumes grown in the fallows, and secondly, as a function of residual fallow nitrogen that caused a more vigourous growth of mustard that also displays a taproot system. Thirdly, we assume a higher earthworm abundance as a function of a better feeding habitat in and after fallowing compared to barley. This hypothesis is underlined by biopore continuity which was determined by infiltrating ink through biopores. The total number of ink-marked biopores was higher even two years after the fallows, and this was largely due to the biopores greater than 5 mm in diameter (Figure 2) formed by earthworms.

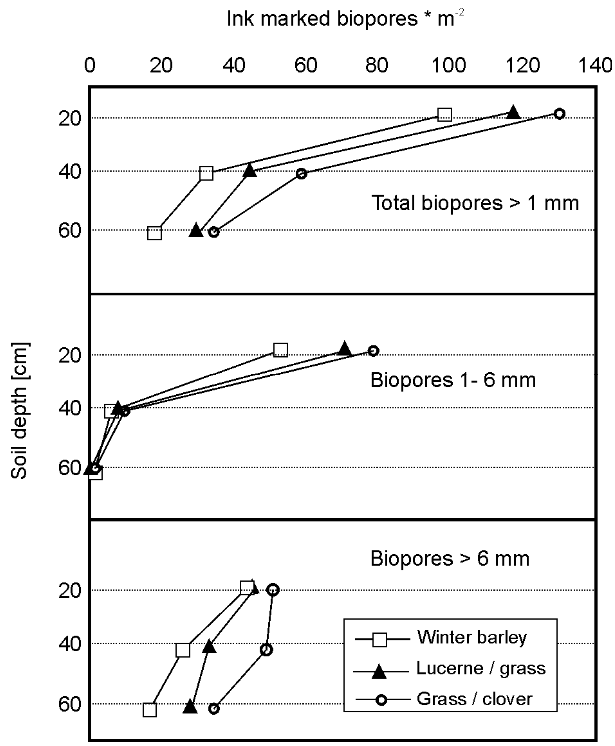


Figure 2. Continous biopores beneath second preceding crop winter wheat (see Figure 1) as a function of different precrops and soil depth

Source: Dreesmann (1993). Pflanzenbauliche Untersuchungen zu Rotklee-und Luzernegras-Grünbrachen in der modifizierten Fruchtfolge Zuckerrüben -Winterweizen - Wintergerste.

Similar results were gained with two series of field trials by the German research unit DFG 1320 that were established in 2007 and 2009. Three forage precrops with different root systems (fibrous/homorhizous roots: tall fescue, *Festuca arundinacea* Schreb. vs. taproots/allorhizous roots: lucerne, *Medicago sativa* L., chicory, *Cichorium intybus* L.) were grown for one, two and three years followed by subsequent non-legumes with fibrous roots and taproots (for details concerning experimental design and site see: Perkons et al. (2014) and http://www.for1320.uni-bonn.de/experimental-design/experimental-design-trialabc.pdf). All subsequent results reported in this paper refer to these field trials.

The taprooted forage crops resulted in significantly higher number of biopores in all biopore classes under study (Figure 3). Combining the extended time of soil rest with taprooting (chicory 2yrs) gave more continuous biopores compared with fibrous roots grown for one year only (fescue 1yr, Figure 4).

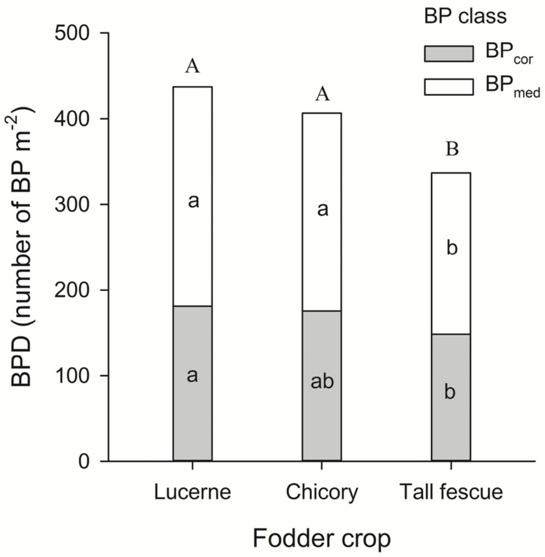


Figure 3. Biopore density after taprooted lucerne and chicory and fibrous root system of tall fescue of coarse-sized pores (BPcor: >5 mm) and medium-sized pores (BPmed: 2-5 mm). Capital letters indicate significant differences between fodder crops of total BPD. Small letters indicate significant differences of crop effects within BP classes (Tukey's HSD, P≤0.05)

Source: Han et al. (submitted). Quantification of soil biopore density after perennial fodder cropping.

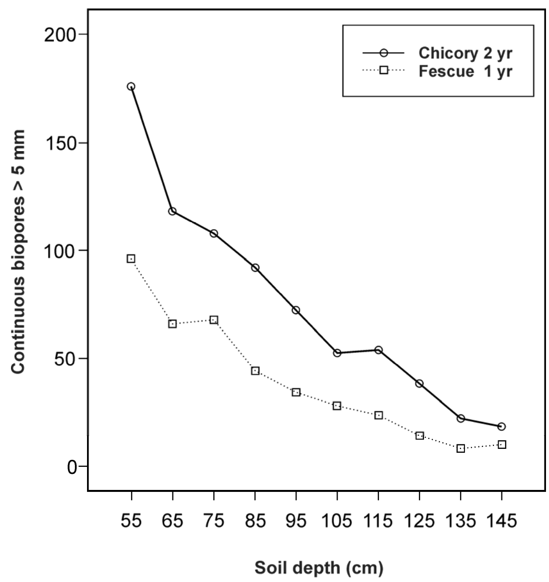


Figure 4. Continous biopores as a function of soil depth after two years chicory and one year fescue preceding crops

Source: Lütke Holz (2011). Bioporengenese durch mehrjährigen Futterbau: Einfluss von Pflanzenart und Anbaudauer auf Porengröße und –kontinuität.

2.2 Advantages of Biopores

During a dry spell in the 2010 season, significantly higher water extraction by the succeeding spring wheat was determined for the 90-105 cm soil depth after two years lucerne compared with two and three years of chicory and one year fescue precrop treatments (Gaiser et al., 2012). Higher biopore density after deep rooting lucerne enabled roots of spring wheat to explore the deeper soil layer more extensively. Subsoil root-length density (RLD) of winter barley grown in 2011 was significantly higher after two years chicory compared with oat-fescue precrops (Perkons et al., 2014).

In contrast to earlier studies that reported most of the roots in the deep subsoil growing inside large sized biopores such as earthworm burrows (e.g. Köpke, 1981; Ehlers et al., 1983), results of Perkons et al. (2014) indicated RLD of winter barley and oilseed rape in biopores comprising only about 21% of total RLD. They found taprooted crops allowing subsequent crops to establish more roots in deep soil layers, both inside and outside of large sized biopores. Increased RLD outside of large sized biopores is attributed to fine pores created by lateral roots of the taproot system or roots re-entering the bulk soil from large sized biopores.

That roots not only enter but may leave a putative soil environment given with the biopore is visualized with the photos of Figure 5 made with a videoscope. The idea of U. Köpke to use *in situ* endoscopy as a new method for studying root growth in biopores avoids dislocation and artifacts by introducing the endoscope 'bottom up' up to about 10 cm into the biopore, a method which has since been further developed (Kautz & Köpke, 2010; Athmann et al., 2013). We consider direct endoscopic observation of root growth in its given environment an essential prerequisite for a better understanding of root-soil relationships.

Figure 5. Root growth in biopores (pore diameters: approx. 10 mm) observed by *in situ* endoscopy. Ingrowing roots of mallow (left); root of mallow leaving the biopore entering the bulk soil (right)

Source: Athmann et al. (2012). Einsatz angepasster Endoskopie zur Charakterisierung des Wurzelwachstums in Bioporen.

The attractiveness of biopores for root growth is not only through lesser soil impedance enabling faster vertical growth to deeper soil layers. Earthworms reallocate nutrients to deeper soil layers creating the nutrient rich pore walls by deposited wormcast, the so-called drilosphere. When compared with the bulk soil most crop growth improving soil chemical and soil microbial parameters of the drilosphere are higher (Kautz et al., 2013a). After taprooted lucerne and chicory crops the P_{CAL} concentration in linings of biopores larger than 2 mm was up to 5 fold higher than the P_{CAL} concentration in the bulk soil and higher than after fescue (Barej et al., 2014).

Figure 6 shows higher soil N and C concentrations in biopores with earthworms when compared with the bulk soil concentrations. Root lengths of winter barley in individual biopores show that elevated N concentrations in pore walls can facilitate the exploration of the subsoil by crop roots (Figure 7). Thus, the effect of earthworm burrows goes beyond bioporing by taproots only.

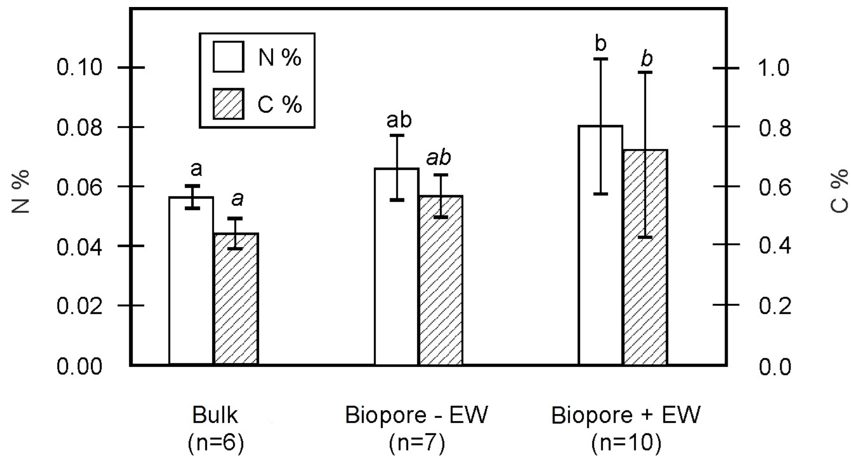


Figure 6. N concentrations and C concentrations in bulk soil and biopores without earthworms (-EW) and with earthworms (+EW) according to endoscopy images

Source: Athmann et al. (2014). Biopore characterization with *in situ* endoscopy: Influence of earthworms on carbon and nitrogen contents.

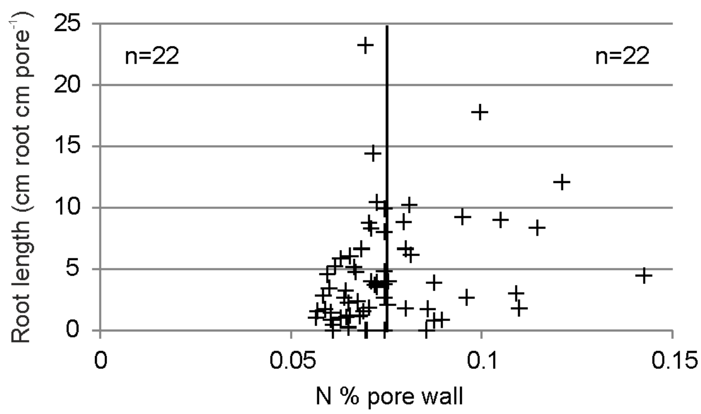
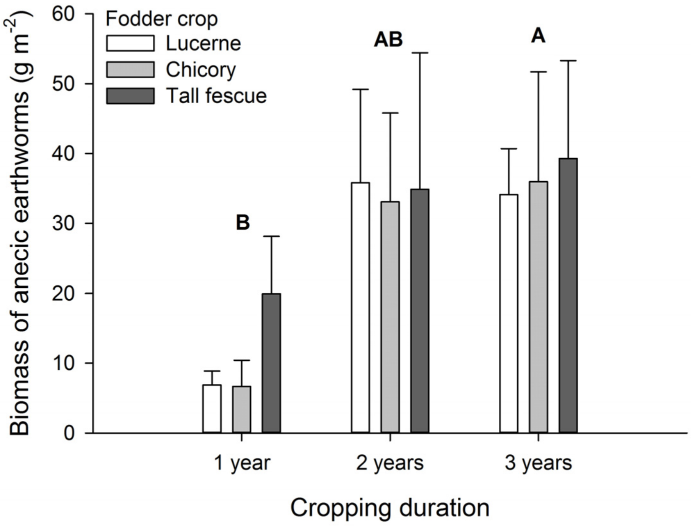


Figure 7. Root length of winter barley as affected by N concentrations of individual pore walls

Source: Kautz et al. (2014b). Growth of barley (*Hordeum vulgare* L.) roots in biopores with different carbon and nitrogen contents.

Since after all fodder crops high amounts of shoot mass were left as mulch on the soil surface, earthworm biomass and abundance were not affected by fodder crop species but significantly increased by cropping duration. On the other hand the duration of soil rest under taprooted fodder crops should not only result in higher abundance and biomass of earthworms (Figure 8) but also in the advantage of bigger sized pores and higher amounts of re-allocated nutrients as a function of the increased share of active adults. Actually, the proportion of adult individuals of *Lumbricus terrestris* re-colonizing existing biopores or creating new pores, thus increasing the drilosphere space was significantly higher compared with sub-adults (Kautz et al., 2014a).



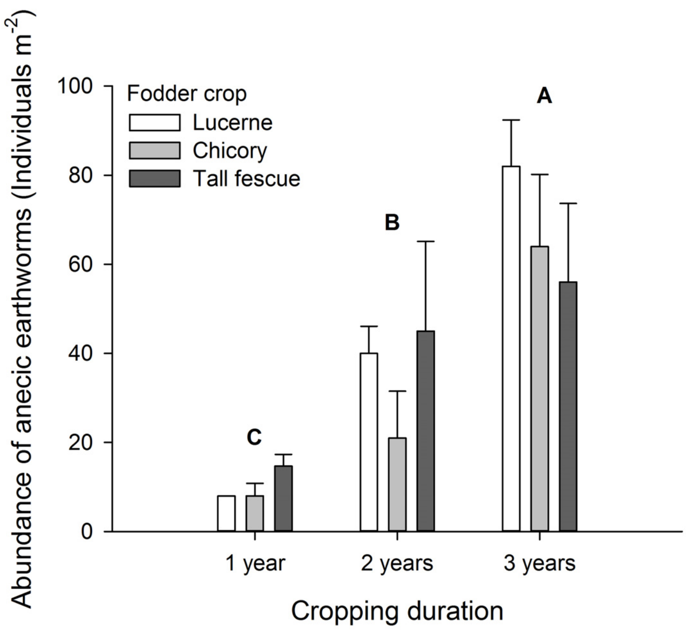


Figure 8. Earthworm biomass and abundance as affected by precrop fodder crops and cropping duration. Letters indicate significant differences affected by cropping duration (Tukey's HSD, P≤0.05)

Source: Han et al. (submitted). Quantification of soil biopore density after perennial fodder cropping.

3. Practical Application-Biopore Management

Since fodder cropping is essential in mixed farms with ruminants, this farm type is able to use taprooted fodder cropping better than arable farms. Nevertheless, new approaches exist in arable and vegetable farms to use fodder legumes as donor crops for N. In so-called 'cut and carry systems' farmers apply the shoot material of the fodder legumes not necessarily included to the crop rotation to high N-demanding and high value crops (Figure 9). Since biopores in the subsoil can persist over years, the strategy 'cut and create' hypothesizes the progression of biopore density as a function of cycling perennial taproot fodder cropping and the use of the mouldboard plough. We assume that cutting the biopores via ploughing ('cut and create') will further increase the number of new taproot created biopores during the next repeated growing cycle since new taproots may not necessarily find and use older biopores from the former taproot cycle.

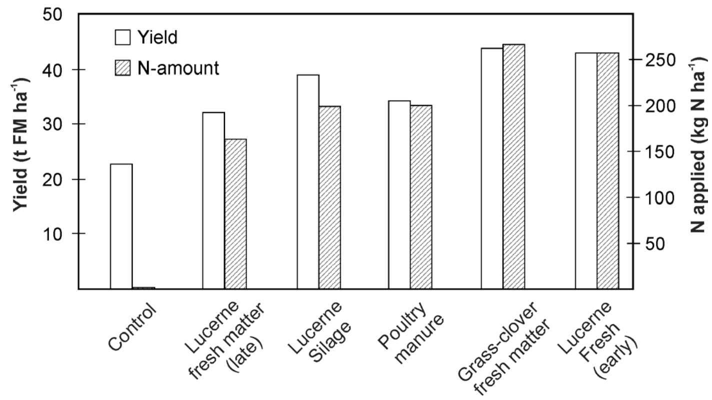


Figure 9. Spinach yield as affected by nitrogen sources of different origin

Source: Burgt et al. (2011, altered and amended). Developing novel farming systems: effective use of nutrients from cover crops in intensive Organic Farming.

In the EU Basic Payment Scheme starting in 2015, farmers have to comply with greening requirements. The aim of Ecological Focus Areas (EFA) is to safeguard and improve biodiversity on farms on at least 5% of set-aside area per farm. Especially in regions dominated by arable farms it is doubtful whether farmers would establish measures like hedgerows and broader sized field margins. But farmers might be interested to use our above outlined strategies on headlands. These parts of arable fields are often poorly structured and compacted, thus resulting in less productivity with lower gross margins compared with within-field soil conditions and resulting productivity. On headland sites of organically managed commercial farms, perennial grass-clover and alfalfa resulted in a higher density of larger sized biopores (Kautz et al., 2010). Thus, the strategy of 'greening the headlands' with perennial taprooted fodder legumes as a cost-efficient and attractive strategy was previously suggested (Köpke & Wiggering, 2013). Besides improving the soil structure, cropping of taprooted flowering fodder crops that are left uncut over winter is considered able to additionally enhance biodiversity - at least of insects, field birds and smaller mammals - via providing feeding and hibernation habitats.

4. Conclusions and Outlook

Extended biopore systems and the properties of the drilosphere are a function of crop specific root systems and earthworm activity. Crop rotation design should include taproot systems of perennials for accessing deeper soil layers in order to make nutrients available from the solid phase and to create biopores. When a soil rest phase and high-quality crop residues are provided, the earthworm population will further increase biopore density and enhance the nutrient status and physical stability of the drilosphere. Pore walls enriched in nutrients re-allocated by earthworms can promote nutrient acquisition from the subsoil. Cutting biopores by tillage and repeating the strategy may lead to increased biopore density and soil quality ('*cut and create*'). Mixed farming systems enable efficient implementation of taprooted fodder crops. Stockless farms can use '*cut and carry*' systems with the same effects of soil improvement. Drought or scarcity of nutrients in the topsoil should increase the share of nutrients taken from the subsoil in total crop uptake. Thus, effects of climate change may better be balanced via these strategies of subsoil structure heterogenization. On headlands soil structure can be improved and above ground environmental services generated ('*greening*', Ecological Focus Area). The effects of enhanced access of crop roots to deeper soil layers and their lasting biopores have been proved for non-swelling loess derived soils and may not hold true for other soils especially coarse sandy soil.

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Functional Biodiversity in Organic Systems: The Way Forward?

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Abstract

Trends in EU agricultural policies recognize an increasingly important role to biodiversity conservation and use in agroecosystems, including organic ones. However, along with their economic success, organic systems are facing a risk of 'conventionalization', i.e. the prevalence of input substitution over agroecologically-based crop management. Understanding what is functional agrobiodiversity and when it can be successfully applied in organics may help strengthen the recognition of organic farming as the reference management system for agricultural sustainability. Here functional agrobiodiversity is defined as a subset of total biodiversity identified at the gene, species or habitat level able to deliver a given agroecosystem service, which extent increases with diversity in the functional group. Different functional agrobiodiversity categories are identified, compared to biofunctionality, and used to illustrate the mechanisms through which they can support agroecosystem services and consequently sustainability. Three case studies taken from the author's own research are used as examples to illustrate functional agrobiodiversity's potential in organic systems as well as open questions. Results show that (i) functional agrobiodiversity has potential to support agroecosystem services but it is not possible to generalize the effects; (ii) a given functional biodiversity element may create conflicts between different target agroecosystem services. In those cases, prioritization of services is required.

Keywords: agroecology, agroecosystem service, biological pest control, field margin, mycorrhizae, weed management

1. Introduction

1.1 Scope and Structure of the Paper

This paper aims to highlight the potential of functional biodiversity to improve organic farming and strengthen its recognition as one of the best models for sustainable agriculture. The paper is structured in four parts. In the first I will present the current trends in sustainable agriculture policies, with special reference to the European Union (EU), and the threats organic farming may face if it rests on its laurels. In the second part I will synthesize the relationships between agriculture and biodiversity as perceived by researchers with different backgrounds and by EU policy makers. In the third part I will provide a working definition of functional biodiversity, illustrate its typologies and present three case studies from our research showing different effect types. In the last part I will draw some conclusions and highlight the links between functional biodiversity and sustainability and recognition of organic farming systems.

2. Trends in EU Sustainable Agriculture and Threats to Organic Farming

There is an ongoing worldwide debate on agricultural sustainability, showing that sustainability priorities may differ among geographical areas. In the last two decades, the EU has decidedly steered its Common Agricultural Policy (CAP) towards the reduction of chemical inputs such as fertilizers and pesticides and the promotion of alternative production methods like organic farming. This trend has recently been reinforced by two important policy decisions. The first is the EU Directive on Sustainable Pesticide Use (European Union, 2009) which states that, from 1 January 2014, all EU farmers should use approaches and methods of Integrated Pest Management (IPM) as their reference way of farming. The second is the new CAP, in place from 1 January 2015, and especially its 'greening' component, which allocates at least 30% of the total subsidies to farmers who are willing to increase on-farm crop diversification and use part of their cropland for ecological infrastructures such as hedgerows, field margins or permanent pasture (http://ec.europa.eu/agriculture/cap-post-2013).

According to the new CAP organic farmers are considered by definition 'green' and hence eligible to those subsidies without further commitment. However, this poses for them the risks of neglecting the importance to improve their environmental sustainability and being tempted to take management shortcuts which may undermine the organic production philosophy. In fact, the difference between prescriptions for IPM farmers (upon the EU Directive on Sustainable Pesticide Use) and for organic farmers (upon the EU Regulation on Organic Farming) is shrinking, thus potentially diminishing the recognition of organic farming as likely the most environmentally-friendly production method. Also, the growing economic success of organic farming increases the risk of 'conventionalization' of organic production practices (Best, 2008; Darnhofer et al., 2010), e.g. simplification, over-reliance on input substitution, and neglection of the importance of the system approach as the best way to ensure long-term soil fertility and reduce pressure from pests, diseases and weeds. If organic products become too similar to conventional or IPM ones why should consumers continue to buy them? This is an issue that needs to be urgently addressed. I propose that application of functional biodiversity in organic systems, once properly defined and turned into practical tools, would not only contribute to increased sustainability but also diminish the risk of conventionalization and the consequent negative implications for the organic sector's recognition.

3. Agriculture and Biodiversity: A Fuzzy Picture

It is well known that agriculture can support biodiversity ('A for B') and biodiversity can support agriculture ('B for A') (Bàrberi et al., 2010), yet the importance of balancing these two approaches is rarely taken into account (Altieri, 2004). This partly derives from the differential importance given to them by ecologists and conservation biologists on one hand and agriculturalists on the other, which is often reflected by dichotomy in the scientific literature (see e.g. Moonen and Bàrberi, 2008 and references therein), but also from the lack of a comprehensive definition of agricultural biodiversity (hereafter 'agrobiodiversity'). For instance, the OECD definition of agrobiodiversity (Parris, 2001), strictly linked to the approach of the United Nation's Convention of Biological Diversity (CBD), does not mention at all crop sequence diversification (e.g. longer rotations, use of cover crops, intercropping and other types of polyculture) among the examples of agrobiodiversity at species level. In contrast, the approach of Agroecology to farming clearly identifies cropping system diversification in time and space as the starting point to redesign agriculture in a sustainable, environmentally-friendly way (Altieri, 1995).

It has long been recognized that, unlike conventional farming, organic farming does care for biodiversity. This issue, however, is often addressed in general terms without clearly distinguishing between production-related agroecosystem services (e.g. crop yield, soil quality, biological pest control) and non production-related ones (e.g. species and habitat conservation, recreational and cultural values) provided by biodiversity. There is not always a clear relationship between biodiversity and the expression of (agro) ecosystem services (Bengtsson, 1998) hence mixing up production- and non production-related services does not help shed light on it. A clearer theoretical framework highlighting the potential of biodiversity to support agroecosystem services is therefore needed. This would help identify which approaches and practical solutions are feasible in any given context. In turn, this would increase the probability of adoption from organic farmers and policy makers, thus contributing to keeping the recognition of organic farming as the most environmentally-friendly production method.

In the EU, the 'A for B' approach has largely dominated in the last decade, both in science and in policy. This is likely due to a stronger perception of the negative environmental effects of intensive agriculture than in other parts of the world, pushed by evidence like the ca. 30% decline in farmland bird populations observed in the UK between 1980 and 2002 (Birdlife International, 2004). The EU agri-environmental schemes (AES), set forth in the early 1990s as part of the CAP, provide financial support to farmers engaged in setting aside part of their land from production and/or introducing specific measures for the conservation of wildlife species and habitats in cropland. Despite considerable financial effort, AES have had dubious effects, likely because the measures were not focused enough and were too little grounded on sound ecological theory (Kleijn & Sutherland, 2003). In contrast, the 'B for A' approach – a pillar of Agroecology – despite having recognized importance for organic farming management worldwide (e.g. in the IFOAM principles) has so far mainly been applied to small scale farming in developing countries (Altieri, 2009), although application in the developed world is progressing. What is currently missing is a clear recognition of the fact that production- and non production-related agroecosystem services are not always competing and that both views can be embraced in a comprehensive definition of functional biodiversity.

4. Functional Biodiversity: Definition and Typologies

Functional biodiversity has been defined in various ways in the scientific literature (see e.g. Pearce & Moran, 1994, Gurr et al., 2003; Clergue et al., 2005) but here I am relying on our own definition, upon which we consider functional biodiversity as that part of total biodiversity composed of clusters of elements (at the gene, species or habitat level) providing the same (agro) ecosystem service, that is driven by within-cluster diversity (Moonen & Bàrberi, 2008). The latter specification is crucial and distinguishes functional biodiversity from biofunctionality, in which the effect of diversity in the functional group (cluster) linked to a given agroecosystem service is disregarded. As an example, if I say that ladybirds predate aphids I am only referring to their biofunctionality whilst if I say that a higher number of ladybird species predate a higher number of aphids I am referring to their functional biodiversity.

In a more recent paper (Costanzo & Bàrberi, 2014) we have refined our definition of functional biodiversity by identifying three categories: (i) *functional identity*, i.e. the presence of a set of homogeneous phenotypic traits that are related to the expression of a given agroecosystem service (e.g. a smothering cover crop); (ii) *functional composition*, i.e. the complementary effect of different traits, expressed by co-occurring elements, on the provision of a given agroecosystem service (e.g. intercropping or variety mixtures), and (iii) *functional diversity* (*sensu stricto*), i.e. the direct effect of heterogeneity within a single crop stand on the expression of a given agroecosystem service (e.g. a wheat composite cross population). We believe that linking crop traits to agroecosystem services should help identifying suitable biodiversity-based options for farmers and policy makers.

Hereafter I present three case studies taken from our research on functional biodiversity in organic agriculture, showing the different effects that biodiversity components can have on the expression of agroecosystem services.

4.1 Case Study #1: Agroecosystem Service Provided by Biofunctionality (No Effect of Functional Biodiversity or Functional Identity)

A pot experiment under greenhouse conditions was set up to investigate the influence of presence and diversity of arbuscular mycorrhizal fungi (AMF) on sunflower growth and weed suppression (Rinaudo et al., 2010). The research hypotheses were that (i) presence of AMF should promote sunflower growth and hence reduce weed biomass (= biofunctionality effect) and that (ii) these effects should be enhanced by the diversity in the AMF community (= functional biodiversity effect). The effect of AMF species (= functional identity) was unknown. Details on treatments are provided in Table 1. When sunflower competed with weeds, total weed biomass was reduced by ca. 40% in the pots where AMF were present, regardless of AMF species (functional identity) and AMF species number (functional biodiversity). Also, AMF presence (all species together) reduced total weed biomass by 25% when weeds did not compete with sunflower. Here, we only detected a biofunctionality effect (the presence of AMF did suppress weeds) but neither a functional identity nor a functional biodiversity effect (all species of AMF were alike and AMF species richness did not increase the weed suppression effect).

4.2 Case Study #2: Agroecosystem Service Provided by Functional Biodiversity (Functional Identity)

A field experiment embedded within the MASCOT long-term experiment (Pisa, Italy) was carried out to investigate the effect of genetic and species diversity on AMF abundance and organic corn performance (Njeru et al., 2014). The research hypotheses were that (i) increasing genetic and species diversity should provide a more favourable environment for AMF activity under organic management, and that (ii) higher genetic and species diversity should improve AMF colonization and consequently maize early growth. Details on treatments are provided in Table 1. Presence of cover crop was beneficial for AMF soil colonization and there was a clear effect of cover crop treatment (*Vicia villosa* > mixture > *Brassica juncea* = control). In turn, higher AMF colonization was positively correlated with corn early growth (shoot dry weight) although the rate of corn biomass increase with % AMF colonization differed between years. In contrast, corn genotype diversity did not show any significant effect. Here, we detected both a biofunctionality effect (presence of cover crops increased AMF colonization which in turn increased corn biomass) and a functional biodiversity effect but only in the case of the cover crop factor. In details, the positive effect of the latter was linked to functional identity (cover crop species) but not to functional composition (the cover crop mixture was not the best treatment). In the case of the corn cultivar factor, the hybrids had the same effect of composite cross population, i.e. no functional diversity effect (as defined earlier) was detected.

4.3 Case Study #3: Agroecosystem Services Potentially Increased or Reduced by the Same Functional Biodiversity Element

A landscape scale study (Moonen et al., 2006) was carried out to investigate the effect of the structure of field margin complexes (FMC, i.e. any non cultivated element comprised between two adjacent cultivated fields) in the arable part of an organic farm on wild flora diversity in the FMC and its effect on arable weed suppression and abundance of aphids' natural enemies (Coccinellidae, Syrphidae and Chrysopidae). The research hypothesis was that a more complex (heterogeneous or diverse) habitat structure surrounding arable fields should (i) reduce weed presence in the FMC and hence risk of weed invasion in the field, and (ii) encourage presence of natural enemies of aphids. FMC heterogeneity can e.g. be related to presence of different vegetation types and/or layers, to FMC width and to its management. Details on the survey are provided in Table 1. Wild flora diversity showed a large variation across the 62 FMCs (α diversity from 10 to 54 species and weediness from 32 to 88%). FMC structural complexity was positively correlated with wild flora diversity which in turn reduced % weediness in the margins. However, abundance of natural enemies was negatively correlated to FMC complexity and wild flora diversity and positively correlated to % weediness in the margins, likely because natural enemies use weeds as alternative feed, shelter and/or reproduction site. Here, we detected a functional biodiversity effect (linked to FMC complexity) which, however, was of opposite sign depending on the target potential agroecosystem service (positive for weed suppression and negative for biological pest control).

Table 1. Synthesis of the three case studies, indicating (i) type or scale of experiment, (ii) experimental material and treatments, (iii) detection of biofunctionality effect[1] (yes/no), (iv) detection of functional biodiversity effect[1] (yes/no), (v) reference

Type/scale	Material/treatments	Biofunctionality effect	Functional biodiversity effect	Reference
Pot	Three species of AMF[2] (*Glomus mosseae*, *G. coronatum*, *G. intraradices*); six weed species (*Setaria viridis*, *Echinochloa crus-galli*, *Digitaria sanguinalis*, *Sinapis arvensis*, *Chenopodium album*, *Amaranthus retroflexus*), one crop species (sunflower). Nine treatments: sunflower + all weeds + each AMF species *or* all AMF species *or* no AMF; sunflower + all AMF *or* no AMF (without weeds); weeds + all AMF *or* no AMF (without sunflower); completely randomized design	Yes	No	Rinaudo et al. (2010)
Field	Three preceding cover crops (*Brassica juncea*, *Vicia villosa*, a mixture of 7 species) + a no cover crop control x five corn cultivars (one conventional hybrid, one organic hybrid, three organic composite cross populations); split-plot design	Yes	Yes (identity) for cover crop factor No for cultivar factor	Njeru et al. (2014)
Landscape	Sixty-two field margin complexes (FMC) classified in terms of structural complexity (ecological niches), management, and disturbance upon a FMC Integrity Index. Vegetation in the FMC was classified in five groups (woody species, grasses, herbaceous dicots, grass weeds, dicot weeds). Eight of the 62 FMC were also sampled for natural enemies abundance	Yes	Yes (positive on weed reduction, negative on abundance of natural enemies)	Moonen et al. (2006)

[1]As based on statistical significance after ANOVA ($P \leq 0.05$), [2]AMF = arbuscular mychorrizal fungi.

5. Conclusion

Results of the three case studies clearly show that practical solutions based on the application of functional biodiversity do exist and can make organic systems more sustainable by increasing soil fertility and reducing abundance of biotic aggressors. Interestingly, effective solutions can be found at any of the three recognized levels of agrobiodiversity (genetic, species and habitat), and is likely that success stories would mainly be found where two or all levels are combined (Bàrberi, 2013). Another benefit often linked to higher functional agrobiodiversity is increased crop resilience against abiotic stresses, e.g. climate change (PAR, 2010). In a wider perspective, additional benefits that can be envisaged are increased resistance against the temptation of organic farmers to walk the pathway of 'conventionalization' and consequently against loss of trust from consumers.

However, it should be pointed out that generalizations on the effects of functional agrobiodiversity should be avoided. The third case study presented here shows that, although provision of multiple agroecosystem services from the same functional element is desirable, it cannot always be attained due to existing conflicts between services. This calls upon the need to clearly prioritize services on a case by case situation and search for functional agrobiodiversity-based best practices accordingly.

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Supporting Innovation in Organic Agriculture: A European Perspective Using Experience from the SOLID Project

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Abstract

Organic farming is recognized as one source for innovation helping agriculture to develop sustainably. However, the understanding of innovation in agriculture is characterized by technical optimism, relying mainly on new inputs and technologies originating from research. The paper uses the alternative framework of innovation systems describing innovation as the outcome of stakeholder interaction and examples from the SOLID (Sustainable Organic Low-Input Dairying) project to discuss the role of farmers, researchers and knowledge exchange for innovation. We used a farmer-led participatory approach to identify problems of organic and low-input dairy farming in Europe and develop and evaluate innovative practices. Experience so far shows that improvements of sustainability can be made through better exploitation of knowledge. For example, it is recognized that optimal utilization of good quality forage is vitally important, but farmers showed a lack of confidence in the reliability of forage production both in quantity and quality. We conclude that the systems framework improves the understanding of innovation processes in organic agriculture. Farmer-led research is an effective way to bring together the scientific approach with the farmers' practical and context knowledge in finding solutions to problems experienced by farmers and to develop sustainability.

Keywords: innovation systems, innovation process, organic agriculture, farmer-led research, SOLID, TP organics

1. Introduction

Innovation and agriculture have always gone 'hand-in-hand' because working with dynamic geographic, climatic, market and political conditions requires constant change (EC-SCAR, 2012). According to Hoffman et al. (2007) farmers have been developing agricultural practices since the beginning of agriculture, about 10,000 years ago. Their innovative power can be seen in many crops species grown and in different animal breeds, in the development of new production systems, farm machinery and equipment and also in social innovations (Hoffmann et al., 2007). Today innovation is seen as the primary instrument for overcoming the sustainability challenges of agriculture at the beginning of 21st century, such as food security, climate change and the conservation of natural resources. The European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI) was set up in response to these challenges (EIP-AGRI, 2012).

Organic farming is recognized as one source for innovation helping agriculture to overcome such challenges: *"Organic farming with its stringent rules on external input use has to be even more innovative to solve production problems, sometimes opening up new avenues"* (McIntyre et al., 2009, p. 384). The European Technology Platform TP Organics describes organic farms as "*creative living laboratories for smart and green innovations*" (Padel et al., 2010). Organic farming can make an important contribution and will continue to innovate in order to adapt to changing conditions in the climate as well as in the developing market.

However, innovation in agriculture is currently frequently understood as referring exclusively to the need for new inputs and technologies that originate from research (Röling, 2009). Garnet and Godfray (2012) referred to this as technological optimism in the debate about sustainable intensification. Much of the agricultural research effort in the last century has been concerned with developing and using external inputs (such as fertilizers and germplasm). Understanding how farmers adopt such science derived innovation was the starting point for the model of adoption and diffusion of innovation (Rogers, 1983). This led to the technology transfer model of the green revolution, where research was seen as the main generator of innovation that had to be transferred to and adopted by the farmers. The adoption/diffusion model was applied to organic farming by Padel (2001). She concluded that early organic farmers share many characteristics with other innovators. However, organic farming could not be characterized as a typical innovation, because it requires complex change, brings often no recognized economic advantage, conflicts with some rural values and is knowledge-intensive, whilst access to information is limited (Padel, 2001). This clearly limits the usefulness of the adoption/diffusion model to understand innovation in the organic sector. In Europe, the conceptual framework of innovation systems is gaining in importance for agriculture (EC-SCAR, 2011) and is underlying the new instrument of the Innovation Partnership of the European Union (EIP-AGRI, 2012).

In this paper we explore how innovation occurs within the organic sector in Europe and how this process can be further supported, using framework of innovation systems and experiences from the ongoing project 'Sustainable Organic Low-Input Dairying (SOLID)'. We first describe the approach of encouraging stakeholder-led innovation that was used in the project and present experiences gained so far. Based on selected examples, we discuss how innovation potentially can support sustainable development within the farming sector. This challenges the widespread perception that innovation in agriculture is mainly about new technologies and inputs and illustrates the importance of using active sharing of existing knowledge and of close collaboration between farmers and researchers in supporting innovation in this sector.

1.1 From Technology Transfer to Supporting the Innovation System

Innovation is a broad concept defined as the development, introduction and application of a new or significantly improved product (good or service), a new marketing method or a new organizational method in business practice, workplace organization or external relations where an economic or social benefit is assumed for individuals, groups or entire organizations (OECD/Eurostat 2005). The concept of 'innovation' is not restricted to invention or a new idea itself, but includes also the embedding of an idea in the relevant sector (Schumpeter et al., 1980).

However, within agriculture innovation is seen mainly as the search for new inputs and technologies (Röling, 2009) while the potential of social/societal innovation for achieving societal and political goals is not recognized (Bokelmann et al., 2012). This maybe not so surprising, given the long period during which "*efficiency came … to mean the application of the new agricultural technologies, which were beginning to emerge onto the market.*" (Morgan & Murdoch, 2000). In arable production, the farmers' 'know-how' was replaced by 'know-what', i.e. what input to use and when (Morgan & Murdoch, 2000). This 'technical optimism' remains strong in contemporary thinking about sustainable intensification of agriculture in the UK, but the need for new perspectives is beginning to be recognized (Garnett & Godfray, 2012).

In contrast, the concept of innovation systems describes innovation as an interactive evolutionary process, from invention to successful adoption by the target group with different participants involved at various stages (Smiths et al., 2010). Innovation occurs when networks of organizations come together with the institutions and policies that affect innovative behavior and bring new products and processes into economic and social use (various authors cited by Hall et al., 2005). Innovation becomes an emergent property not only of science or the market, but of interaction between stakeholders that allows opportunities to develop (Röling, 2009). The relevance of this concept for agriculture in Europe is increasingly recognized (e.g. Bokelmann et al., 2012, EC SCAR, 2012). The concept of innovation systems differs from the technology transfer framework also in the types of innovation considered, with the former focuses mainly new technologies, whereas the later differentiates between consumer driven, technology driven and organizationally driven pathways to innovation. The European Innovation Platform for Agricultural Productivity and Sustainability that wants to use partnerships and bottom-up approaches, linking farmers, advisors, researchers, businesses, and other participants in so called Operational Groups is based on this concept (EIP-AGRI, 2012).

Following on from *Farmer First* (Chambers et al., 1989), many authors argue that it is important to put the farmer back at the center of knowledge production (e.g. MacMillan and Benton, 2014). Farmer involvement is thereby critical in all stages of the process, so that novel technologies and practices can be learned directly and then adapted to particular agro-ecological, social and economic circumstances (Pretty et al., 2011). Others refer to 'co-innovation' that can involve a diverse range of participants other than farmers, such as rural entrepreneurs, regional governments, researchers and knowledge brokers (EC-SCAR, 2011; Knickel et al., 2009).

1.2 The Role of Knowledge in Innovation in the Organic Agriculture Sector

Innovation is the application of knowledge to achieve desired social and/or economic outcomes. This knowledge may be acquired through learning, research or experience, but the process is not considered as innovation until the knowledge is applied more widely (Hall et al., 2005). Sustainable agriculture makes productive use of human and social capital in the form of knowledge sharing to adapt and innovate to resolve common landscape-scale problems (Pretty et al., 2011). The techniques and practises used in organic farming are knowledge intensive (Lockeretz, 1991) and knowledge sharing between farmers is at the heart of the agrecology movement (Wezel et al., 2009).

Faced with new challenges of productivity, environmental change, and market conditions, organic farmers also have to evolve and innovate. Some innovation in organic farming occurs through the reapplication of existing knowledge. The European Technology Platform TP Organics referred to 'know-how innovation' to distinguish innovation that relies entirely on recombining and applying existing knowledge from other technological or social/societal and organizational innovation (Padel et al., 2010). Examples of such 'know-how innovation' include securing essential supply of vitamins and minerals in animal diets from natural sources, using composts for plant protection or encouraging predators by creating suitable habitats (e.g. flowering field margins). The definition of 'know-how innovation' used by the platform is very similar to the concept of *exploitative* knowledge strategies as compared to *explorative* ones (Li et al., 2008; March, 1991). In an *exploitative* strategy firms focus on levering existing knowledge to rapidly create new organizational products and processes, whereas in an e*xplorative* one they strive to develop capabilities to create or acquire new knowledge. Knowledge *exploitation* fits well into innovation systems concepts, whereas the *explorative* knowledge strategy has similarities to concept of 'technological innovation' (e.g. new germplasm or new machinery). TP organics argued that 'know-how innovation' is crucial to the organic farmer's ability to innovate, i.e. to respond effectively to new challenges, such as saving and protection of natural resources, and for improving the multi-functionality and sustainability of agriculture (Padel et al., 2010).

2. Approach to Encourage Innovation Through Stakeholder Engagement and Participatory Research in the SOLID Project

The European Union (EU) funded SOLID project (Sustainable Organic Low-Input Dairying) carries out research to improve the sustainability of low-input/organic dairy systems, aiming to improve the health and welfare, productivity and product quality by better understanding how contrasting genotypes adapt to such conditions, and to improve the supply of nutrients from forages and by-products through the use of novel feeds. The five year project also performs environmental, economic and supply chain assessments and promotes knowledge exchange. We report here from one work package that aims to facilitate innovation by actively involving farming stakeholders (i.e. organic and low-input dairy farmers, farmer groups and farm advisors) and stakeholder partners together with researchers in a participatory approach.

We used a farmer-led approach to identify problems of organic and low-input dairy farmers and develop and evaluate some potentially innovative solutions. In addition to research partners (from institutes and universities), the project also involved enterprise partners (small and medium size milk companies (SMEs) that work with groups of organic and low input dairy cow and goat producers in nine countries. The participatory approach progressed in four steps.

1. Identifying topics where farmer feel knowledge or innovation is needed.
2. Developing appropriate research approaches and experimental procedures to test innovative solutions for topics identified in Step 1.
3. Carry out the proposed research with small number of farms or groups of farmers (between one and five per country).
4. Report on the lessons learned and communicate the result to farmers, consultants and researchers.

The work is still on-going so experience has so far mainly been gained with the first and the second step of this approach which are described in some detail here.

2.1 Identification of Potential Topics for Participatory Research

The emphasis in this step was on working *with* producers to identify topics for the development, implementation and analysis of relevant, producer-led projects. At first, we carried out a rapid sustainability assessment on ten farms in each country, encouraging the farmers to think not only about immediate practical needs but reflect on the overall sustainability of their farms. Farms were chosen among the SME members to illustrate the range within low-input and organic farms in terms of size, intensity/level of input use, breeds, products, marketing channels and geographical area in the respective country/region and to highlight potential sustainability hotspots. The assessment of different strands of sustainability used a tool developed by Organic Research Centre adapted to the project (Gerrard et al., 2011; Marchand et al., 2014). After some initial hesitation, both farmers and researchers viewed the process mainly positively, but expressed also questions about specific data requests and the validity of some indicators.

The results of the sustainability assessments were presented at meetings, attended by between 10 and 25 farmers, aimed at identifying research needs and constraints of the industry and to formulate potential solutions which could subsequently be tested. A common protocol for the workshops encouraging farmers to discuss successes and innovative or unusual practices on their farms provided a link between everyday practical issues and sustainability, before moving to ideas how to further develop strength and address the perceived problems. The facilitators' role was to draw out areas of common interest related to the farmers' practical situations as well as remaining relevant to the overall issue of sustainability (see Leach et al., 2013 for details of approach).

2.2 Developing the Appropriate Research Method

Further discussion between the farmers, SMEs and researchers lead to the narrowing down of suitable research topics and to the setting-up of specific on-farm research projects. Not all topics and themes initially suggested could be investigated, because only a limited number of studies could be carried out. The following methods were used:

- *Farm case studies* were based on monitoring certain aspects on a single farm, using a variety of data collection methods both quantitative and qualitative. This allows for observations to be made in context of a specific farm (see Maxwell, 1986; Padel, 2002). In some cases we used *comparative case studies*, where this approach was extended to several farms and observations could be compared between different farms.

- *On-farm trials* introduced a specific treatment (e.g. use of new feed resources) which was compared with a control group or with performance before the treatment was introduced.

- Several projects were carried out as *group discussion*, which are the facilitated exchange of farmer experience and other knowledge sources among participating farmers with the aim to improve practice. This approach is inspired by the Farmer Field Schools (SUSTAINET EA, 2010), the Danish concept of Stable Schools (Vaarst et al., 2007), the approach of field labs developed in the UK (MacMillan & Benton, 2014) and focus groups.

The choice of method depended on the topic under study and in some cases involved the combination of some of the elements. A common template for reporting outlining also the farmers' background to a specific topic and the experience with the approach was developed.

3. Experience So Far

3.1 Identifying Research and Innovation Needs

Evaluating the sustainability of selected farms was intended to 'set the scene' and consider sustainability in its broadest sense whilst identifying suitable topics for participatory research. The results illustrate the diversity of low-input and organic dairy farms in the nine countries in terms of size and intensity. Cow farms varied from less than 20 ha (Austria and Italy) to more than 400 ha (Denmark, UK), with herd sizes ranging from nine (Finland) to over 300 cows (Italy, Denmark, UK) and milk yields ranging from less than 2500 kg/cow (Austria and Romania) to more than 8000 l/cow (Denmark). There was landless dairy goat farming in Spain and Flanders, but also grazing on more than 300 ha of common land in Spain and Greece with herd sizes between 22 goats (Spain) and 1150 (Belgium) and milk yields between 117 and 900 l/year. After the assessment, twelve workshops were held to identify knowledge and research needs from the farmers' point of view. They were attended by 161 dairy producers (the majority of which kept cows) in nine countries, and by some staff of the SMEs and facilitated by researchers and/or consultants. The farmers welcomed the opportunity to participate, related to their view that research specifically providing knowledge for organic/low input production was lacking. Further details of the outcomes of the sustainability and the workshops are reported by Leach et al. (2013).

Carrying out a structured sustainability assessment stimulated discussion, both during the visit and in the group meetings. Most farmers' own perception of sustainability included economic sustainability. Exposed to changing markets they do not see any future in farming, if they cannot run the businesses profitably, but the farmers were also aware of some other components of sustainability. The use of the tool encouraged them to think about the wider aspects. Some topics initially viewed sceptically, sparked interest and led to further discussion and some topics emerged from the sustainability assessments. For example, biodiversity management was discussed at first very critically among the mountain farmers in Austria but was eventually chosen as the research topic. Farmers in Denmark and in the UK strongly felt that they should improve in relation to greenhouse gas emissions by using more renewable energy and to diversify their farms.

Topics for which the farmers wanted to see further research effort have been summarized under the broad headings of animal feeding and forage production, natural resource management, animal management, product differentiation and marketing.

3.2 Feeding Practices and Forage Production

Topics included forage quality (i.e. protein), forage productivity and reliability, establishment and utilization of forage crop (such as diverse swards) and cultivation and feed value of protein rich crops (such as lupins, beans, and lucerne). Many dairy farmers reported not feeling confident about growing these crops, despite existing information on the subject. There were also a range of very specific suggestions, such as equipment and energy needs for drying forage (Austria), using various plant species (including for browsing) and identifying drought resistant plants and varieties (Italy, Romania, Spain, UK). Interest in diverse pastures was related to several different expected benefits, such as using them as natural sources for the supply of minerals (mainly in Denmark), improvements in forage quality (UK), creating marketing opportunities through improved product qualities (Austria, Italy) and improving soil quality (UK, see 3.2.2). The Greek farmers were interested in the use of irrigation for pastures. The use of novel forage is also investigated in other parts of the SOLID project (e.g. Rinne et al., 2014).

Some unusual feeding practices used on farms could be applied more widely, illustrating the potential value of knowledge sharing. Goat farmers in the Netherlands used by-products from a muesli factory and Austrian cow farmers 'grass cobs' to reduce purchased concentrate. The cultivation of some vetches as feedstuffs for goats was commonly place in some countries, but considered innovative elsewhere. Romanian farmers referred to trying 'forgotten' feeds such as turnips, millet and sorghum. The discussions and suggestions for further research show that good use of forage is of vital importance for low-input and organic dairy farms, but there is a lack of confidence in the reliability of forage production both in terms of quantity and quality.

3.3 Natural Resource Management

Farmers in the UK wanted a better understanding of the soil to be able to diagnose potential problems with declining productivity under organic conditions and suggested research into topics of increasing soil organic matter. Austrian farmers discussing manure application were not fully aware of the considerable amount of information that already exists on this subject.

Farmers in Denmark and Finland showed the greatest concern about energy use and climate change, perhaps as a result of national policies and legislation and the demonstration of energy saving practices. The Austrian farmers used biomass from their own forest to fuel a hay drying installation. The assessment of environmental impact of low-input and organic dairy farming is a topic that is also covered elsewhere in the SOLID Project (e.g. Hietala et al., 2014).

3.4 Animal Management

Despite some ongoing research on the subject, the choice of cow breeds and animals best suited to low input and/or organic systems was raised as research need in Denmark, Austria, Italy and the UK and by the goat farmers in Greece. The suitability of breeds for organic and low-input systems is also investigated in on-station experiments of the SOLID project (e.g. Horn et al., 2013).

Although *animal health and welfare* scored well in sustainability assessment, the farmers identified at least one health or welfare related issue in each workshop, including using fewer antibiotics (UK), improving health and longevity (Finland), parasite and disease control in goats (Belgium) and determining risk factors for neonatal losses and sub-clinical mastitis (Greece), even if on many of these subjects, research knowledge is available. Less common practices with innovative potential included seasonal calving and rearing calves on mothers and nurse cows (UK and Denmark), once-a-day milking (UK) and extending goat lactations (Belgium).

3.5 Product Differentiation and Marketing

Farmers were interested in product differentiation and in improved communication with consumers about the value of their products. One Italian farm aimed to standardize a high forage diet to market milk with a high nutritional value. This topic has been studied in several research projects (several authors cited by Leach et al., 2013) but so far farmers or SMEs have not developed related differentiation strategies. The topic was not taken up further in this project.

Farmers used specific attribute in selling directly to the public, e.g. in connections with agro-tourism in Austria, by offering a good product range in Greece or by selling raw milk through authorized dispensing machines in Romania. In Spain, one cheese-making farm developed an 'a la carte' strategy, targeting high-end restaurants for different types of flavored goat cheeses (matured in olive oil, with herbs).

3.6 Setting up the Participatory Research Projects

The next stage involved further discussions to narrow down the topics, because the number of projects in each country was limited. Setting the ‘right’ research question is important for the successful conduction and the quality of any research and this is equally important for participatory studies. In this case, the experience of the farmers’ in what treatments can be implemented and what indicators can be monitored under practical conditions had to be brought together with the researchers’ knowledge of experimental design, data analysis and statistics. The process is illustrated with two UK examples.

One UK farmer, with the aim of increasing soil organic matter, established very diverse and herb-rich swards and grazes in an extended rotation, along the lines of “mob grazing”. The topic was of interest also to several other UK farmers, so a case study for monitoring the farm was developed (Leach et al., 2014).

The UK SME partner wanted to further explore the link between diet and cow health on a number of farms. However, given the variability on management practices across farms and the difficulty in identifying parameters that could be manipulated under practical conditions of different farms made clear that this question was not suitable for this type of research. As a result we opted for an approach that can account for potential confounding effects due to different farm practices and conditions with the aim to study how different farm management practices can affect the concentration of iodine in milk in view of the iodine supplied by the feed which was also of great interest to the SME partner.

The final choice of topics summarized in Table 1 reflects priority for the farmers and suitability for on- farm research, and a suitable approach was developed using the different methods described in Section 2.2. Although farmers in several countries were also very interested in product differentiation and marketing no on-farm experiments were selected in this area, but the results of Austrian, Italy studies could support this in future.

Table 1. Topics of farmer-led research in the SOLID* project and the adopted study methods

Thematic area	Topic	Approach	Country
Feeding and forage	Home grown proteins	On-farm trials	Finland
	Use of by-products	On-farm trials	Spain, Romania
	Irrigation of pasture	On-farm trial	Greece
Natural resources use and environmental impact	Soil management, pasture productivity and grazing	Farm case study with monitoring of forage production	United Kingdom
	Responding to climate change	Moderated discussion group and farm case studies	Denmark
	Impact of different protein sources on carbon footprint	Case study using LCA (Life Cycle Analysis) method	Italy
	Impact of intensification on biodiversity	Comparative farm case studies with assessments and modelling	Austria
Animal management	Reducing antibiotic use	Moderated discussion group followed by on-farm trials	United Kingdom (jointly with DFF~)
	Herbs in pasture	Comparative case studies	Denmark
	Maternal /nurse cow rearing of calves	Farm case study with monitoring of calf growth	United Kingdom and Denmark
	Impact of farm practices on concentration of iodine in milk	Comparative farm case studies	United Kingdom

Source: Own data.

* for a description of the protocols and future publication of results please see www.solidairy.eu), SOLID (Sustainable Organic Low-Input Dairying)

~DFF is the Duchy Future Farming program of the Soil Association (http://www.soilassociation.org/fieldlabs).

4. Discussion

4.1 Innovation in Organic Agriculture through Knowledge Exploitation

The research and innovations topics discuss by the SOLID farmers include many examples of *exploitative* innovation strategy (see March 1991) where already a considerable amount of research exists. For example, sustainability could be improved by mobilizing knowledge about growing and feeding many different forage crops. Incremental change based on better exploitation of existing knowledge by producers, e.g. through re-combining it in different ways, appears very important for further development of organic and low-input farms, but is not likely to be restricted to these sectors. However, examples of breeding new varieties of forage legumes or other feed crops with high protein content illustrate that there also is a need for *explorative innovation*.

This importance of both *explorative* and *exploitative* strategies is also reflected in responses of low-input and organic dairy farmers to a list of innovation statements that they were shown in another part of the SOLID project. The aim of the survey was to contrast views about acceptability of innovation statements between different actors in the supply chain (farmers, processors/retailers and consumers) in Belgium, Finland, Italy and the UK, using Q sort methodology (Nicholas et al., 2014). The farmers strongly liked statements referring to *exploitative* innovation, such as developing techniques to improve feed and forage quality, reduce the use of purchased concentrate as well as improving feed quality and efficiency and animal welfare. They disliked some *explorative* statement that referred to what they saw as 'unnatural' innovation, such originating from GM or semen sexing, but strongly liked statements of 'developing of new forage varieties specific for low input and organic farming' (Nicholas et al., 2014).

4.2 The Role of Open-Access in Supporting the Innovation Process for Sustainable Development

In our view, it is also necessary to reflect on who will benefit from future innovation in organic agriculture or related systems. Some innovation will generate specific benefits for farmers, such as increased profitability, but much will generate public benefits, such as reduced natural resource use, improvement of soil fertility, of biodiversity and of animal health. Such innovation is a necessary part of sustainable development. We agree with the conclusion of Buckwell et al. (2014) that as part of sustainable intensification of European agriculture the 'knowledge per hectare' should to be intensified, including knowledge about how to manage the ecosystem services on which agriculture relies. We would like to emphasize again that 'innovation' is not necessarily a product, but a reflected part of continuous process, which involves creative thinking and knowledge sharing through learning in communities. In the United States, the idea of the open-access knowhow to farming is well established but also in Europe there are some good examples of open-access, for example the research archive for organic agriculture (e.g. http://orgprints.org).

4.3 How Can Locally Generated Knowledge Be Valuable in Other Contexts?

We believe there are three main reasons that limit the universal nature of locally-generated knowledge: ecology, economic and market context, and social/cultural values. Knowledge about the ecology of the given environment is location-specific and becomes only transferable where workable model of the ecological interactions under various pedo-climatic conditions exists. The interest in increasing home-grown protein crops illustrates that sharing relevant knowledge about specific crops could help the farmers to become more confident in growing them, but uncertainty remains under which conditions which corps are worth trying. And organic sector development will influence access to specific organic inputs, for example for organic feed. Finally, existing knowledge is also specific to personal goals and styles, social norms and cultural contexts. Curry and Kirwan (2014) conclude that the complex set of objectives, values and styles of implementing sustainability agriculture at various locations has an impact on how much knowledge can be seen as universal.

Farmers are aware that research often excludes variables that they know to be important for their decision-making but they may feel unable to express these clearly. This is likely to be a reason why they often have greater trust of farmers than of other experts. The farmer (tacit) knowledge, grounded in the farmers' observations of the various parts of their system and of the local environment, is important for the success or failure of new practices. Therefore farmers need to be recognized as active contributors to generating innovation rather as than passive recipients of knowledge transfer.

However, science derived knowledge cannot be replaced by context or farmer knowledge. Science derived knowledge needs to include basic ecological principles and the state of resources and ecosystem services on which agriculture depends. To foster innovation, this scientific knowledge must be complemented by location specific knowledge related to the ecology, economics and culture. And farmers and researchers as the two main actor groups contributing knowledge (as well as advisors, consultants and other intermediaries) need work closely together. The experience in SOLID has shown that farmer-led research is a good way to stimulate this dialogue between the farmers and scientists as equal partners in trying to find solutions to the problems experienced by the farmers and develop sustainability.

4.4 Supporting Active Farmer Learning for Innovation for Sustainability

How should such knowledge exchange systems be organized to support innovation for sustainability of agriculture? This shift away from dissemination and 'technology transfer' towards recognizing the role of farmers implies learning as active knowledge construction (Koutsouris, 2012). Farmers need to become confident observers of their own systems, so that they can learn the lessons, draw their own conclusions and recombine elements to develop their own solutions. The discussions among UK farmers identifying soil fertility as a research topic illustrate this point: some organic farmers had observed that productivity of some of their swards had dropped, but did not feel that could identify the causes and implement solutions using standard soil analysis so they wanted to know more about biological soil processes. Ongoing activities in the project are aimed at testing simple diagnostic tools that the farmers can use.

A study of learning and Innovation Networks for Sustainable Agriculture (LINSA) concluded that such groups' need to adopt a strong focus on the process of learning to effectively support innovation in the farming sector. In particular, the dimension of social learning with groups of farmers has received attention, but this is not to say that education in schools and colleges does not deserve to be considered to foster change. In the LINSA groups, social learning emerges from a shared interest in a problem, challenge or activity and all the actors bring all their expertise to the table. Social learning is linked to processes of trust building, trial and error and of mutual support and can provide answers to very complex problems, because mutual reflection on knowledge and consciously hearing different perspectives on one common issue will enhance the portfolio of potential solutions (Moschitz et al., 2014).

5. Conclusions

- The conceptual framework of innovation systems uses a broad definition of innovation and describes it as the outcome of a stakeholder interaction process. This framework is more suited to understand and support innovation for sustainability and within organic agriculture than the technology transfer model.
- Farmers are active contributors to agricultural innovation, who contribute context specific knowledge as well their creativity. The restrictions of certain inputs and the focus and direction of organic standards encourage organic farmers to try a range of alternative solutions.
- Knowledge *exploitative* and *explorative* innovation strategies are likely to be equally important to improve sustainability of organic and low-input dairy farming. An example of exploitation is improving forage production and utilization, and examples of explorative innovation are new forage cultivars and species.
- Innovation for sustainability generates private but also much public benefits, such as reduced natural resource use, improvement of soil fertility, of biodiversity and of animal health. The open-access model of knowledge sharing is compatible with supporting this process and should be more widely used.
- Knowledge exchange supporting innovation for sustainability needs to bring science-based and farmer (tacit) knowledge together. Farmer-led research is an effective way for researchers and the farmer together to develop sustainability of agriculture.

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Enhancing Yields in Organic Crop Production by Eco-Functional Intensification

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Abstract

Organic agriculture faces challenges to enhance food production per unit area and simultaneously reduce the environmental and climate impacts, e.g. nitrate leaching per unit area and greenhouse gas (GHG) emissions per unit mass produced. Eco-functional intensification is suggested as a means to reach these objectives. Eco-functional intensification involves activating more knowledge and refocusing the importance of ecosystem services in agriculture. Organic farmers manage agrobiodiversity by crop rotation (diversification in time). However, sole cropping (SC) of genetically identical plants in organic agriculture may limit resource use efficiency and yield per unit area. Intercropping (IC) of annual grain species, cultivar mixes, perennial grains, or forage species and forestry and annual crops (agroforestry) are examples of spatial crop diversification. Intercropping is based on eco-functional intensification and may enhance production by complementarity in resource use in time and space. Intercropping is based on the ecological principles of competition, facilitation and complementarity, which often increases the efficiency in acquisition and use of resources such as light, water and nutrients compared to sole crops, especially in low-input systems. Here we show that IC of cereals and grain legumes in European arable organic farming systems is an efficient tool for enhancing total grain yields compared to their respective sole crops. Simultaneously, we display how intercropping of cereals and legumes can be used as an efficient tool for weed management and to enhance product quality (i.e. cereal grain protein concentration). We discuss how intercropping contributes to efficient use of soil N sources and minimizes losses of N by nitrate leaching via *Ecological Precision Farming*. It is concluded that intercropping has a strong potential to increase yield and hereby reduce global climate impacts such as GHG kg^{-1} grain. Finally, we discuss likely barriers and lock-in effects for increased use of intercropping in organic farming and suggest a roadmap for innovation and implementation of IC strategies in organic agriculture.

Keywords: crop diversification, grain legumes, cereals, intercropping, ecological precision farming

1. Introduction

Organic agriculture is based on a set of principles one of these being the principle of ecology. This principle states that organic agriculture should be based on ecological processes, cycles and systems. To a large extent this is achieved by promoting ecosystem services such as biological nitrogen fixation, soil carbon sequestration, nutrient circulation, pollination and biological pest control. However, this often results in a certain trade-off between the high yield of commodities versus the lower environmental impact and maintenance of natural capital (e.g. biodiversity, soil organic matter) for ecosystem services delivery, also in a longer term perspective. Crop yields only represent one dimension in the range of ecological, social and economic services delivered by farming systems. Simple yield comparisons between organic and conventional systems, without considering externalities, product quality and net margins, are thus inappropriate. However, global food production must increase while considering new ways of better distribution, the global diet, planetary boundaries and ability of agricultural systems to supply ecosystem services in the long term (McIntyre, Herren, Wakhungu & Watson, 2009; Rockström et al., 2009; Foley et al., 2011). The key argument is to ensure future food security and sovereignty and in this context organic agriculture is a system that has much to offer.

Recent meta-analyses have revealed that the "yield gap" of organic agriculture to conventional agriculture is 19-25% (Seufert, Ramankutty, & Foley, 2012; Ponisio et al., 2015). However, yield differences are highly contextual, depending on cropping system and site characteristics, and range from 5% lower yields in organic agriculture (rain-fed legumes and perennials) to 34% lower yields (Seufert et al., 2012). With good management practices, particular crop types such as legumes, fruits and perennials can result in organic yields comparable to conventional yields. Ponisio et al. (2015) indicate that the 19% "gap" may be an overestimate. However, more research and innovations are needed to increase yields in organic agriculture, both in developed and developing countries to safeguard food security and ensure low levels of global environmental impacts, such as GHG emissions (Knudsen, Halberg, Hermansen, Andreasen, & Williams, 2010). Furthermore, while decision makers and public institutions affecting the future of organic agriculture often base their decisions on simple yield comparisons and environmental impact assessments relative to conventional systems, holistic and multi-criteria systems analyses will be required to guide organic agriculture as well as conventional agriculture towards improved sustainability.

Niggli, Slabe, Schmid, Halberg, and Schluter (2008) introduced the principle of eco-functional intensification of agriculture. According to the definition by the International Federation of Organic Agriculture Movements organic agriculture relies on ecological processes, agrobiodiversity, cycles adapted to local conditions, and agro-ecological approaches. Eco-functional intensification in organic agriculture means intensifying the beneficial effects of ecosystem services, including soil fertility and biodiversity, and using the biological elements of the ecosystems in a structured, organized and more efficient way. Therefore, eco-functional intensification with improved nutrient cycling techniques and agroecological methods for enhancing diversity and health of soils, crops and live-stock is a priority in organic agriculture. In addition, eco-functional intensification is based on the knowledge of stakeholders; it relies on powerful information and decision-making tools and the cooperation and synergy between different components of agriculture and food systems (Niggli et al., 2008). Subsequently, the Royal Society (2009) in their report "Reaping the Benefits" awakened the principle of "sustainable intensification" (from Pretty, 1997), which they define as agriculture where yields are increased without adverse environmental impact and without the cultivation of more land. Later, Bommarco, Kleijn and Potts (2013) developed the principle of "ecological intensification" into entailing the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices, which do not differ from the principles of eco-functional intensification.

Planned functional agrobiodiversity in time and space of cropping systems are fundamental to agroecological and organic production systems (Altieri, 1995; Vandermeer, van Noordwijk, Anderson, Ong & Perfecto, 1998). Agrobiodiversity is achieved through crop rotations, which include the use of cover crops, to reduce weeds, pests and soil-borne diseases, enhance nutrient use efficiency and improve soil quality (Karlen, Varvel, Bullock and Cruse, 1994). Agrobiodiversity in space may be implemented by annual or perennial grass-legumes mixtures, within species varietal mixtures, annual or perennial grain intercrops, agroforestry and field spatial design. Even though intercropping offers many significant advances and was common before "fossilization" of agriculture, it may appear as if organic agriculture did not strongly enough consider the possibility of redesigning systems to include more intercrops, but rather adapted the SC principle from conventional agriculture. An important question could be raised whether organic agriculture while expanding the cropping area forgot to re-designing the agroecosystem for planned spatial crop diversity as an important management tool? The aim of this review is to analyse the potential of crop diversification in space, exemplified by intercropping cereal and grain legumes, as a means of eco-functional intensification, which can contribute to enhancing crop yields in organic agriculture potentially without enhanced negative environmental impact.

2. Intercropping – the Intentional Use of Functional Agrobiodiversity

It has been demonstrated that intercropping (IC), the growing two or more crop species on the same piece of land at least during part of their development (Willey, 1979; Figure 1) significantly improves the use of plant growth resources, frequently reduces pests, diseases and weeds, enhances the yield per unit area over SCs and the yield stability over years, makes the crop more resilient to stress and improves the quality of the grain in conventional and organic agriculture (Willey, 1979; Vandermeer, 1989; Jensen, 1996a; Hauggaard-Nielsen, Jørnsgaard, Kinane, & Jensen, 2008, Bedoussac & Justes, 2010).

Intercropping is based on the intentional use of functional agrobiodiversity to maintain and intensify the use of associated ecosystem services, such as soil fertility, control of pests and diseases, pollination and improvement in nutrient use and water use across both spatial and temporal scales due to species complementarity (Jackson, Pascual, & Hodgkin, 2007; Kremen, Iles, & Bacon, 2012; Costanzo & Barberi, 2014). Besides functional agrobiodiversity, intercropping is based on the ecological principles of competition, complementarity and facilitation. If interspecific competition for growth factors is lower than intraspecific competition, species share only part of the same niche and reduced competition or the competitive production principle is in action (Vandermeer, 1989). This principle says that two different species occupying the same space (based on the soil surface) will use all of the necessary resources more efficiently than a single species occupying that same space, e.g. via a better use of the whole soil volume and various nutrient biogeochemical niches (Vandermeer, 2011). In the case of high input cropping systems, including use of mineral fertilizers, pesticides, irrigation, and mechanization, resource complementarity is less likely to occur, due to the high availability of growth resources. However, in such cases, intercropping may deliver other services such as regulating weeds and improving the product quality. In organic agriculture which often may have greater environmental variability than in intensive conventional agriculture, yield advantages through the competitive production principle often occur (Vandermeer, 2011). Crop species may complement one another in both time and space when species differences give rise to a better overall use of resources in intercrops than in the separate sole crops. Facilitation describes species interactions that benefit at least one of the participants and cause harm to neither. This process may occur when plants ameliorate the environment of their neighbors and increase their growth and survival, as an example one species may solubilize soil P which otherwise would be unavailable to the other companion species in the intercrop stand (Zhang & Li, 2003; Hinsinger et al., 2011).

Figure 1. Intercrop of fababean and wheat in Swedish in organic agriculture (Photo: ES Jensen)

3. Intercropping – the Case of Cereals and Grain Legumes in Organic Agriculture

Research on IC in organic agriculture has increased during the recent decade, especially in France, Denmark and Sweden. A study was undertaken to integrate and analyse a comprehensive amount of data (Bedoussac et al., 2014; Bedoussac et al., 2015) from 22 IC experiments at 13 sites in Toulouse and Angers (France) and near Copenhagen (Denmark) during 2001-2010 with two grain legumes (fababean, *Vicia faba* L. and pea, *Pisum sativum* L.) and three cereals (durum wheat, *Triticum durum* L.; soft wheat, *Triticum aestivum* L. and spring barley, *Hordeum vulgare* L.).

In 91% of the experiments, total grain yields of cereal and grain legume intercrop were greater than the mean SC yield, with mean intercrop yields being 3.3 Mg ha^{-1} compared to mean SC yield being 2.7 Mg ha^{-1} (Figure 2a). At an average sole crop yield of ca. 3 Mg ha^{-1} the yield advantage of the intercrop is up to 66% (Bedoussac et al., 2014). Similarly, total intercropping yields were greater than SC cereal yields (Figure 2b) and SC grain legume yields (2c), when SC grain legume or cereal yields were lower than 4.0 to 4.5 Mg ha^{-1}. However, comparing dry matter production of different qualities such as cereal grains with protein rich grain legumes only gives an indication of the yield advantage. Several indexes have been developed to be able to better evaluate the performance of an intercrop compared to the SCs grown on similar area of land, but split into the same proportion as the components in the intercrop. The most commonly used index is the Land Equivalent Ratio (LER), which gives the relative area required from growing SC to obtain the same yield (of both species) as in the intercrop (Willey, 1979; Vandermeer, 1989). The LER value for an intercrop is calculated as sum of the ratios (partial LER of each species or pLER) of the intercrop yield and the SC yield of each component. If the LER is greater than 1 there is an advantage from IC in terms of yield and land use, e.g. $pLER_{legume} + pLER_{cereal} = 0.5+0.7 \Rightarrow LER = 1.20$, indicating that 1.2 m² of SCs are required to obtain the same production as from 1 m² of IC, i.e. there is 20% advantage from intercropping. If LER ≤ 1 there is no advantage from intercropping. A basic requirement is that the farmer is interested in growing both crops.

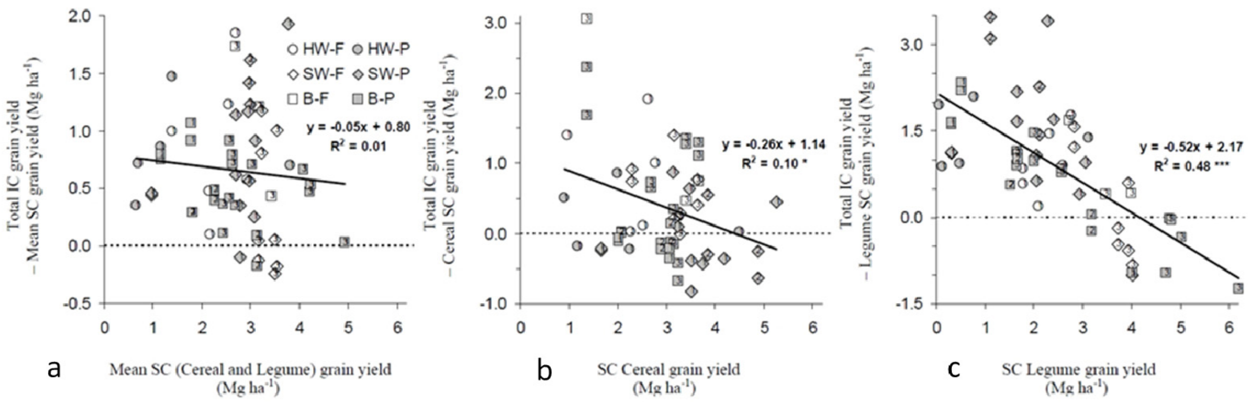

Figure 2. Difference between intercrop and sole crop yields as function of sole crop yields

Relationship between total grain yield of the intercrop (IC; cereal + Legume) and (a) mean sole crop (SC), (b) cereal SC and (c) legume SC. Numbers inside the symbols indicate the experimental site (1: Toulouse; 2: Angers and 3: Denmark). HW: Durum wheat; SW: Soft Wheat; B: Barley; F: Faba bean and P: Pea. Single asterisk and triple asterisks indicate that linear regressions are significant at P=0.05 and P=0.001, respectively. (N=58). Source: Bedoussac et al. (2014). Copyright Springer Science + Business Media.

Figure 3 shows that almost all of the 58 intercrops in this analysis had LER greater than 1 as indicated by the dotted line. The average LER is 1.27, indicating on average 27% yield advantage and improved resource use from IC compared to sole cropping. Furthermore, Figure 3 shows the variability of LERs within different groups and treatments.

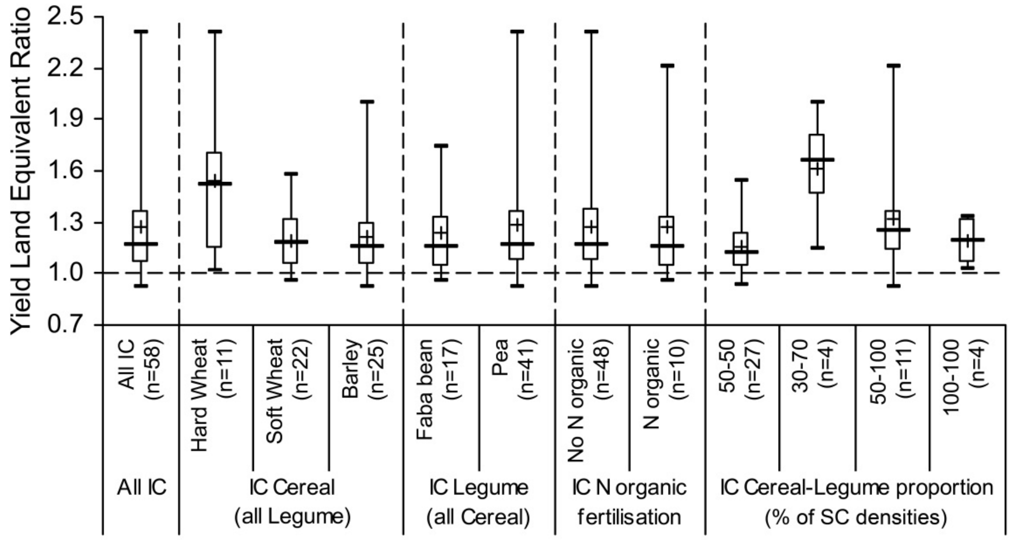

Figure 3. Land Equivalent Ratio based on grain yield of 58 intercrops from France and Denmark

Grain yield-based LERs shown as overall means for selected groups of ICs. Base of the vertical rectangle: first quartile; Lowest horizontal bar: minimum; Wide bar in rectangle: median; +: mean, Highest horizontal bar: maximum; Top of the vertical rectangle: Third quartile. Source: Bedoussac et al. (2014).

In the intercrops the cereal is normally more competitive than the grain legume and the final intercropping grain yield usually contains a greater proportion of cereal than the original proportion sown in the intercrop (Bedoussac et al., 2014). It has also been shown that the available soil mineral nitrogen (N) is an important factor for determining the outcome of the competitive interaction between species and the advantage of IC compared to SC (Jensen, 1996a; Hauggaard-Nielsen et al., 2008, Bedoussac & Justes, 2010). The greater the level of available soil mineral N, the less the IC advantage. This is explained by the uneven sharing of soil mineral N between the cereal and the grain legume. The cereal will, due to its better competitive ability for soil mineral N, use a much higher proportion of the soil mineral N than its "share" as defined from the intercrop composition. This will make the grain legume fix a greater proportion of its N requirement from atmospheric N_2 (Jensen, 1996a; Hauggaard-Nielsen et al., 2007; Hauggaard-Nielsen et al., 2009). Facilitation from the annual legume in terms of N transfer to the cereal, is normally not significant or only modestly contributing to the N supply of the cereal (Jensen, 1996a; Jensen, 1996b; Shen & Chu, 2004), due to the lack of synchrony between mineral N release from decomposing grain legume residues and the narrow window of N acquisition of the cereal in an annual intercrop.

Several additional services are obtained from the IC of grain legumes and cereals. The more efficient use of soil mineral N and the more balanced carbon-to-nitrogen ratio of the crop residues compared to sole crops contributes to a more balanced mineralization-immobilization turnover of N. This may result in reduced net mineralization of N and nitrate leaching losses in the autumn as compared to SC grain legumes (Hauggaard-Nielsen, Ambus, & Jensen, 2003) and reduced net immobilization of N in the spring as compared to the incorporation of SC cereal crop residues. Even though the cereal is able to recover a higher proportion of the soil N than "its share", competition occurs for other growth factors such as non-N nutrients and water. This results in increased protein concentration and baking quality of the cereal as compared to the SC cereal even if the SC cereal is supplied with extra N (Hauggaard-Nielsen et al., 2008; Gooding et al., 2008; Bedoussac & Justes, 2010; Bedoussac et al., 2014; Figure 4a). In almost all intercropped cereals the protein concentration was greater than in the sole cropped cereals, but the greater the SC cereal protein concentration the lower the IC advantage (Figure 4a).

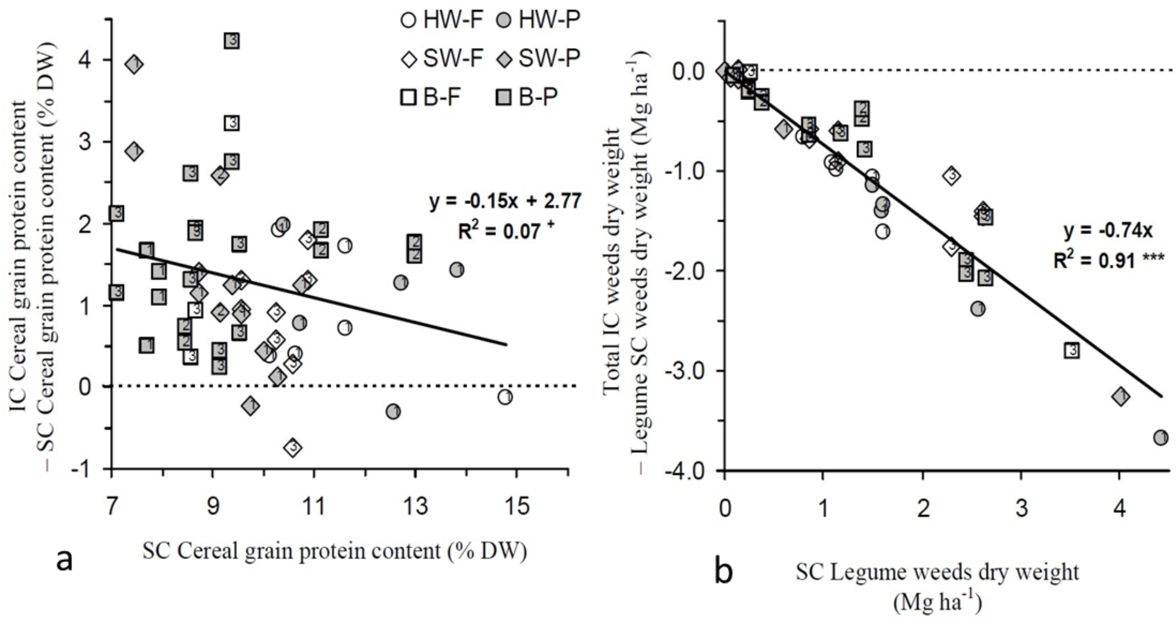

Figure 4. Effect of intercropping on the cereal protein concentration (a) and the weed biomass (b) compared to SC cereal and SC legumes, respectively. See Figure 2 for explanation to figures. Source: Bedoussac et al. (2014). Copyright Springer Science + Business Media

In addition to N use efficiency and cereal grain quality, IC significantly reduces the weed pressure as compared to SC grain legumes in organic agriculture (Corre-Hellou et al., 2011; Bedoussac et al., 2014). In the analysis of the IC experiments in France and Denmark, IC almost eliminated weeds as compared to SC legumes resulting in the relationship shown in Figure 4b. Furthermore, it has been shown that the yield stability over several years may be greater in ICs than the SCs especially compared to SC grain legumes (Jensen, 1996a). Part of these effects are explained by reduced grain legume lodging in IC, more efficient use of light and nutrients such as S, P, K, and reduced plant diseases (Hauggaard-Nielsen et al., 2008).

4. Discussion

This analysis clearly demonstrates the significance of intercropping as means to enhance yields and improve use of growth factors in organic agriculture. From an organic agricultural perspective the complementarity in use of N sources by the components of the cereal-grain legume intercrop is important in relation to N use efficiency. First, available soil mineral N is often a limiting resource in organic agriculture, whereas N_2 from fixation in principle is unlimited. Growing a SC cereal will not result in N_2 fixation. Growing a SC legume will result in the use of available soil mineral N, while the legume could cover its N supply by N_2 fixation, i.e. the legume SC could be considered a soil mineral N “wasting”. Secondly, soil mineral N is varying at the landscape and at minor scales depending on the C-N cycling. In conventional farming, N-fertilization, and especially using precision farming technology with differential supply over the field, aims at reducing the variability in available soil N.

We propose that intercropping is considered as an *Ecological Precision Farming* Technique, since the intercrop will adjust its botanical composition and acquisition of N from both sources – soil mineral N and N_2 fixation - according to available soil mineral N by competitive interactions. The cereal will thrive in the places of the field with the higher availability of soil N and use it efficiently while in places with lower soil mineral N availability legumes will thrive. Thirdly, the improved use of N sources may reduce losses of N from nitrate leaching and nitrous oxide emission as compared to SC of grain legumes without a subsequent cover crop.

There is a significant potential of using functional agrobiodiversity, e.g. by intercropping, to a greater extent in organic agriculture and one can wonder why IC technology in a modern context has not been implemented to a greater degree. The yield advantages are obvious and Ponisio et al. (2015) in their recent meta-analysis found that the “yield gap” is only 9% in favour of conventional sole crops relative to organic intercrops.

However there are barriers, lock-in and challenges to be solved research and development in participatory learning and action research with stakeholders in the food system, including the farmer to the consumer. Challenges and some key points in a roadmap for research are:

a. *Farmer and advisory service values and knowledge*. Intercropping might be considered as old-fashioned technology, and there is insufficient knowledge among organic and conventional "sole crop farmers" about the potential of intercrop systems.

b. *The homogeneity paradigm.* Lock-in effects by wholesalers and retailers, who are not used to handle mixed grain (Magrini, Triboulet & Bedoussac, 2013). Thus, the current market for intercrops are restricted to on-farm use for feed, or alternately on-farm sorting of intercrop grains before selling - sorting machinery is readily available.

c. *Breeding of cultivars suitable for IC, including perennial cereals and legumes*. Currently arable crops are only bred for sole cropping. Breeding programmes should be established for developing cultivars suited for intercropping in organic agriculture, including the matching of cultivars for simultaneous harvest.

d. *Integration of intercrops in the crop rotation.* Long-term research is needed to study the integration of intercrops in crop rotations without diminishing the important crop rotation effects, especially in term of reducing soil-borne diseases. Analysis of how the pre-crop value of sole crop legumes in term of N effect is affected by intercropping should be integrated in the research programme. A study with a rotational sequence of pea SC, oat SC and a pea-oat intercrop followed by two subsequent cereal crops was encouraging. No significant difference was found between pea and pea-oat as pre-crop to the subsequent two cereal crops (Hauggaard-Nielsen, Mundus & Jensen, 2012).

e. *Climate-smartness of intercropping.* There is a need for knowledge and data on GHG emissions from intercrops as compared to sole crops.

f. *Multicriteria sustainability assessment of IC systems.* Analyses of the sustainability of intercropping systems are required, based on the use of appropriate tools for analysing environmental, economic and social effects of intercropping systems.

5. Conclusions

We conclude that there is great potential for functional agrobiodiversity to strengthen eco-functional intensification in organic agriculture. Intercropping enhances ecosystem services including crop yield, N use efficiency, pest and weed management, and reduces nitrogen losses to the environment. Developing and implementing intercropping systems in organic agriculture will be an important means to further reduce the organic to conventional "yield gap", while considering additional ecosystem services and low environmental impact. We support the statement of John Vandermeer (2011): "nevertheless, little doubt exists that in the future, as systems become more ecologically sophisticated, intercropping and agroforestry are likely to be more important components of overall productive systems".

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The Role of Trees and Pastures in Organic Agriculture

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Abstract

Environmental concerns associated with annual row crop grain production – including soil erosion, soil carbon loss, intensive use of chemicals and petroleum, limited arable land, among others – could be addressed by converting conventional livestock production to an organic pasture based system. The inclusion of tree crops would further enhance the opportunity for feeding pasture- raised livestock by providing shelter and alternative feed sources. Biodiversity is an essential aspect of an organic farm plan. The idea of including tree crops and other perennials into the vision of an organic farm as a "living system" is very much compatible with the goals and philosophy of organic farming. Before modern no-till farming systems were developed, tree crops and pasture systems were found to provide similar benefits for controlling soil erosion and conserving soil carbon. For example, J. Russell Smith's *Tree Crops: A Permanent Agriculture* (Smith, 1950) and pioneered tree crop agriculture as the alternative to annual row crops for protecting soils from erosion while producing livestock feed such as acorns, nuts, and fodder. A survey of Mid-Atlantic USA soils under pasture found 60% higher soil organic matter content than cultivated fields. Because United States Department of Agriculture's National Organic Program (USDA-NOP) standards require dairy cattle consume pasture forage and limited grain (7 C.F.R. pt. 206), organic milk contains higher concentrations of omega-3 and fewer omega-6 fatty acids than conventional milk. Organic standards also state "the producer must not use lumber treated with arsenate or other prohibited materials for new [fence posts] installations or replacement purposes in contact with soil or livestock." Black locust (*Robinia pseudoacacia*) is a fast growing renewable alternative to treated lumber with many attributes compatible with organic farming. This versatile tree fixes nitrogen (N), provides flowers for honey bees and other pollinators, and produces a highly durable dense wood ideal for fence posts useable for up to 50 year.

Keywords: soil quality, biodiversity, livestock, milk, fat soluble vitamins, silvopasture

1. Introduction

Organic agriculture operates as an ecologically-oriented management system integrating trees and pasture into productive farming operations, especially those including livestock. This paper reviews the theoretical foundation and current regulatory requirements underlying organic agriculture's ecological orientation and then examines specific aspects of the ecological functions of trees and pasture on organic farms with livestock.

The very earliest characterizations of organic agriculture emphasized its ecological foundations by identifying it as a closed loop system in which farmers balance productivity, efficiency and stability by managing natural resources through biological processes. For example, widely acknowledged (Heckman, 2013; Paull, 2011; Tanner & Simonson, 1993) as the seminal work on organic agriculture, *Farmers of Forty Centuries*, *Permanent Agriculture in China Korea, and Japan* (King, 1911) described the scrupulous recycling of natural resources through biologically-driven practices. These included the use of composting, manures, cover cropping with legumes and crop rotation to explain the continuous cultivation of the same crop land for more than four millennia by Asian peasant farmers. King, a former Chief of Soil Management at the United States Department of Agriculture (USDA) and a number of his peers had grown alarmed by the rapid deterioration of soil quality on domestic farmland managed for a fraction of that period. King identified the parallels between traditional Asian farming practices and naturally occurring ecological systems, especially the continuous recycling of inputs and the regeneration of soil fertility through internal processes, as the foundational tenets of what others would later define as organic agriculture (Northborne, 1940; Conford, 2001; Heckman, 2006).

Perhaps most notable among King's theoretical descendants was Sir Albert Howard who often co-authored with his wife, Lady Gabrielle Howard, journal articles and books based on their many years of research experience with the traditional farming systems of India. In their view, an ideal organic farm functioned as a living entity bound together through the "great linkage between the soil, the plant and the livestock" (Howard, 1947). This characterization from *The Soil and Health* emphasizes the centrality of an integrated, biologically-driven and self-sustaining operation underpinning organic agriculture. According to Howard, "Mother earth never attempts to farm without livestock; she always raises mixed crops; great pains are taken to preserve the soil and to prevent erosion; the mixed vegetable and animal wastes are converted into humus; there is no waste; the processes of growth and the processes of decay balance one another; ample provision is made to maintain large reserves of fertility; the greatest care is taken to store the rainfall; both plants and animals are left to protect themselves against disease." (Howard, 1947)

Like King, Howard and those who came to embrace his holistic approach to agricultural management were deeply skeptical of the rapid transformation of agriculture during the twentieth century. These changes included the introduction of synthetic fertilizers and pesticides, the mechanization of agricultural labor and the specialization of farms into monocultures segregating crop and livestock production. Adoption of these more industrialized production practices contributed to measurable decreases in soil biological activity and wild biodiversity sharing the agricultural landscape. Howard noted that by increasing dependence on purchased non-renewable inputs, especially for fertility and energy, these agricultural innovations undermined the organic principle that farms should be self-sustaining. He also observed that diminishing the ecological integrity of a farming system would inevitably diminish the integrity of the food it produced.

The term "organic" as a system of farming was first put forth by Lord Walter Northborne (1940) in his book *Look to the Land.* Before this terminology was adopted Howard described his model of farming as "nature farming" where natural ecosystems served as models. Consistent with observations from natural ecosystems, and drawing from the work of King, Howard stressed the principle of the "law of return." Farming by this principle means that all types of natural and organic waste products are to be recycled to soil (Heckman et al., 2009). Composting was used to process and prepare these materials for return to the land.

The idea of an organic farm functioning as a living system was further characterized by Walter Northborne in terms of "wholeness" as in an organic farm "must have a biological completeness" and have a "living entity" where every "branch of the work is interlocked with all others" (Northborne, 1940). Other organic pioneers that followed further elaborated these agro-ecological principles underlying organic farming (Balfour, 1976; Coleman, 2011). A living organic farm would ideally include trees, pastures, and livestock as valuable components of the system (Wild Farm Alliance, 2008). Crop rotation, composting, and closure of nutrient cycles are additive practices and monocultures segregating crop and livestock production are limiting practices.

Historically and philosophically organic agriculture has embraced biodiversity as a way of creating an ecological system of farming. Furthermore, USDA- NOP standards mandates conservation of biodiversity National Organic Program 7 C.F.R. pt 205 (2015); USDA, Draft Guidance for National Resources and Biodiversity Conservation for Certified Organic Operations, (2015), with trees, pastures, and livestock regarded as valuable organisms to work into an organic farm plan. As a result and in contrast to modern conventional agriculture, where a few annual row crops dominate the production system on an industrial scale, organic farming systems are more likely to utilize many woody and herbaceous perennials and forbs of pastures for food and fiber production.

These ecological practices that include increased biodiversity, crop rotation, and avoidance of monoculture are factors that enable a farm to function effectively as an "organic living system."

2. Agronomic Role of Pasture in Organic Farming

In modern conventional farming the separation of crop production from livestock is the norm and the use of synthetically manufactured N substitutes for biologically based N. Well-designed organic farming systems can acquire sufficient N for crop production by careful management of the N cycle (Heckman et al., 2009; Adam et al., 2012). This requires practicing the "law of return" (Howard, 1947) for natural waste materials, composting, crop rotation with legumes, and cover crops among other organic practices. The Haber-Bosch (Smil, 2004) process for industrial N manufacture allows conventional farmers to forego these and is widely regarded as a necessary invention for feeding humanity (Erisman et al., 2008). This assumption is seldom questioned (Heckman, 2013).

The use of synthetic N fertilizers enabled separation of crop production from livestock operations, decreased the emphasis on feeding livestock on pastures and forages, encouraged the movement towards concentrated feeding operations, and increased problems associated with poor utilization of manures. Organic livestock farming systems in general and especially dairy in particular, tend to run counter to these trends with better integration of crop and livestock production. In fact, NOP standards require pastures for dairy operations (National Organic Program, 7CFR, Part 205.240 (2015)) and prohibit monocultures (National Organic Program, 7 CFR, Part 205.203 (2015)).

Well before organic was founded as a system of farming, a popular soil fertility textbook (Vivian 1908) recognized that pasture-based dairy farming was one of the most economical and effective ways to maintain soil fertility. Organic farms with NOP compliant crop rotations integrated with pastures and perennial legumes, can normally supply adequate N for crops (Heckman et al., 2009; Kirschenmann, 2007; Clark, 2009). As a result an N deficiency in crops may be regarded as deficiency of the farming system.

A survey of fields in the Mid-Atlantic region of the USA measured 60% more organic carbon in the top 15 cm of pastureland compared to soils under annual row crop (Heckman et al., 2010). This accumulated soil organic matter associated with pasture serves as a reservoir for stored N (Heckman et al., 2009). Pasture forage generally includes a mix of grasses and legumes. The legume produces on-farm N and the dense root systems of grass plants prevent the leaching of N from the soil (Heckman et al., 2009). Soil building can also be accomplished by growing cover crops (Sustainable Agriculture Research and Education Program, 2007). While cover crops do provide many useful ecosystem services, pastures and forage crops consumed by livestock also serve to both feed the life in the soil and at the same time produce nutrient rich food for people. When or if pasture sod is eventually broken or tilled for the purpose of rotating to row crop grains, the accumulated soil fertility is released. In such rotations there is generally little or no need for purchase of off-farm nitrogen fertilizers. A special feature of the N cycle in organic farming is that it is largely solar powered (Heckman et al., 2009) in contrast with the Haber-Bosh process where industrial N fixation is produced with natural gas (Smil, 2001).

Soil improvement is a stated goal of the USDA-NOP standards (NOP 7CFR 205.203 (2015)) National Organic Program). Rotations using perennial forages and pastures are good ways to achieve this objective. Well-managed perennial pastures maintain soil cover and protect against erosion. Also pasture serves as a cover crop while at the same time enables a cash flow through sales of animal products. In contrast, cover crops grown strictly as vegetative cover, may in some regions, tie-up a fraction of the growing season without producing food or an income stream. Well managed perennial pastures maintain soil cover and protect against erosion. Although almost rarely stated as such, pasture-based farming is in fact a no-till farming system and has advantages over conventional no-till farming systems with annual crops because of the dependence on chemical herbicides and synthetic N. These advantages include conservation of time and energy for planting, permanent living ground cover to prevent soil erosion and leaching of nutrients, and maintaining a pleasantly green pastoral scenery for the viewing public (Franzluebbers, 2009; Heckman, 2012).

3. Role of Pasture in Organic Farming on Food

Beyond encouraging good soil management the USDA-NOP standards say little about how organic farming methods may improve food quality or human health. The pioneers of the organic farming movement, however, were very much concerned with connections between soil health, food quality, and human health (Howard, 1972). Albert Howard for example wrote that “Soil fertility is the basis of the public health system of the future”. The Farming Systems Trial (FST) at the Rodale Institute comparing different management schemes over three decades has demonstrated remarkable improvements in soil quality in association with organic management practices (Rodale, 2013). The further step of making the connection between farming system and human health, however, remains tenuous (Carr et al., 2012). Consumers frequently ask if there are any meaningful differences in organic versus conventional foods. For plant based foods there has been has an ongoing unsettled debate. What is clear is that organic plant based foods generally have less pesticide residue (Baker et al., 2002)

Fewer studies have examined animal based foods as a way of comparing organic versus conventional production. At least for dairy products the organic versus conventional nutritional differences are measurably evident based on laboratory analysis. A recent study (Benbrook et al., 2013) looked at the type of fats in organic vs. conventional milk across the USA. In almost every region there was a significant difference in the omega 6 / omega 3 ratios. The one exception was in Northern California where organic and conventional dairy cows are both pasture-based. In all other regions the ratio was more favorable for organic milk because in those cases pasture was a more significant feed source for the organic cows. The study also found that conjugated linoleic acid (CLA), in pasture-raised organic milk increases in the spring and summer months in association with the return of cows to pasture. Concentrations of CLA in organic milk are maximized during grazing season while in the conventional milk it remains flat regardless of season. The relatively new USAD-NOP pasture standard requiring grazing for 30% or more of dry matter intake may be a key factor (NOP 7 CFR Part 205.240). The authors of this study (Benbrook et al., 2013) on how organic production enhances milk quality conclude that "increasing reliance on pasture and forage-based feeds on dairy farms has considerable potential to improve the FA [fatty acid] profile of milk and dairy products" and "it is far more common – and indeed mandatory on certified organic farms in the U.S. – for pasture and forage-based feeds" and "improvements in the nutritional quality of milk … should improve long-term health status and outcomes, especially for pregnant women, infants, children, and those with elevated CVD [cardiovascular disease] risk." Other studies have also reported differences in composition of animal products as a result of pasture feeding. A review on Grass and Human Nutrition by Karsten and Baer (2009) found that in meat, milk, and eggs there are higher levels of CLA, and vitamins A, E, and B12.

4. Needed Research on Pasture-Raised Animals and Food

Pasture-raised animal foods are generally believed to be good sources of the fat soluble vitamins A, D, E, and K2 (Rheaume-Bleue, 2012). Only a few studies, however, have measured vitamins D and K2 in meat, milk, and eggs in association with type of production system. A study comparing pasture feeding to confinement layers found that pasture enhanced vitamin A and E content in eggs (Karsten et al., 2010). However, they did not measure vitamins D or K2.

The organic pioneers were especially interested in how food systems influenced human health. Eve Balfour (1976), for example, as shown in her book *The Living Soil*, attempts to interpret and summarize the work of Dr. Weston A. Price and other nutrition pioneers. Albert Howard and Jerome Rodale (1948) also discussed the findings of Dr. Price. Weston (1950) was a dentist who studied nutrition and traditional diets in relation health. The presumption was made that the peoples studied were eating "organic" before there was any type of certification. Price's work had a particular focus on fat soluble vitamins. This aspect of his work was mostly unappreciated or misunderstood by many of the organic pioneers. In all healthy groups Price studied, had a rich source of something he termed the "X-factor" in their diets. Current research indicates that this X-factor was very likely vitamin K2 (Rheaume-Bleue 2012, Flore et al., 2013). Price was able to isolate and concentrate this X-factor from butter produced by cows eating rapidly growing green grass. This unidentified substance served as a catalyst for mineral adsorption and helped people develop excellent teeth and bones. This so called X-factor has properties that match up very well with what has since become known as vitamin K2 (Masterjohn, 2007a). In a review, Masterjohn (2007b) argues the case that it is in fact vitamin K2.

Vitamin K2 has historically been underrated and misunderstood because of confusion with vitamin K1. Vitamin K1 aids in blood clotting. Vitamin K2 can also do this but much more. Because vitamin K1 is recycled in the body deficiency is rare. Vitamin K2 is a catalyst for mineral absorption especially for calcium (Ca). Vitamin K2 protects heart health and builds strong bones and teeth. Taking calcium or vitamin D supplements alone without sufficient vitamin K2 intake may lead to nutritional imbalances. Vitamin K2 works in association with vitamins A and D – the so called "fat soluble vitamins". Some preliminary evidence suggests that animals grazing good pasture concentrate vitamin K2 in milk, meat, and eggs (Rheaume-Bleue, 2012).

More research is needed on vitamin K2 sources and influence of organic farming systems on its levels in food. Vitamin K2 levels in organic milk may follow a trend similar to CLA levels. When the organic cows are pastured in the spring and summer months, vitamin K2 levels in milk butter fat may similarly increase. The molecular precursor to vitamin K2 is phylloquinone which would be concentrated in the green leaves of pasture plants. Grazing animals convert this phylloquinone to vitamin K2 (Rheaume-Bleue, 2012). In order for people to receive the benefits from the presence of fat soluble vitamins in pasture-raised foods they must eat sufficient amounts of fat (Masterjohn, 2013). Unfortunately modern dietary guidelines have unwisely warned against eating animal fats (Hoenselaar, 2012).

5. Pasture Feeding

Once a dairy farmer decides to put cows on pasture, taking the next step to go organic is relatively easy (Dr. Hubert Karreman, personal communication). However, pasture feeding is not a dairy farming system that maximizes per cow production, but it is in line with traditional organic philosophy of "Refusing to Push the Cows" (Saucier 2014). For a variety of reasons, pasture feeding included, organic dairy operations generally have fewer animal health problems (Karreman, 2007). Good animal health and prevention are critical aspects of all animal husbandry. This is especially important because many of the usual veterinary drugs are prohibited for organic dairy production (Karreman, 2007; Karreman, 2011).

Beyond a system of production, pasture feeding influences consumer demand and marketing (Dmitri & Oberholtzer, 2009). With increasing awareness about the effect of pasture feeding on food quality and animal welfare, increasing numbers of people are seeking out pasture-raised animal products (Black, 2015). Perhaps, to the extent that USDA-NOP encourages livestock feeding on pasture, consumers seek out the organic label.

Eggs produced by chickens on pasture have a noticeable difference in quality and color, ranging from dark yellow to orange color of egg yolks is typical (Karsten & Baer 2009). When chickens are given a chance to graze the leaves of wheat or rye plants in the winter, the egg yolks take on an especially deep orange character (Heckman, 2011). Currently little data is available on the nutritional quality or the levels of fat soluble vitamins in such eggs.

Unlike organic dairy, there is no specific pasture requirement for egg production, although the NOP rules do require “year-round access for all animals to the outdoors… (NOP 7 CFR 205.239).” Pasture only provides about 10% of feed for egg laying hens. One of the main benefits is that organic egg producers keeping hens on pasture may earn a price premium over the average organic egg. At Whole Foods grocery stores, pasture raised organic eggs are currently priced \$8.99 compared to \$4.69 for regular organic eggs, corresponding to a 91% higher price (Black, 2015).

6. Example of a Pasture Based Organic Farm

“The Family Cow” near Chambersburg, Pennsylvania is an example of a highly diversified pasture based organic farm. This farm has found ways to scale up poultry production on pasture where egg layers or broilers are rotated over pasturelands after the grazing of dairy cows. The manures deposited by the poultry fertilize the grass. The chickens may also help with fly control. A dog lives with the flock of egg layers to protect the birds from predators. The eggs are collected from the specially designed egg mobile wagons via a conveyer belt.

Farm tours, available by appointment from The Family Cow website, helps make this organic farming operation transparent and educational for the public. This rather innovative organic farm produces raw milk, eggs, broilers, turkeys, beef, and pork, all from animals on pasture. The farm products are directly marketed from an on-farm store and via their website and delivered to 48 receiving points in Pennsylvania. People buying from such diversified organic farms are able to purchase most of their food needs without going into a commercial grocery store. This integrated system of pasture farming and marketing was inspired by Joel Salatin (Edwin Shank, personal communication). Pasture-based farming systems have become popular with increasing awareness of the value of pasture raised foods as a result of the educational programs of the Weston A. Price Foundation, publication of the bestselling book *The Omnivore’s Dilemma* by Michael Pollan, and documentary films such as *Farmaggedon*, *American Meat*, and *Food Inc*.

7. Role of Trees in Organic Farming

Tree crops offer additional ways to feed livestock. Silvopasture is a farming system that integrates trees with pastures. The trees in this system provide valuable shade and shelter and can also produce livestock feed such as seeds, fruit, nuts, acorns, flowers, or foliage (Brunetti, 2014).

The idea of feeding livestock with tree crops instead of annual row crop grains was promoted by J. Russel Smith in his classic book on *Tree Crops, A Permanent Agriculture* (Smith, 1950). Smith, a geographer traveled widely and witnessed extensive soil erosion on sloping lands. He proposed tree crops as a viable alternative form of agriculture for land areas vulnerable to soil erosion. He argued that if the same attention in plant breeding and selection used for annual crops were to be applied to tree crops, agricultural productivity could be greatly expanded on marginal lands. Researchers at Rutgers University, inspired by the concepts in Smith’s book, seek to advance tree crops through a global search for germplasm resources for selection, and plant breeding. This work was initiated by the late Dr. Reed Funk who had made great advances in grass breeding before deciding to turn his attention to breeding tree crops (Molnar et al., 2013)

The Rodale Institute, a center for organic farming research, also has an active research program called “Tree as a Crop” (The Rodale Institute, 2015), recognizing that many farms have some land that can be devoted to trees. Managed as silvopastures, this land may be used for pasturing many kinds of livestock. On very hot, cold, or windy days, livestock may be protected by tree shelter.

8. Special Attributes of Trees

As perennials, trees have a range of beneficial attributes. For example, after establishment, their deep extensive root systems become a long-term no-tillage system offering protection against soil erosion. Many tree species, such as the oaks, have the potential to produce livestock feed. Unlike row crop grains, tree crops do not require annual applications of starter fertilizers. Also, the pattern of nutrient uptake from soil by trees takes place over extended periods of time whereas with annual cropping systems the nutrient uptake period is short. Once an annual root system dies it offers no resistance to leaching of nutrients. Tree crops tend to be less “leaky” of nutrients over the fall and winter seasons. Furthermore a large pool of nutrients are conserved within living tissues such as bark, stems, and roots, and these nutrients are recycled internally from season to season (Youssefi et al., 1999).

Compared to annual crops, one of the main disadvantages of tree crops is that they require more time between generations for plant breeding improvement. Probably for this reason, plant breeding efforts have focused primarily on selections of annuals for yield. Perennial crops and especially trees in particular offer an under-utilized opportunity for plant breeders to select for yield and other agronomic traits (Molnar et al., 2013).

Mainstream agriculture is dominated with the annual cropping paradigm but this could change if new proposals for establishing research programs and centers for tree crops were ever taken seriously. Greater use of both woody and herbaceous perennials could contribute significantly to the productivity of organic farming simply by exploiting their extended window for photosynthetic activity. This property was eloquently described by Wes Jackson (2011) “Humans have forever looked for ways to increase the food supply of the world when all around us, year in year out, it should be apparent that the most rewarding way would be to increase the proportion of the year when the land is covered by a photosynthesizing leaf canopy”. In this way trees and pasture plants are well suited towards this goal in both conventional and organic agriculture.

9. Trees Grow Natural Lumber and Fence Posts for Organic Farming

Aside from direct roles in productivity, certain types of trees are valued for providing fiber, building materials, and shelter. Natural untreated wood products are especially valued in organic agriculture. For example, the USDA-NOP standards provide “The producer must not use lumber treated with arsenate or other prohibited materials” (NOP 7 CFR 205.206 (2015).

Some newly established organic pasture based farms in New Jersey, are reporting a short supply of available locust wooden post for fencing (Profeda Farms, personal communication). Black locust wood is very decay resistant with an effective useful life as a fence post of 50 years or more.

Black locust is a particularly valuable tree species in organic agriculture because it can serve so many useful functions (Chedzoy, 2015). It is a very fast growing leguminous tree that carries out biological N fixation. Because it casts only a light shade it performs very well in silvopasture systems. The tree is very easy to establish. After only about ten years of growth on good sites, the stems can be harvested as fence posts. After harvest, the trees regenerate quickly from stump sprouts. Thus, once established, there is no need to replant this most renewable resource. The wood is highly durable and decay resistant. The flowers on black locust trees are a favorite for honey bees.

A 1930, publication by the USDA Forest Service provides excellent guidance on growing black locust (USDA Farmers Bulletin No. 1628). One pest problem with black locust is the locust borer. Fortunately, this pest is absent from Europe where black locust is grown in plantations for many uses.

10. Conclusion

Trees and pasture thoughtfully integrated into the farm ecosystem have much to contribute to the sustainability of organic agriculture. Including pasture in a crop rotation is one of the most effective ways to build soil organic matter content. Herbaceous and woody perennials, even on hilly lands, protect soils from erosion. The nutritional quality of animal foods is improved when produced by livestock on pasture. People choosing to eat organic pasture raised foods are indirectly contributing to and helping fund soil improvement. Future research on organic food quality as it relates to pasture feeding of livestock should look beyond fatty acid composition to levels of the fat soluble vitamins A, D, E and K2 in the food product. Organic farmers building pasture fences and animal shelters may benefit from growing silvopastures that include black locust. The very durable wood from this tree is an excellent alternative to commercial lumber treated with unapproved toxic materials. Altogether, trees and pastures are parts of the living fabric of organic farms that create a web of connections between soils, plants, animals, and people while building healthy and sustainable ecosystems.

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Water Quality in Organic Systems

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Abstract

Non-point source contamination is a major water quality concern in the upper Midwestern USA, where plant nutrients, especially NO_3-N, are susceptible to leaching due to extensive subsurface draining of the highly productive, but poorly drained, soils found in this region. Environmental impacts associated with intensive mineral fertilization in conventional production have encouraged producers to investigate organic methods. The USDA-ARS Organic Water Quality (OWQ) experiment, established in 2011, compares organic (C-S-O/A-A) and conventional (C-S) crop rotations and an organic pasture (bromegrass, fescue, alfalfa, white clover) system. Thirty fully-instrumented, subsurface-drained plots (30.5 m × 30.5 m) laid out in a randomized block design with 5 field replications, isolate subsurface drainage from each plot and permit comparison of treatment effects on subsurface drainage water flow and nutrient concentrations. Objectives for this study were to quantify growing season subsurface drainage water flow, NO_3-N concentrations, and NO_3-N loads for conventional and organic grain cropping systems from 2012-2014. Temporal patterns of subsurface drainage water flux were similar for all cropping systems for all years, except for the pasture system in 2012 and subsurface drainage water N concentrations were highest in the conventional C-S system except for the early spring 2012. Subsurface drainage water N loading loss for the entire 3-year period from the conventional C-S system (79.2 kgN ha^{-1}) was nearly twice as much as the N loss from the organic C-S-O/A-A system (39.9 kgN ha^{-1}); the pasture system (16.5 kgN ha^{-1}) lost the least amount of N over the 3 years. Results of this study suggest that organic farming practices, such as the application of composted animal manure and the use of forage legumes and green manures within extended cropping rotations, can improve water quality in Midwestern subsurface-drained landscapes.

Keywords: organic farming systems, water quality, subsurface drainage, nitrate leaching

1. Introduction

The Midwestern U.S. is one of the most productive agricultural regions in the world, but conventional agricultural management of this land has led to serious, negative environmental consequences. Nitrate contamination of surface waters, primarily from the discharge of subsurface drainage water and shallow ground water, is causing increasing concern because a significant proportion of the nitrate in the Mississippi River comes from agricultural land in the Midwest (Goolsby et al., 1999; Jaynes et al., 1999) and this nitrate contributes significantly to hypoxia in the Gulf of Mexico (Rabalais et al., 1996). Environmental impacts associated with intensive mineral fertilization in conventional production (Pimentel et al., 1989) have encouraged producers to investigate organic methods. Increasingly, organic producers are being asked to provide evidence that organic farming practices, such as the application of composted animal manure and the use of forage legumes and green manures within extended cropping rotations, are environmentally benign.

Water quality in the Midwestern USA: Non-point source contamination is a major water quality concern in the upper Midwest, where plant nutrients, especially NO_3-N, are susceptible to leaching due to extensive subsurface draining of the highly productive, but poorly drained, soils found in this region (Gast et al., 1978; Baker & Johnson, 1981; Randall et al., 1997; Zhao et al., 2001; Magner et al., 2004). The drinking water standard for NO_3-N concentration in the USA is 10 mg NO_3-N $liter^{-1}$. Nitrogen fertilizer management alone will not be successful in lowering drainage water NO_3-N concentrations to meet water quality standards (Dinnes et al, 2002). Jaynes et al. (2001) found that NO_3-N concentrations of drainage water were greater than 10 mg L^{-1} at N fertilizer rates that were substantially below the economic optimum N fertilizer rates for corn grain production. Subsurface drainage water NO_3-N concentrations were above 10 mg L^{-1} even following a soybean crop when no N fertilizers were applied the previous spring (Cambardella et al., 1999; Jaynes et al., 2001).

Water quality in organic systems: The scientific literature on water quality and water flux in organic systems is very limited. Many of the published studies in the past decade use nutrient concentration data obtained from lysimeters to estimate NO_3-N loss (Biro et al., 2002; Askegaard et al., 2005; Pimentel et al., 2005; Stopes et al., 2005; Loges et al., 2008; Hatch et al., 2010). Estimates of water flux are estimated mathematically (Askegaard et al., 2005; Hatch et al., 2010), modeled (Hansen et al., 2000; Loges et al., 2008) or ignored (Biro et al., 2002; Pimentel et al., 2005).

On-farm studies conducted in England compared NO_3-N leaching losses from organic and conventional farms in the arable and grass phase of the rotations. Nitrate losses following arable crops averaged 47 and 58 kg N ha^{-1} for the organic and conventional systems, respectively. Nitrate losses during the organic grass phase, which included winter plowing, were similar (45 kg N ha^{-1}) to the grass phase of conventional grass-arable rotations (50 kg N ha^{-1}) (Stopes et al., 2002). An organically-managed oil seed pumpkin (*Curcurbit pepo*)-potato (*Solanum tubeosum*) rotation in Hungary resulted in significantly lower cumulative (over 200 consecutive days) NO_3-N load (~20 mg NO_3-N per lysimeter) than a conventionally-managed rotation pumpkin-potato rotation (~280 mg NO_3-N per lysimeter) (Biro et al., 2005).

A simulation study of two Minnesota watersheds comparing conventional with alternative cropping systems that included perennial crops concluded that adding perennials to the crop rotation reduced N and P loads (Boody et al., 2005). A study conducted in southwest Minnesota examined effects of both alternative (including organic management) and conventional farming practices on NO_3-N loss in subsurface drainage water from glacial till soils (Oquist et al., 2007). Results indicate that alternative farming practices reduced subsurface drainage discharge by 41% compared with conventional practices. Flow-weighted mean NO_3-N concentrations during subsurface drain flow were 8.2 and 17.2 mg L^{-1} under alternative and conventional farming practices, respectively.

The long-term goal of this research is to evaluate the environmental impact of organic farming systems, including effects on water quality, water retention, carbon sequestration, and soil health. Specific objectives for this study were to quantify growing season subsurface drainage water flow, NO_3-N concentrations, and NO_3-N loss for a conventional C-S rotation, an organic C-S-O/A-A rotation, and an organic pasture from 2012-2014.

2. Materials and Methods

Experimental Design: The USDA-ARS Organic Water Quality (OWQ) experimental site is located at the ISU Agronomy Research Farm, near Boone, Iowa, on the Clarion-Nicollet-Webster soil association. Thirty-year average annual rainfall and temperature for Boone IA are 97.4 cm and 8.81 °C, respectively (NOAA National Climate Data Center, verified 2/13/15). Soils at the site are mapped as Clarion (fine-loamy, mixed, mesic Cumulic Hapludoll), Canisteo (fine-loamy, mixed (calcareous), mesic Typic Haplaquoll), and Webster (fine-loamy, mixed, mesic Typic Haplaquoll). The field site was cropped to a conventionally managed corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] (C-S) rotation prior to planting an oat (*Avena sativa* L.) /alfalfa (*Medicago sativa* L.) crop in 2006. No agricultural chemicals or fertilizers have been applied to the field since fall 2006. The 4.1-ha site consists of 30 field plots (30.5 m × 30.5 m) laid out in a randomized complete block design with five replications. Installation of subsurface drainage lines under each plot and instrumentation to collect water samples and monitor subsurface drainage water flow and nutrient loss, including flow barriers and sump pits, was completed in September 2011. A fully-instrumented weather station and tipping bucket rain gauge are located immediately adjacent to the field plots. Weather data, including ambient temperature and precipitation, are recorded every hour and downloaded for easy access through laboratory computers. Three cropping systems were established in the spring of 2012. Each phase of the cropping system is present every year and identical, non-GMO varieties are planted at the same seeding rate in conventional and organic plots. Experimental treatments include an organically managed corn-soybean-oat/alfalfa-alfalfa (C-S-O/A-A) rotation, an organically managed perennial pasture system (bromegrass, *Bromus;* fescue, *Festuca;* alfalfa; and white clover, *Trifolium repens*) and a conventionally managed C-S rotation. Results from a companion long-term experimental site located in south central IA USA, show that this 4-year organic rotation increased soil quality variables (for example, soil organic carbon, total N, and N mineralization potential) critical for minimizing nutrient leaching potential and optimizing water cycling and retention (Delate & Cambardella, 2004). The fully-instrumented, subsurface-drained research site provides the opportunity to conduct long-term, statistically robust experiments using production-scale farm machinery to assess environmental, soil and agronomic response for the extended cropping rotations typically used in organic agriculture.

Agronomic practices: The organic corn and oat plots are amended with composted dairy cattle manure in early spring (March 15, 2012; April 25, 2013; April 14, 2014); compost is immediately incorporated using a chisel plow. Compost application rate is based on total N in the compost at a target rate of 171 kgN/ha to the organic corn plots and 57 kgN/ha to the organic oat plots. Corn and soybean were planted on May 22 in 2012, May 15 in 2013, and May 29 in 2014. Grain yield is measured using a weigh wagon. Alfalfa is mowed 2-3 times per year and the biomass is raked and baled. Weeds are managed using rotary hoeing and row cultivation until crop canopy closure. The organic pasture system is maintained through mowing at appropriate intervals per local organic practices, and biomass is not removed. Agronomic practices for the C-S system are typical for this region and soil type, including chisel plow tillage. Urea ammonium nitrate (UAN) liquid fertilizer is sidressed using a spoke injector in late spring (June 8, 2012; June 11, 2013; June 16, 2014) ~3 weeks after corn planting at a rate of 171 kgN/ha. Phosphorus and K fertilizer are applied in the fall at rates based on soil test results. Weeds are managed with herbicides. Insects and diseases, if encountered, are managed based on Iowa State University recommended treatment rates and application intervals.

Water sampling and analysis: Subsurface drainage water from each plot is collected in dedicated sumps with a pump that empties the sump whenever the water level exceeds a preset level. Only the center drainage line under each plot is monitored for drainage volume and NO_3-N concentration. Subsurface drainage water N loss is estimated from flow proportional water samples taken from the drainage water sampling systems (Bjorneberg et al., 1996). Collection of subsurface drainage water flow data began in December 2011 and evaluation of subsurface drainage water quality was initiated in the spring of 2012. Subsurface drainage water flow is recorded every 30 minutes and the electronic data are supplemented with weekly manual meter readings. Subsurface drainage water sub-samples for measuring NO_3-N concentration are taken every week when the subsurface drains are flowing and analyzed for (NO_3 + NO_2) using a colorimetric method and flow injection technology (Lachat Instruments, Milwaukee, WI). Nitrogen loading loss in the drainage water is calculated using subsurface drainage flow volume and NO_3-N concentrations and are expressed as kg N ha^{-1}. Annual system-wide results were calculated as the mean of the average annual flow-weighted NO_3-N concentration or as the sum of the average annual N loss for each phase of the rotation.

3. Results

3.1 Rainfall and Temperature

Rainfall and ambient temperature patterns across the growing season (March-October) for each of the three years of the study were dramatically different (Table 1). Average annual growing season precipitation for Boone IA is 75.8 cm, with 62.8% of the rainfall occurring between May and August. An unusually dry and warm spring followed by a dry, hot summer in 2012 was accompanied by nearly 50% less rainfall (45.9 cm) than average during this time period. Overall, 2013 growing season precipitation was lower (57.2 cm) than the 30-yr growing season average. Higher than average rainfall amounts, accompanied by cooler temperatures, were observed in March, April and May 2013 but the remainder of the 2013 growing season was drier than average. In 2014, growing season rainfall (86.0 cm) exceeded the 30-yr growing season average and ~25% of the total growing season precipitation fell during the month of June. In addition, temperatures were cooler than average.

Table 1. Average monthly growing season rainfall (cm) and temperature (°C)

	2012†		2013		2014		30-yr Average‡	
	Temp	Rain	Temp	Rain	Temp	Rain	Temp	Rain
March	10.6	5.5	-1.8	3.1	-1.4	1.5	2.1	5.3
April	11.4	9.9	6.8	13.1	8.5	11.6	9.2	8.7
May	18.9	4.1	14.9	16.5	16.1	8.8	15.2	11.7
June	22.3	6.9	20.9	7.2	21.0	22.2	20.4	12.8
July	25.4	3.1	22.6	2.5	20.3	5.4	22.8	11.9
August	20.9	7.1	22.2	5.3	21.6	19.6	21.8	11.2
September	16.5	4.3	19.1	3.3	16.4	9.7	17.2	7.7
October	9.0	5.0	10.0	6.2	10.3	8.1	10.4	6.5

† On-site weather station. ‡ Boone, IA USA (NOAA, verified 2/13/15).

3.2 Crop Yield

Organic and conventional corn and soybean yields and organic oat yields were similar to county-wide average yields for Boone County IA in 2012 (Table 2), despite reduced rainfall from May-August. A cool, wet spring followed by a dry summer in 2013 contributed to lower than county average grain yields for conventional and organic corn and soybean. Organic corn yields were especially impacted by the weather conditions in 2013. Yields for organic corn were ~30% lower than the county wide average yield for corn. In 2014, organic soybean yield was higher than the county wide average and organic oat yields were nearly twice as high as the county wide average (Table 2). The highest soybean yields for the three year study period were observed in 2014 when organic and conventional soybean yields were similar. Corn yield in 2014 did not differ for the conventional and organic systems and yield from both systems was more than 35% lower than the county-wide average.

Table 2. Grain yield

Cropping System	Grain Yield (Mg ha^{-1})		
	2012	**2013**	**2014**
Organic Corn	9.24 (1.0)†	7.14 (0.6)	7.91 (1.0)
Conventional Corn	9.79 (0.9)	9.04 (1.0)	7.64 (1.4)
County Average Corn	9.99‡	10.50	12.30
Organic Soybean	3.06 (0.3)	2.24 (0.1)	3.84 (0.4)
Conventional Soybean	3.86 (0.5)	2.17 (0.3)	3.68 (0.4)
County Average Soybean	3.06	2.79	3.44
Organic Oats	4.28 (0.6)	4.96 (0.5)	6.80 (0.5)
County Average Oats	4.92	No data	3.56

† Mean of 5 field replicates (Standard deviation).‡ www.nass.gov for Boone County IA USA.

3.3 Subsurface Drain Flow

Cumulative average subsurface drain flow in 2012 in the organic C-S-O/A-A (67,006 liters) and the conventional C-S (75,747 liters) systems was similar and an order of magnitude lower than in the organic pasture plots (230,891 liters). Subsurface drain flow did not correlate with precipitation in 2012, except for a sharp peak in flow in mid-April for all cultivated plots (Figure 1a and Table 1). In 2013, cumulative average subsurface drain flow was similar for the three systems: conventional C-S (170,096 liters); organic C-S-O/A-A (192, 839 liters); and organic pasture (179,333 liters). Three large and distinct peaks in flow occurred for all the cropping systems in 2013, and the relationship between peak flow and rainfall amounts was much more evident than in 2012 (Fig 1b and Table 1). Cumulative average subsurface drain flow for the conventional C-S (203,948 liters) and organic C-S-O/A-A (207,507 liters) systems were similar in 2014 and twice as great as flow for organic pasture (100, 570 liters). Subsurface drain flow peaked for all three systems in July 2014 following 22.2 cm of rain in June and peaked again in late August-early September following 19.6 cm of rain in August (Figure 1c and Table 1).

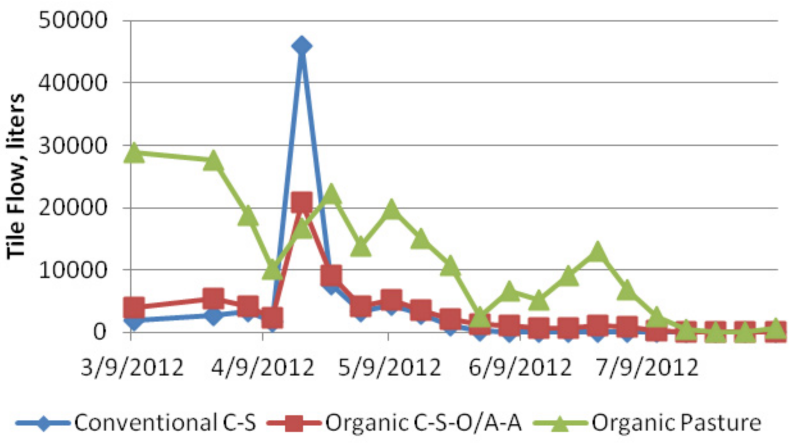

Figure 1a. Subsurface drainage water flow 2012

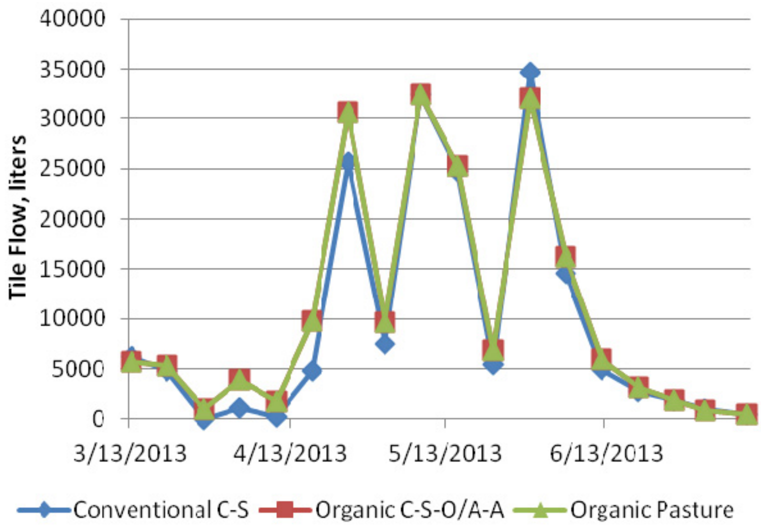

Figure 1b. Subsurface drainage water flow 2013

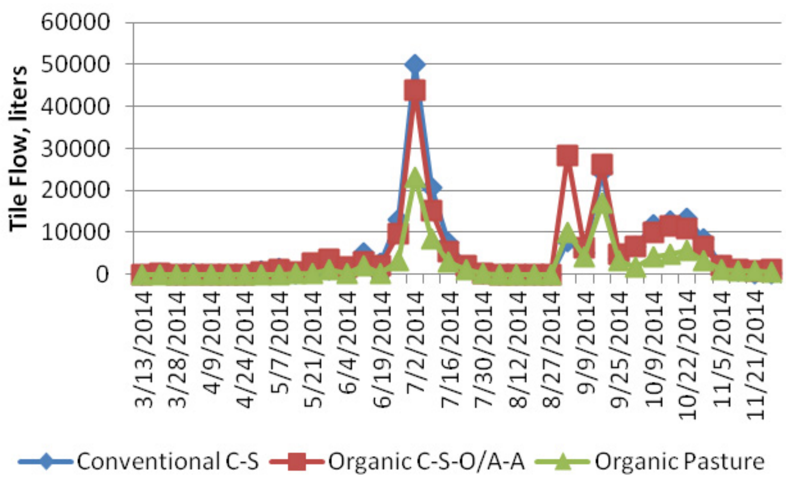

Figure 1c. Subsurface drainage water flow 2014

3.4 Subsurface Drainage Water NO_3-N Concentrations

Subsurface drainage water NO_3-N concentrations differed among the three cropping systems and varied across the three years of this study. Flow weighted NO_3-N concentrations were generally lowest for the pasture and highest for the conventional C-S system for all three years (Figure 2a-2c and Table 3). In the first growing season after subsurface drain installation, NO_3-N concentration in subsurface drainage water trended down from spring into early summer for the two grain cropping systems but not for the pasture system. Nitrate-N concentrations increased after fertilizer application for the conventional C-S rotation (Figure 2a) and remained high until subsurface drain flow ceased in early August 2012 (Figure 1a). In March 2013, subsurface drainage water NO_3-N concentrations were less than 5 mg N liter^{-1} for all three systems, rapidly increased to a maximum of ~35 mg N liter^{-1} and ~15 mg N liter^{-1} in the conventional C-S and organic C-S-O/A-A systems (Figure 2b), respectively, and remained high in the conventional C-S system until flow ceased in early August 2013 (Figure 1b). A similar pattern for subsurface drainage water flow and flow weighted NO_3-N concentrations for the three cropping systems was observed for spring through mid-August during the 2014 growing season (Figure 2c). Unlike 2013, subsurface drain flow continued into mid-November in 2014 (Figure 1c).

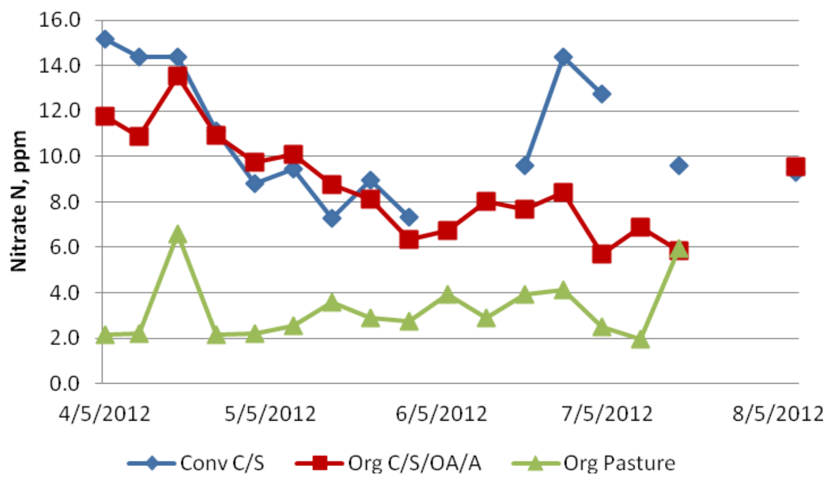

Figure 2a. Flow-weighted subsurface drainage water NO_3-N concentrations 2012

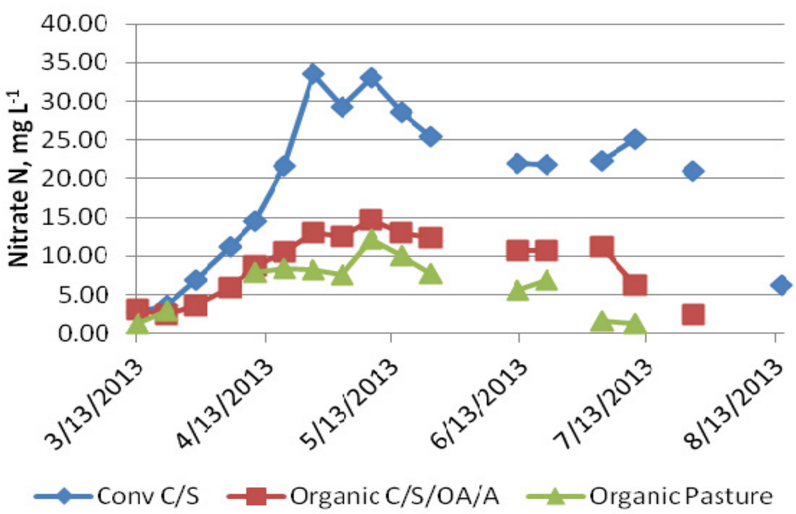

Figure 2b. Flow-weighted subsurface drainage water NO_3-N concentrations 2013

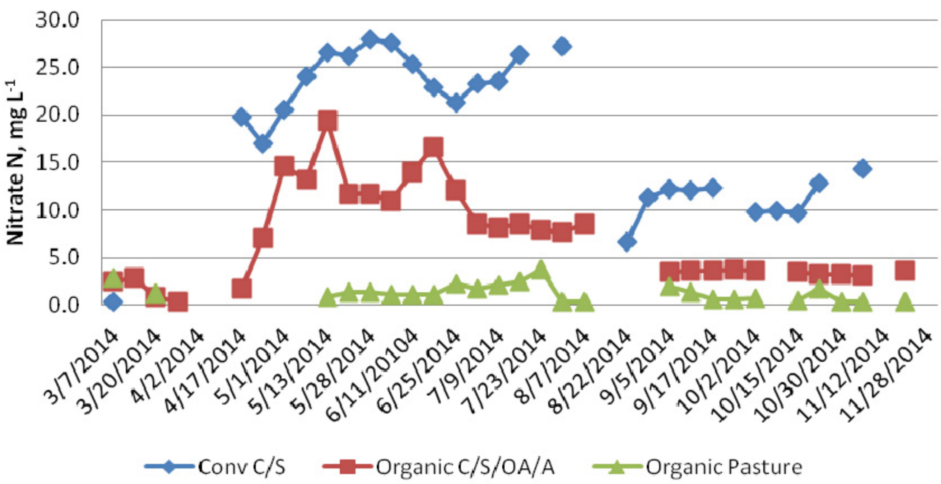

Figure 2c. Flow-weighted subsurface drainage water NO_3-N concentrations 2014

Subsurface drainage water NO_3-N concentrations were higher than ~10 mg N liter^{-1} in the conventional C-S system and less than 5 mg N liter^{-1} in the organic C-S-O/A-A rotation from early September through November (Figure 2c). During the winter of 2014/2015 subsurface drains continued to flow, and NO_3-N concentrations were consistently higher for conventional C-S than for the organically managed C-S-O/A-A rotation. Average subsurface drainage water NO_3-N concentration from November 28, 2014 through February 9, 2015 was 12.9, 3.6 and 0.4 mg L^{-1} for conventional C-S, organic C-S-O/A-A and organic pasture, respectively.

3.5 Subsurface Drainage Water NO_3-N Loading Loss

Subsurface drainage water NO_3-N loading loss for the entire 3-year period from the conventional C-S system (79.2 kgN ha^{-1}) was nearly twice as much as the N loss from the organic C-S-O/A-A system (39.9 kgN ha^{-1}). The 3-year N losses represent 5.8% of applied N in the organic rotation and 15.4% of applied N in the conventional rotation. The pasture system (16.5 kgN ha^{-1}) lost the least amount of N over the 3 years. Subsurface drainage water N loss for 2012 was much lower than 2013 and 2014 for the conventional and organic crop rotations and the difference in N loss between the two systems was the smallest in 2012 (Table 3). The conventional C-S system lost 100% and 132% more NO_3-N in subsurface drainage water than the organic C-S-O/A-A system in 2013 and 2014, respectively.

Table 3. Flow-weighted annual subsurface drainage water NO_3-N concentration and annual nitrate-N loss

Cropping System	**NO_3-N Concentration (mgN liter^{-1})**	**NO_3-N Loss (kgN ha^{-1})**
2012		
Organic C-S-O/A-A	8.8 (2.2)†	7.7 (0.9)†
Conventional C-S	10.9 (2.8)	10.1 (2.2)
Organic Pasture	3.3 (1.4)	5.8 (3.6)
2013		
Organic C-S-O/A-A	8.8 (4.2)	17.7 (6.3)
Conventional C-S	19.4 (10.1)	34.7 (14.0)
Organic Pasture	6.3 (3.5)	9.5 (7.5)
2014		
Organic C-S-O/A-A	7.2 (5.0)	14.5 (5.7)
Conventional C-S	18.1 (7.8)	34.4 (9.6)
Organic Pasture	1.3 (0.9)	1.2 (1.3)

† Mean of 5 field replicates (Standard deviation).

4. Discussion

Nitrate-N contamination of surface water is a major water quality concern in the upper Midwest USA. Environmental impacts associated with agricultural production have encouraged producers to investigate alternative management practices, including organic farming methods. Mechanisms underlying improved environmental conditions on organic farms have included an improved capacity for greater water and soil nutrient retention due to enhanced soil organic matter content from more diverse crop sequences and application of organic-based amendments, including cover crops and manure (Liebig & Doran, 1999). This study quantified growing season subsurface drainage water nitrate-N losses for conventional and organic grain cropping systems from 2012-2014. Subsurface drainage water was isolated from each plot by installing subsurface drain pipes under and between each plot and around the entire perimeter of the experimental site. The experimental approach used in this study is rare in the literature because of the high cost of establishing subsurface drainage water monitoring infrastructure.

Average cumulative growing season NO_3-N loss for the C-S-O/A-A system for 2012-2014 was 13.3 kg N ha^{-1}. The magnitude of N loss from the organic system in our study is similar to N loss from organic corn-soybean rotations in PA, USA (17 kg N ha^{-1}) (Pimentel et al., 2005) and lower than N losses reported for organic small grain based rotations in Denmark (26-106 kg N ha^{-1})(Askegaard et al., 2005), Germany (20.7 kg N ha^{-1})(Loges et al., 2008) and the UK (55.9-93.9 kgN ha^{-1})(Hatch et al., 2010). Subsurface drainage water nitrate-N loss for the 3-year period from the conventionally managed C-S system (79.2 kgN/ha) was nearly twice as much as from the organically managed C-S-O/A-A (39.9 kgN/ha). Research conducted in Norway on loamy and silty sand soils showed that 42% more nitrogen was lost in subsurface drainage from conventionally farmed land than from organic land (Korsaeth & Eltun, 2000).

Results of this study suggest that organic farming practices, such as the application of composted animal manure and the use of forage legumes and green manures within extended cropping rotations, can improve water quality in Midwestern subsurface-drained landscapes.

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Organic No-Till with Roller Crimpers: Agro-Ecosystem Services and Applications in Organic Mediterranean Vegetable Productions

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Abstract

In sustainable/organic farming systems, Agro-ecological Service Crops (ASC) may provide many beneficial ecosystem services, when they are introduced as buffer zones, living mulches or break crops. This outlook paper focuses on: i) the role of ASC genotype and mixtures as catch crops for soil mineral nitrogen (NO_3^-) surplus, which is returned to the system after their termination; ii) living mulches and break crops management strategies, particularly comparing ploughing under (green manure) with termination by roller crimper; iii) summary of three recent case studies that have assessed the effectiveness of ASC management by no-till with roller crimper for tomato, zucchini and melon crops, under Mediterranean conditions. Recently, in central Italy yield and quality results on organic tomato indicated that this crop was suitable following termination of leguminous ASC by roller crimping. Similarly, this ASC management increased yield by about 70% compared to green manure in zucchini crop. In southern Italy, no substantial differences were found in the ASC management and organic fertilizer interactions in organic melon, confirming the suitability of matching these strategies to sustain crop production. More studies should be encouraged to further empower the use of ASC in a wide range of agro-climatic conditions. Furthermore, additional studies on the roller crimper should be performed, mainly to understand the dynamic of N mineralisation in the soil-mulch interface and synchronisation of N release with cash crop N requirements. Finally, Decision Supporting Systems (DSS) for ASC introduction into vegetable cropping systems should be developed.

Keywords: agro-ecological service crops, break crops, buffer zones, living mulch, termination strategies

1. Background of the Study

Various terms have been used to identify crops with multiple agro-environmental functions (i.e. catch crops, cover crops, complementary crops, green manure, etc.). Therefore, the new terminology of *Agro-ecological Service Crops* is being introduced to overcome the lack of a comprehensive and all-embracing term, to include all crops used in agro-ecosystems to provide or enhance its environmental functions (i.e. as buffer zones, living mulches and break crops), irrespective of their position in the crop rotation and/or independently of the method (green manure *vs* flattened crop) that can be applied to terminate them. Therefore, ASC are generally not directly aimed at improving crop yield, even if most of the time they indirectly contribute to sustain agricultural production by a wide range of mechanisms (Canali, 2013).

In sustainable/organic farming systems, ASC represent a powerful tool for farmers to positively influence the agro-ecosystem by promoting the whole soil-plant system equilibrium in space and time (Kremen & Miles, 2012; Canali, 2013; Wezel et al., 2014). ASC may have impact on soil fertility (Thorup Kristensen et al., 2012; Montemurro et al., 2013), occurrence of weeds (Bàrberi, 2002; Hayden et al., 2012), diseases and pests

(Masiunas, 1998; Patkowska et al., 2013). They increase soil carbon (C) sink potential (Mazzoncini et al., 2011), influence greenhouse gasemission (Sanz-Cobena et al., 2014) and improve system energy use efficiency (Gomiero et al., 2008; Canali et al., 2013). ASC can also greatly reduce leaching of nutrients like soil nitrate (NO_3^-) (Kristensen & Thorup-Kristensen, 2004).

2. Including ASC in Agro-Ecosystems

2.1 Buffer Zones

The introduction of ASC in agro-ecosystems is achieved by several complementary strategies that should be taken into account when designing the cropping system. Accordingly, ASC can be cultivated as '*ecological compensation areas'*, in the border of the fields and/or in their immediate surroundings, using the parts or portions of a farm/field that are generally not destined to grow the cash crops (i.e. high slope areas, border of ditches, etc; Marshall & Moonen, 2002; Tilman et al., 2002). This environmental structure may act as a buffer zone (or strip) and function in water quality improvement. Indded, buffer zones can play a role in reduction of NO_3^- contamination of surface waters due to runoff from agricultural fields. Also wetland riparian zones have bee identified as effective to reduce the amount of NO_3^- of agricultural origin which reaches surface waters.

2.2 Living Mulches and Break Crops

The ASC can also be introduced in the cropping system as *living mulches* (LM): ASC is intercropped with a cash crop and maintained as a living ground cover throughout the growth cycle. Living mulched systems are managed in order to make most of the system resources (i.e. water, nutrients, light) available to the harvestable crop. Simultaneously, management of the ASC is optimised to provide its environmental services at field/farm level (i.e. increase nutrient availability, contribute to weed, pest and diseases management, biodiversity conservation, NO_3^- leaching reduction, etc.) and to reduce competition with the cash crop (Swenson et al., 2004; Vanek, 2005; Bath et al., 2008; Theriault et al., 2009; Canali et al., 2014). However, many attempts to use LM in annual cropping systems have resulted in reduced yields of the cash crops (Hiltbrunner et al., 2007; Chase & Mbuya, 2008). According to Masiunas (1998) the success of such systems depends on the capacity to rapidly establish a ground cover and smother weeds, without competing for resources with the associated crop.

Vegetables with a high nitrogen (N) demand, such as cauliflower, can cause intensive leaching of NO_3^- to the environment in conventional as well as in organic production. In organic cropping system, the use of an in-season LM may decrease the risk of NO_3^- leaching after harvest, when left to grow in the field to the end of the leaching season in spring. It has been recently demonstrated that the continued presence of LM in the field over winter may reduce the soil mineral N content compared to bare soil after the sole crop during the leaching season and, as a consequence, contribute to lower the NO_3^- leaching risk from the horticultural systems (Kristensen et al., 2014).

Another option for designing sustainable cropping systems in accordance with agro-environmentally sound criteria, is the use of ASC as *break crops*. These crops are cultivated as sole crop in the rotation, between two consecutive cash crops. Low input/sustainable and organically managed agro-ecosystems for vegetable production that are widespread in the European environments are often include break ASC in the rotation. In Central and Northern Europe break ASC crops are mainly cultivated in the winter season to avoid direct competition for land with the cash crops, which, conversely, are mainly cultivated during the warm season (Masiunas, 1998). In milder Mediterranean climatic areas (i.e. Southern Europe), vegetable cropping systems are based on rotations in which cash crops are grown either in the warm or in the cold winter seasons. From an economic point of view, these vegetable cropping systems are rather important, since they provide quality products to be consumed locally or exported to the Northern European areas year round. In the Southern European areas, farmers grow ASC in the rainy season, to exploit rain water, which is not a limiting factor in this season. Nonetheless, those farmers would also be interested in the possibility to design suitable cropping systems that include warm season break ASC, in order to optimise the rotations and to achieve the best economic and environmental performances (Butler et al., 2012). However, ASC and especially grass species can take up all the available water in the soil, so there could be a shortage of water for the following cash-crop, particularly during the summer, unless irrigation is used.

In vegetable cropping systems, the break ASC may reduce the risk of NO_3^- losses principally because they take up mineral N from the soil especially if it is left bare. This circumstance happens when the vegetable cash crops are not grown because of adverse climatic conditions (i.e. winter in Central and Northern Europe) and/or due to unfavourable market opportunities. The effectiveness of break ASC at lowering the risk of N losses is remarkable when they are introduced in the period of the year with high rain intensity. During those periods, soil mineral N not used by the previous crop and/or mineralised during the bare period, is highly potentially leachable. Mineral N taken up by the break ASC and converted into organic matter, is then returned to the cropping system after termination at the end of the ASC cropping cycle. Depending on to the ASC termination techniques (see section 4), the mineralisation rate of plant material may be modulated to synchronise the availability of soil mineral N with the N needs of the subsequent cash crop (Canali et al., 2013).

3. The Role of ASC Genotype and Mixtures of ASC

A wide range of plant species belonging to different botanical families can be utilised as ASC. However, most of them belong to three families: *Graminaceae* (grasses), *Brassicaceae* (brassicas) and *Leguminosae* (legumes), and only a minor number of species belong to other families (i.e. *Polygonaceae* or *Boraginaceae*).

Since plants of the different families show differences in terms of physiology and agronomic characteristics, they have different abilities to provide agro-environmental services. In relation to N, grasses and brassicas have great nutrient requirement, and can take up large quantities of N during their cropping cycle. If this N is not available in the soil, their growth is limited. Conversely, the growth of legumes is not limited by N shortage in the soil since they get the element by biological nitrogen fixation (BNF). It is probably worth to underline that, similarly to the non-legume ASC, legumes also use soil mineral N to grow if available, instead of BNF processes (Moller et al., 2008; Zhou et al., 2011). Therefore, all ASC could behave as catch crop of excess mineral N, contributing to reducing the risk of NO_3^- leaching. According to Dabney et al. (2010), the average reduction in NO_3^- leaching has been identified to be about 70% for grass or brassica and about 23% for legume covers. Nitrogen fixed (in the case of legumes) or taken up by the ASC is returned to the system after their termination, when plant tissues incorporated into the soil or used as surface mulch, mineralise and release mineral N. The mineralisation process is controlled by environmental (i.e. soil temperature and moisture) and intrinsic factors related to plant materials characteristics (i.e. lignin and cellulose content, total and soluble N content, C/N ratio; Jensen et al., 2005). In particular, the C/N ratio of the plant material, even if considered only an approximate guide to the likely net mineralisation, is often able to provide a valuable prediction of N mineralisation and can be effectively utilised in the current practice (Canali et al., 2011). In general, legume ASC have, at termination, a lower C/N ratio than the non-legumes crops. Grasses, in particular, have the highest values of this parameter. For this reason, the legume plant materials are generally considered less resistant to mineralisation and release N in the inorganic form more rapidly than the other crops families.

Mineral N derived from ASC plant materials is available to subsequent cash crops and the prediction of the mineralisation rate is a key aspect to synchronise it with the following crop needs. Indeed, if mineral N release is not well synchronised with crop needs, its nutritive efficiency is reduced. Moreover, if adverse environmental conditions (i.e., heavy rainfall) occur after ASC termination, the nitric component of the mineralised N may also be leached (Neeteson et al., 2003). However, N mineralisation from different organic sources can be opportunely managed if a mixture of residues with variable quality is used, including low N (high C/N ratio, as grasses tissue) and high N (low C/N ratio, as legume tissue) plant materials (Sikora & Enkiri, 2000; Nyiraneza & Snapp, 2007). Therefore, the selection of different ASC species and families, because of their different properties and potential mineralisation rate, is an effective tool to manage N nutrition and the risk of NO_3^- leaching.

Farmers can decide to seed pure (100%) legume ASC if high amounts of N are needed in a short term (i.e. nutrition of high demand vegetable crops) or, conversely, they may seed pure grasses in case of low N requirement of the next crop and/or, in climatic conditions with high potential risk of NO_3^- leaching. Moreover, sowing a *combination (a mixture)* of different proportions (i.e 50/50 or 30/70) of legume and non-legume ASC can determine a range of intermediate scenarios, useful for "fine-tuning" N dynamic in the soil-plant system (Tosti et al., 2012).

4. ASC Management Strategies

4.1 Living Mulches Management

As far as the management of LM is concerned, recent scientific literature reports emerging evidences of the influence of several factors on the effectiveness of this technique in providing agro-ecosystem services, in particular modulating NO_3^- leaching risks. One of these factors is the time of sowing of LM in respect to the transplanting of the associated cash crop (Adamczewska-Sowińska & Kołota, 2010). In addition, differences in term of soil mineral N content and potentially leachable soil NO_3^- have been observed between LM substitutive (reduction of cash crop plant density to leave room to LM) and additional design (same crop plant density), and these differences have been attributed to the different N uptake ability of the LM and the cash crop (Canali et al., 2014; Kristensen et al., 2014).

4.2 Break Crops: Green Manure vs Roller Crimper Technology

ASC need to be terminated prior to the subsequent cash crop planting in order to provide their services to the system and avoid competition. The phenological stage of the crop, the time and method of termination represent crucial management factors, especially in vegetable cropping systems where complex rotations and peculiar soil/plant interactions are in place.

The traditional, and most widespread, technique used to terminate the cropping cycle of the ASC is the incorporation as *green manure* into the soil by tillage (i.e. plough and/or rotary tiller) (Watson et al., 2002). However, since tillage is an energy and labour consuming and soil disturbing operation, in recent years, systems that use no/reduced tillage have received increasing interest. In this perspective, the *rolling crimper technology*, which terminates ASC by flattening, represents a promising choice (Mäder & Berner, 2012). The technique consists of one or two passages of the roller crimper, thus leaving a thick mulch layer into which the next crop is sown or transplanted (Teasdale et al., 2012). The roller crimper is comprised of a steel cylinder (about 41-51 cm diameter) with steel blades welded perpendicular to the cylinder in a chevron pattern. Prior to ASC termination, the cylinder is filled with water to provide an additional weight to aid in mechanical termination. Accordingly, due to the formation of this natural mulch on the soil surface, derived from the ASC plant materials, the potential capability of the roller crimping technology to control weeds, reduce soil erosion, maintain or increase soil organic matter content, as well as reduce labour use and fossil fuel energy consumption, has been acknowledged (cfr. Special Issue in Renewable Agriculture and Food Systems, 2012). In addition, evidences of the potential of the roller crimper technology to provide vegetable cropping systems resistance to pathogen and pest attacks are emerging (Bryant et al., 2013). Furthermore, the roller crimper technology has been recently investigated as a potential technique to mitigate NO_3^- leaching risk in vegetables production (Montemurro et al., 2013).

When an ASC is terminated by green manuring, its entire belowground and aboveground soil biomass is incorporated into the soil. According to the biomass amount and the N content of the plant tissue, it is likely that 50 to 200 kg ha^{-1} of organic N, ready to be mineralised, are incorporated into the soil. Depending on the characteristic of the plant biomass (i.e. C/N ratio), and soil moisture and temperature, mineralisation rates vary greatly, up to very high values in favourable conditions. Indeed, in the case of break ASC green manure in spring or in early autumn, large quantities of mineral N may be rapidly released in the soil. If the subsequent cash crop is not ready to take up the mineral N (i.e. not yet in the fast growing phenological phase), this mineral N is potentially leachable and/or can be subjected to re-immobilisation processes in the soil, contributing in a limited extent to the cash crop N nutrition. On the other hand, when the break ASC is terminated by the roller crimper, the soil is no or minimally tilled and the ASC aboveground biomass is not incorporated into the soil. In these conditions, the mineralisation of the organic matter, of the ASC plant material, occurs in the soil-mulch interface, and the mineral N release may proceed slower than in the green manure (Parr et al., 2014), due to the root biomass which may comprise as much as 12% of crop biomass amounts (Montemurro et al., 2013).

5. Organic No-Till With Roller Crimper: Case Studies in Organic Vegetables

Recent studies have assessed the effectiveness of conservative ASC management in providing ecosystem services and sustaining crop production for different organic vegetables under Mediterranean conditions. In particular, in this section, three case studies on applications of no-till with roller crimper are briefly described for tomato, zucchini and melon crops.

5.1 Effect of Termination of Hairy Vetch as ASC Preceding Organic Tomato

A two-year field experiment was performed at the MOVE (MOnsampolo VEgetables) organic long-term experiment (Campanelli & Canali, 2012) of the CRA-Research Unit for Vegetable Crops, located at Monsampolo del Tronto (Central Italy). Hairy vetch (*Vicia villosa* Roth var. Minnie) was grown as break autumn-winter ASC followed by tomato (*Solanum lycopersicum* L. cv. SAAB CRA) for fresh consumption. The following treatments were compared on three large plots: i) roller crimper (cover crop flattened by a roller-crimper - RC); ii) green manure (cover crop biomass chopped and plowed into the soil - GM); in comparison with iii) fallow artificially mulched with Mater-Bi® bioplastic (AM).

No significant differences were found in tomato marketable crop production in RC with respect to GM and AM, suggesting that tomato was suitable to be grown after termination of the ASC by roller crimping (Table 1). This result was supported by the lowest unmarketable yield obtained in RC treatment, which was lower by about 42% than the average of GM and AM treatments, confirming Campiglia et al. (2011) findings. The obtained results suggest that flattened vetch may have promoted a gradual release of N to tomato during the cropping cycle, matching the needs of the crop, thus improving its nutritional status (Montemurro et al., 2013). No significant differences were found among treatments for fruit weight and °Brix, therefore, both yield and quality indicate that ASC management that includes leguminous crops could enable the reduction of off-farm N fertilizers application (Doane et al., 2009).

Table 1. Effect of ASC management on marketable and unmarketable tomato production

Treatments	Marketable yield								Unmarketable yield			
	Fruits plant^{-1}	Std. dev.	t ha^{-1}	Std. dev.	g fruit^{-1}	Std. dev.	° Brix	Std. dev.	Fruits plant^{-1}	Std. dev.	t ha^{-1}	Std. dev.
RC	11.3 a	0.64	55.7 a	2.72	224 a	13.6	5.13 a	0.28	1.25 a	0.07	4.30 b	0.24
GM	10.6 a	0.72	52.9 a	2.64	229 a	13.2	5.36 a	0.34	2.04 a	0.13	6.86 a	0.37
AM	10.2 a	0.56	44.4 a	2.44	200 a	14.0	5.38 a	0.29	2.33 a	0.13	7.87 a	0.36

Note: RC= roller crimper; GM= green manure; AM= fallow artificially mulched with Mater Bi. The mean values in each column followed by a different letter are significantly different according to Fisher LSD at the P≤0.05 probability level.

5.2 Roller Crimper Technology for Weed Control in Organic Zucchini

A two-year field experiment was carried out in the same site of the previous experiment. Transplanted zucchini (*Cucurbita pepo* L.) was grown to compare the effect of ASC (barley, *Hordeum vulgare* L.) management strategies (no cover crop control - CT; green manured barley - GM; flattened barley mulch obtained by roller crimper technique - RC) on crop agronomic performace. Energy consumption and total energy cost were also evaluated, recording number and type of mechanical tillage operations for each treatment.

Zucchini cultivated by RC technique yielded 69% more than the zucchini preceded by the GM and similarly to the CT (Table 2). Moreover, the highly significant effect of ASC management for the zucchini total yield and the crop residues suggested the effectiveness of the mulch obtained by the RC in controlling weeds, although other influencing factors cannot be excluded. Weed above ground biomass was 22 and 91% lower than the CT, in the GM and in the RC treatments, respectively. High level of weed control was likely due to a direct effect of the barley mulch layer, which formed a barrier able to intercept solar radiation, thus reducing the stimulation for weed germination and physically impeding the weed growth (Altieri et al., 2011). Moreover, the conservative ASC termination reduced by 56% nonrenewable fossil energy consumption for tillage operations (data not shown) in comparison to GM, which is the most widely used system by organic farmers to manage cover crops. Results demonstrated that adoption of the RC could enhance the sustainability of organically managed vegetable cropping systems.

Table 2. Effect of ASC management on zucchini total and marketable yield, zucchini above ground crop residues biomass and weed biomass

Treatments	Zucchini total yield	Std. dev.	Marketable yield	Std. dev.	Zucchini crop residues	Std. dev.	Weed above ground biomass	Std. dev.
	t ha^{-1}		kg plant^{-1}		t ha^{-1}		t ha^{-1}	
CT	18.5 ab	1.03	2.7 a	0.16	8.7 a	0.51	31.9 a	1.94
GM	13.7 b	0.87	1.7 b	0.11	5.1 b	0.34	24.9 b	1.39
RC	23.1 a	1.36	2.6 a	0.15	9.9 a	0.56	3.5 c	0.23
	**		***		**		***	

Note: CT= control; GM= green manure; RC= roller crimper. The mean values in each column followed by a different letter are significantly different according to DMRT at the reported probability level. ***, P ≤ 0.001; **, P ≤ 0.01.

5.3 Combining ASC Managements and Organic Fertilization Strategies in Organic Melon

The suitability of different termination strategies of ASC (vetch, *Vicia sativa* L. ‘Buza’) was studied on melon crop (*Cucumis melo* L. var. Emerson F1) at Metaponto (MT), in southern Italy, in a field located at the experimental farm of the CRA-Research Unit for Cropping Systems in Dry Environments. The following treatments were tested: i) fallow (FA), without ASC; ii) green manure - GM, vetch chopped and plowed; and iii) roller-crimper - RC, vetch flattened by a roller-crimper, in combination with organic fertilizers (allowed in organic farming) application: i) commercial humified fertilizer - CHF; ii) anaerobic digestate - AD; iii) composted municipal solid wastes - MSW, as compared to iv) unfertilized control - NO.

Total yield was similar among treatments. In NO the RC produced significantly lower total yield than GM and FA (by 46 and 33%, respectively) (Table 3). This might have been the result of less N supplied by the ASC with this strategy, because only the root biomass was totally available for mineralization from the beginning of the melon cropping cycle, while the above soil biomass mineralized in a slow process at the mulch–soil interface. No substantial differences were found in all the other ASC management by fertilizer interactions, confirming the suitability of matching these strategies (Rizk, 2012) also on melon crop.

Table 3. Effect of ASC management and fertilizer treatments on melon total yield (t ha^{-1}) and marketable fruit weight (kg)

Total yield								Average marketable fruit wt						
	FA	GM	RC	CHF	AD	MSW	N0	FA	GM	RC	CHF	AD	MSW	N0
	56.9b	52.8bc	48.1bc	65.3a	50.7bc	45.8c	48.6bc	2.57ab	2.49ab	2.57ab	2.96a	2.61ab	2.28b	2.33b
CHF	74.7a	60.1a	61.3a					3.48a	3.09a	2.32a				
AD	51.1a	49.5a	51.5a					2.44a	2.70a	2.69a				
MSW	51.8a	39.5a	45.9a					2.29a	2.12a	2.45a				
NO	50.1a	62.1a	33.5b					2.06a	2.09a	2.85a				

Note: FA= fallow; GM= green manure; RC= roller crimper; CHF= commercial humified fertilizer; AD= anaerobic digestate; MSW= composted municipal solid wastes; NO= unfertilized control. Means of cover crop managements and organic fertilizer treatments followed by different letters within rows are significantly different according to DMRT ($P < 0.05$).

6. Conclusion and Research Needs

Despite the wide acknowledgement of the contribution of the Agro-ecological Service Crops to sustain agricultural production and to promote environmental protection by a wide range of mechanisms, their diffusion within organic and sustainable low input cropping systems is still limited. This is due to low awareness on the selection of the most appropriate genotypes and termination strategies (i.e. technology, time of termination, etc.). Accordingly, to further empower the use of ASC in a wide range of agro-climatic conditions, research activities specific to various areas should be encouraged.

Indeed, with specific reference to the European Mediterranean eco-climatic zones, the cultivation of warm season break ASC is limited by several constrains (i.e. lack of knowledge about the best performing genotypes, slow growth, high water needs) and, in the last decades, research activities to overcome these problems has been limited. Consequently, nowadays Southern Europe (organic) vegetable farmers have no or very limited feasible options, hence reducing or disabling the possibility to design more resilient cropping systems. Accordingly, research activities aimed to verify the effectiveness of warm season ASC to contribute to build up soil N fertility as well as to reduce NO_3^- leaching at the beginning of the leaching season (autumn) should be highly encouraged.

For alternative termination strategies, the roller crimper technology to terminate by flattening ASC has been successfully tested in few cropping systems and eco-zone across Europe. However, the experiences acquired so far and the current scientific literature have identified some constrains in the use of this technology. These include: (i) the production of proper amount of cover crop biomass before rolling, (ii) the cover crops re-growth during the subsequent main crop cycle, (iii) nitrogen (N) immobilisation and the difficulty in applying fertilisers in the ASC residues forming the mulch, and (iv) low quality of the transplanting or sowing bed preparation. These constrains could further limit success of the roller crimper technology in the Continental and Northern Oceanic eco-climatic area of Europe, where the cash cropping season (spring – summer) is short and soil temperatures remain low for a longer period. Moreover, the application of the roller crimper technology could be limited in vegetable cropping systems because of the low competitive ability of vegetables relative to other species (i.e. cover crops and weeds) and their high nutrients demand (Mortensen et al., 2000). Therefore, further studies are needed to test the effectinveness of the technology in other parts or Europe. In detail, additional studies should be aimed to understand the dynamic of N mineralisation in the soil-mulch interface and the synchronisation of release of mineral N with the subsequent cash crop N requirements.

Moreover, more effective machinery to perform an extremely reduced tillage system relying on the concept of "in-line tillage" to implement the vegetable transplanting and use of the roller crimper should be further developed. Such a machine is being developed by slightly modifying a roller crimper (Canali et al., 2013). In particular, a sharp vertical disk and a coulter (or chisel) were installed in-line at both the front and rear of the roller. This prototype machine allows to flatten the cover crops and to obtain a 0.2 to 0.3-m deep and few centimeters wide transplanting furrow in a single pass.

Lastly, in order to give guidance to farmers and technisscisans among the different available options regarding the introduction of (mixtures of) ASC into vegetable cropping systems, the choice of the suitable ASC genotypes and the proper terminations strategies to be adopted, ready to use Decision Supporting Systems (DSS) should be developed, tested and disseminated to farmers.

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Nutrient Cycling and Soil Health in Organic Cropping Systems - Importance of Management Strategies and Soil Resilience

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Abstract

Organic field crop systems are characterized by complex rotations with high spatial and temporal vegetative diversity, an enhanced use of legumes, and reduced external nutrient (nitrogen (N) and phosphorus (P)) use. At the same time, a core premise of certified organic agriculture is that this farming system provides benefits to soil health via enhanced microbial diversity. The following short review, drawing primarily upon selected studies from North America, examines the impact of farming systems, and various management strategies within these, on soil organic matter, N and P dynamics, and soil microbial and macrofaunal abundance and diversity. Organic cropping systems are shown to provide benefits with respect to reduced farm N and P surpluses, in combination with maintenance of soil organic matter and improved soil health. However, soil health benefits appear consistently achieved only for larger soil organisms partly due to the resilience of the soil microbial community. Recent research examining soil P dynamics and P uptake in relation to legume biological N_2 fixation and bacterial and mycorrhizal community diversity provide evidence of the resilience of the soil microbial community with respect to functionality, if not diversity of microbial community composition. These latter results may challenge organic agriculture core premises of consistent benefits to soil health via enhanced microbial diversity, but in its place may lead to an improved understanding of how specific cropping practices and production system intensity overall, rather than farming system per se, influences both nutrient cycling and soil ecosystem functioning.

Keywords: organic agriculture, soil health, soil fertility, microbial diversity, soil resilience

1. Introduction

A core premise of certified organic agriculture is that this farming system benefits soil health via enhanced microbial diversity, with ancillary benefits with respect to soil quality, nutrient dynamics and broad farm ecology generally (Stockdale & Watson, 2009; Gomiero et al., 2011). But what do we mean by soil health? Faced with growing evidence of the remarkable resilience especially of the soil microbial community, however, – is soil microbial diversity *per se* a key goal or is it more appropriate and beneficial to focus on the abundance and diversity of higher trophic levels? Postma-Blaauw et al. (2010) for example, found the abundance of taxonomic groups such as earthworms, microarthropods and nematodes was much more affected by agricultural intensification than that of bacteria, fungi and protozoa. Is the primary interest of organic farming systems in soil biota diversity or in its functioning, and as relates to the farm ecosystem or broader ecological intensification? Finally, are 'farming systems', that is, certified organic versus conventional production, the dominant driving factor or is the intensity of management, whether within organic or other production systems, a more important determinant of soil and nutrient dynamics?

The following short review is designed to offer reflection, and hopefully generate a discussion, on these important questions. This may challenge the organic agriculture premise of consistent benefits to soil health via enhanced microbial diversity, but in its place lead to an improved understanding of how soil microbial resilience, and production system intensity and specific cropping practices, rather than farming system per se, influence these important soil system outcomes. Such an improved understanding of plant and soil biota relationships as influenced by farming practices will provide a more refined framework for approaches to beneficial management of these relationships and their influence on nutrient dynamics and efficiency and farming system productivity.

The following review draws upon recent reviews and ongoing field research by the author and colleagues with a primary, but not exclusive, focus on organic cropping systems in North America, and with respect to nutrients, a particular focus on nitrogen (N) and phosphorus (P) dynamics in relation to soil health.

2. Linking Nutrient and Soil Management in Organic Cropping Systems

The challenge of balancing agricultural productivity with provision of key ecosystems services (soil and water quality; conservation of pollinator communities, biodiversity and biological pest control; climate regulation etc.) has led to calls for 'ecological intensification' and agricultural system redesign (Cassman, 1999; Swinton et al., 2007; Drinkwater, 2009, Reganold et al., 2011). Organic farming takes the perspective that the preservation and enhancement of soil quality and health through optimized farm management practices is the critical underpinning to maintaining system productivity while also achieving a balance with maintenance of diversity and provision of key ecosystem services. Studies, primarily from Europe, indicate organic farming promotes vegetative diversity, often accompanied by other facets of belowground and aboveground diversity (Bengtsson et al., 2005; Hole et al., 2005; Gomiero et al. 2011; Tuck et al., 2014). The limited relevant scientific literature of Canadian and US origin also suggest that among taxa, vegetative diversity is most consistently influenced by farming system. This benefit of organic farming has sometimes also been found, depending on management of non-crop habitat and the complexity of the surrounding landscape, to extend to other taxa (Boutin et al., 2008; Lynch et al., 2012a; Girard et al., 2014).

2.1 Soil Organic Matter and Soil Biota

In recent years there has been increasing interest in determining whether organic cropping systems enhance soil organic matter (SOM) levels, or at least reduce losses in SOM, when compared with conventional production systems. This interest is driven by acknowledgement of the central role of SOM in soil quality and health, productivity and ecosystem services goals, concerns regarding the impact of continued use of tillage in organic farming on SOM, along with an interest in having organic farming potentially acknowledged as a means of enhancing C sequestration in soil. In a recent review, Lynch (2014) presented results of comparative SOM levels from some of the best long-term comparative farming systems trials in North America (Table 1), along with selected studies from elsewhere. Allowing for acknowledgement of the complexity and methodological challenges inherent in such comparisons, which were also discussed, the consensus of the data suggests that organic field crop production at least sustains SOM when compared with conventional systems. A meta-analysis of changes in soil organic carbon (SOC) stocks with organic farming using data from 74 long-term studies, similarly found that when the dataset was restricted to those studies reporting external C and N inputs and soil bulk densities, farming systems (organic and non-organic) failed to differ in topsoil C sequestration rates (Gattinger et al., 2012).

Broad comparisons of SOM stocks may hide important system differences of relevance. Indeed the data are perhaps more persuasive regarding the benefits of organic systems in enhancing the quality, if not the quantity of SOM, and in particular the labile pools of SOM, including the microbial biomass and particulate SOM – the turnover of which provides nutrients and energy for crop and wider ecosystem benefits. For example, a study in Denmark found that although four-different organic management regimes (varying in manure, green manure and catch crop use) returned C to soil at levels 18-91% greater than conventional cropping, SOC levels after 11 years were the same for all systems (Chirinda et al., 2010). However, in the organic system microbial biomass and activity (respiration) increased correspondingly with the greater return of C, evidence of a more biologically active soil. Many studies have shown enhanced labile SOM (particulate organic matter (POM) etc.) fractions under organic than under conventional management regimes (Marriot & Wander, 2006; Lynch, 2014). In this regard organic systems may be considered closer to achieving the balanced approach to management of soil C as proposed by Canadian soil scientist H. Janzen in his elegant paper 'The soil carbon dilemma:shall we hoard it or use it' (Janzen, 2006). That is, how to store C in soil while also 'feeding the soil' with inputs of energy and nutrients for the soil biota to provide both crop and broader ecosystem benefits. As elaborated further below, changes to soil quality and microbial abundance and activity do not necessarily correspond with concomitant changes in soil microbial diversity per se. In addition, both with respect to nutrient flows and soil health, differences between management approaches and practices within a farming system, along with temporal variation, may be as important as determining factors than are differences between farming system (organic versus conventional) per se. Finally, the relative response of higher trophic levels in soil to the influence of farming system may differ notably from that of the soil microbial community (Postma-Blaauw et al., 2010).

The abundance and diversity of higher tropic level organisms (beetles, earthworms, spiders etc.) appear particularly sensitive to the enhanced spatial and temporal diversity of organic farming systems. In horticultural systems, use of mulches and approaches to weed management may result in even greater modifications in the quantity and quality of soil organic matter which in turn influence nutrient dynamics and soil biota. In highbush blueberry systems in Atlantic Canada, mulch type and quality substantially influenced weed community and abundance, N dynamics and crop productivity (Burkhard et al., 2009). Subsequent research documented how ground floor management (mulching and or weeding) in highbush blueberry systems, shifted Carabidae and Staphylinidae diversity and potential for biological control of immature blueberry maggot (Renkema et al., 2012a, b). Under the extended (5-year) rotations common to organic potato production in Atlantic Canada, microbial quotient (microbial biomass C as a fraction of total SOC) and earthworms recovered from a sharp decrease during the potato phase of the rotation to levels of undisturbed pasture reference sites (Nelson et al., 2009). A novel laboratory-based test using the Collembola bioindicator (*Folsomia candida)* confirmed a positive response to the greater POM and microbial biomass found under such organic potato, but not conventional, potato production systems (Nelson et al., 2011). Recent research in Ontario by Girard et al. (2014) found the greater food biomass (arthropods etc.) for nestlings (young songbirds) in organic than conventional soybean fields was attributable specifically to the longer rotations found in the organic production systems.

Zero tillage of green manures (using a roller crimper) is a relatively new technology recently being evaluated for organic field crop production in North America. While the agronomic benefits of this novel approach to management of green manures are increasingly being assessed (Vaisman et al., 2011; Mirsky et al., 2012), the impact on soil biology and plant-microbe relations remains relatively unexplored. It has been suggested that roller crimping of green manures may further enhance benefits for earthworms and larger soil organisms as a result of the modification of the surface soil environment by the large volume of green manure mulch retained on the soil surface (up to 8 Mg ha^{-1}) (Marshall, 2014). In contrast to Europe the wider ecological impact of vegetative complexity of crops and field margins as influenced by organic versus conventional management and landscape complexity on arthropods generally, and native pollinator abundance and diversity, remains relatively unexamined in North America. While the above review suggests soil health may benefit from organic management, depending on cropping system, at the soil microbial level, functional groups such as decomposers appear to exhibit a high degree of resilience to farming system influences (Postma-Blaauw et al., 2010; Lynch et al., 2014; Tuck et al., 2014). The implications of such microbial resilience (i.e. stability and resistance to change of microbial community composition) with respect to N and especially P dynamics are discussed further below.

Table 1. Comparison of soil organic carbon storage of organic (Org) and conventional (Conv) field cropping systems from long-term comparative field trials

Authors	**Region**	**Study Period (years)**	**Org < Conv**	**Org=Conv**	**Org > Conv**
Mahli et al. 2009	Canada	12		√	
Bell et al. 2012	Canada	18	13-15%[1]		
Pimentel et al. 2005	US	22			20-25%[2]
Teasdale et al. 2007	US	9			19%[3]
Wortman et al. 2011	US	11		√	
Robertson et al. 2000	US	8	12%		
Leifeld et al. 2009	Switzerland	27		√	
Kirchmann et al. 2007	Sweden	18			16%
Chirinda et al. 2010	Denmark	11		√	

[1]SOC stocks reported to 120 cm depth. Differences between farming systems were smaller for the alfalfa/crop (13%) compared to annual crop (15%) rotations. [2]Higher gains (25%) were recorded for the 'organic animal' then 'organic legume' (20%) system [3]Compared to a no-till treatment. Adapted from Lynch (2014) with permission of Taylor and Francis Group, LLC, a division of Informa plc. Copyright 2014 from *Managing Energy, Nutrients, and Pests in Organic Field Crops* by R.C. Martin and R. MacRae (Eds).

2.2 Productivity, and Nutrient Dynamics as Influenced by Farming System Management

2.2.1 Nutrient Dynamics and Efficiency as Influenced by Cropping System Management

Legume-derived N from biological N_2 fixation (BNF) is critical to the sustainability of organic crop (annual and perennial) production systems on commercial farms (Woodley et al., 2014), and contributes substantially to sustainability with respect to reduced energy use on organic farms (Lynch et al., 2011). However, productivity and nutrient (N and P) loading and risk of losses, and nutrient use efficiency from organic production systems can vary with specific management practices and overall farm intensity of production; furthermore seasonal variation affects soil N mineralization and potential synchrony of soil available N supply with cash crop demand (Lynch et al., 2012a,b). In Denmark, three vegetable plus cereal organic cropping systems varied in autumn catch crops, green manures and intercrops (Thorup-Kristensen et al., 2012). In this study, the green manures when present in a rotation doubled soil exploration by roots, which reduced N leaching. It has been demonstrated that while organic potato yields were lower (~20%) when compared with those maintained under a conventional fertilization regime, nitrogen use efficiency (NUE; measured as tuber yield per unit crop N uptake) was higher for the organically managed crops (Lynch et al., 2012b). This is in agreement with findings in Europe (Möller et al., 2007). In contrast a long-term (18 year) cropping systems study in Sweden found NUE was lower for the organic crop management regime (Kirchmann et al., 2007). Agronomic strategies and tools to further improve management of N and NUE in organic cropping are increasingly being examined. For example, the *in situ* use of anion and cation exchange probes have been used to predict soil N availability in potato production (Sharifi et al., 2009).

2.2.2 The Issue of Phosphorus

A growing body of literature has reported low (<10 mg kg^{-1}) soil test phosphorus (STP) levels for Canadian organic crop and livestock sectors (Entz et al., 2001; Martin et al., 2007; Roberts et al., 2008; Knight et al., 2010; Main et al., 2013). Such low bioavailable P levels suggest potential crop P deficiencies have potential to negatively impact on yields, legume biological N_2 fixation (BNF) and overall farm productivity and sustainability. Application of rock phosphate and approaches such as green manure phytoextraction of rock phosphate P has been found to be inadequate for enhancing soil P supply on the predominantly alkaline soils in much of these cropping regions (Arcand et al., 2010). Appropriate sources and volumes of manure, particularly in western Canada are largely unavailable (Woodley et al., 2014). However, as noted above with respect to NUE, farm P status within specific organic sectors varies significantly with organic management strategies and intensity of production. Three distinct groupings of commercial organic dairy farms were identified in Ontario (Roberts et al., 2008). Their very different management strategies represented a spectrum from targeting feed self-sufficiency as a priority to other organic dairy farms where the goal was to maximize productivity. These variations in intensity of organic management strongly impacted not only farm livestock density (livestock units ha^{-1}) but also on whole-farm N, P and K nutrient surpluses and efficiencies. In more recent work on many of the same dairy farms the relationship between STP (and forage (alfalfa/grass mixtures) productivity and BNF (Main et al., 2013) showed that forage yields and BNF were not inversely related to STP levels in these long-term organically managed soils. This indicates biological and biochemical solubilization of soil organic P, and a likely enhanced role for arbuscular mycorrhizal fungi (AMF), play an important role in these systems.

3. Soil Health and Nutrient Dynamic Linkages as Influenced by Production System

Soil health is defined as 'the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health' (Doran & Zeiss, 2000). Soil organisms, including the abundance and diversity of bacteria, fungi, and nematodes, are considered key indicators of changes in soil health as they 'respond sensitively to anthropogenic disturbance' (Doran & Zeiss, 2000). Our recent reviews, and research from long-term experiments and paired organic versus conventional farming systems, however, suggests a high degree of resilience of soil microbial community diversity to farming system management, when compared to the influence of temporal shifts or specific crop sequence influences (Postma-Blaauw et al., 2010; Lynch, 2014). For example, studies conducted within the long-term DOK trials in Switzerland have found bacterial community structure (Widmer et al., 2006) and fungal community structure (Schneider et al., 2010) to be more influenced by temporal effects and individual crops than farming system per se. In the US, Kong and Six (2012) tracked the microbial turnover and assimilation of 13C-labelled hairy vetch root tissue as affected by 14 years of conventional, organic or low-input crop production. Using PLFA techniques they found the soil microbial community structure processing the incoming root C was similar across all farming systems.

Functional properties, however, such as enhanced biochemical and biological turnover of organic phosphorus, appear to be enhanced by organic farming systems, and may contribute to enhanced phosphorus use efficiency

(PUE) in these systems. While the mechanisms involved remain poorly understood it may entail legumes influencing not only the abundance (root colonization), but also the community composition, of AMF. In Western Canada, even under conventional management and high STP, legume roots (of lentil and peas) can host a richer, more diverse, and even AMF community compared to wheat roots (Bainard et al., 2014). Higher soil microbial richness in organic wheat systems in Alberta has been attributed to be partially due to greater prevalence of weeds in these systems, however mycorrhizal fungi were not promoted as most weeds in that study were non-mycorrhizal (Nelson et al., 2011b). Although wheat yields were lower, the Claroideoglomus genus of AMF was found to be more prevalent in organic wheat fields, and was associated with enhanced wheat PUE by Dai et al. (2014). Under controlled conditions *C. claroideum* enhanced legume (*Medicago truncculata*) PUE (Lendenmann et al., 2011) while Wagg et al. (2011) suggested *C. claroideum* provides a competitive advantage to legumes. Houlton et al. (2008) suggested legumes ability to support soil phosphatase enzyme activity is another key strategic evolutionary advantage in low P status soils, although a strong body of evidence to support this hypothesis has not yet been produced.

Our recent research (Fraser et al., 2015) examined alkaline phosphatase enzyme activity and bacterial *phoD* gene abundance as influenced by long-term management at the Glenlea long-term (20 years) rotation study of the University of Manitoba, which includes an Organic – no inputs system (ORG); an Organic with manure application in 2007 (ORG-M) (*not discussed further here*); a Conventional (CON) production system each maintained under a four year rotation of flax-alfalfa-alfalfa-wheat. An additional system examined included restored native prairie (PRA). The STP levels in each system were greater in the CONV (19.3 mg kg^{-1}) and PRA system (29.6 mg kg^{-1}) than for the ORG (7.6 mg kg^{-1}), attributable to the history of export of alfalfa from this system with no manure returned. However, alkaline phosphatase (ALP) activity was higher in the ORG soils with lower bioavailable P. In spite of lower bacterial diversity (*phoD* community structure) and low STP level under the organic cropping regime, *phoD* gene expression was positively correlated with alkaline phosphatase enzyme activity (ALP), and was higher in the organic farming systems when compared with prairie or conventional cropping. Thus, while these results indicated higher bacterial diversity in conventional soils, this diversity was not critical for maintenance of the important soil functions that relate to biochemical and biological turnover of organic phosphorus.

4. Conclusions

The distinctiveness of organic systems (legumes, vegetative diversity, high C but low P inputs etc.) is advancing our scientific understanding, and opportunities to manage, plant and soil microbial relations for improved nutrient cycling and ecosystem health. These farming systems are adept at promoting soil life generally. In light of recent research, however, there is a need to refine what might be considered organic agriculture core premises of consistent benefits to soil health including enhanced microbial diversity. This should be replaced with a more refined understanding of how specific cropping practices and intensity of production, rather than necessarily farming system per se, influences both nutrient cycling and soil ecosystem functioning. An improved understanding of these edaphic, agronomic and agro-ecological impacts of organic cropping strategies, and their inherent tradeoffs with productivity, can only lead to improved management overall.

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Managing Bees for Delivering Biological Control Agents and Improved Pollination in Berry and Fruit Cultivation

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Abstract

Targeted precision biocontrol and improved pollination were studied Europe-wide in the EU ERA-NET CORE ORGANIC 2 project BICOPOLL (Biocontrol and Pollination). A case study was conducted on the management of strawberry grey mold *Botrytis cinerea*, with the biocontrol fungus, *Gliocladium catenulatum*, vectored by honey bees or bumble bees. A joint field trial carried out in five countries targeted strawberry cultivations in open field, and included four treatments: untreated control, chemical fungicide, entomovectored biocontrol, and chemical and biocontrol combined. In organic fields, no pesticide treatments were included. The proportion of moldy berries, and/or the marketable yield of healthy berries were recorded from each treatment, along with other parameters of local interest. A pilot study was started in Finland in 2006, and, by 2012, large commercial farms were using entomovectoring. In 2012, field trials were started in Estonia and in Italy, and in 2013-14, these experiments were expanded to Slovenia and Turkey. In total, 26 field tests were conducted using entomovectoring and *Gliocladium catenulatum* (Prestop® Mix) on strawberry, with five additional trials on raspberry. Efficacy results have been excellent throughout the field studies. The results show crop protection equalling or exceeding that provided by a full chemical fungicide program, under all weather conditions, and over a wide geographical range (from Finland to Turkey). Under heavy disease pressure, entomovectoring provided on average a 47% disease reduction, which was the same as multiple fungicide sprays. Under light disease pressure, biocontrol decreased grey mold by an average of 66%, which was greater than fungicide sprays. The concept has proven to be effective on strawberries, raspberries, pears, apples, blueberries, cherries, and grapes. A conservative estimate for Finland is that over 500 ha of strawberry cultivation currently use the technique (≈15% of the strawberry growing area). To make full use of the entomovectoring technique, organic berry and fruit growers are encouraged to (i) keep bees, or to hire the service from local beekeepers for entomovectoring; and (ii) manage vegetation within and around the target crop to support the activity of bees and other pollinators, which can help to disseminate the beneficial microbial populations within the crop. Beekeepers are encouraged to (i) market pollination and biocontrol services to fruit and berry growers, and (ii) ensure that all operations are effective in mananging bees and their microbe dissemination activity. Biocontrol product manufacturers are encouraged to further develop products and their formulations specifically for entomovectoring, because current formulations are suboptimal as they are initially optimized for other uses (e.g., mixing into the soil).

Keywords: antagonist, *Apis mellifera*, biological control, *Bombus*, *Clonostachys rosea*, dispenser, entomovectoring, fungal diseases, *Fusarium avenaceum*, organic production

1. Introduction

1.1 Constraints Facing Organic Berry Producers in the EU

Organic berry and fruit production suffers heavily from the lack of effective disease and pest management tools, and from inadequate insect pollination at times. As a consequence, the expanding demand on organic berries and fruit cannot be satisfied today (European Commission, 2014). In our study we focused on the grey mold caused by *Botrytis cinerea* on strawberry and raspberry, with an additional pilot study on apple. The EU is the biggest producer of strawberries in the world, and of the single member countries, Spain is number two producer after the USA (FAO, 2011). Turkey is the third most important strawberry producer in the world, and of the other countries involved in the BICOPOLL project, Italy is 9th, Germany 10th, and Belgium 19th in global strawberry production. In total, strawberry area in the EU was 111,801 ha in 2008 (FAO, 2011). In terms of economic importance, strawberry is the 12th most valuable agricultural commodity in Finland (after animal-based products such as meat, milk, and eggs, and barley, wheat, oats, potato and rapeseed), and ranks similarly among the top 20 agricultural commodities in Germany (15th), Estonia (15th), and Belgium (16th).

Organic strawberry growing has rapidly expanded in Europe. Grey mold (*Botrytis cinerea*) is the most important biotic threat to the crop, and conventional growing methods with fungicides usually require 3-8 treatments per season, depending on weather conditions. The industry is concerned about the slow progress in the development of biological control methods (biofungicides) against *Botrytis* (Agriculture and Agri-Food Canada, 2009), as the chemical fungicides rapidly lose their ability to control the disease. Currently organic strawberry growers have no means of preventing grey mold on their crop, and consequently, they occasionally lose the harvest almost entirely. Conventional growers suffer, on average, 10-20% pre-harvest crop losses to grey mold (Stromeng, 2008), and up to 25-35% (IPM-Centers, 2011), despite the numerous fungicide treatments.

Early trials on biological control of *Botrytis* have relied on spraying biocontrol agents (BCA) on strawberry flowers. Extensive field trials in Finland showed that three spray applications with Prestop® (Verdera Oy, Espoo, Finland) formulation at flowering time remarkably decreased the number of moldy berries and increased the marketable yield (Lahdenperä, 2006). However, despite the efficacy of *Gliocladium* sprays against *Botrytis*, the method could not be widely used because of high treatment costs. Blanket spraying could not be adjusted to deliver the BCA only to the inflorescence, at the different developmental stages of flowers, and within the required time frame to prevent grey mold growth. In contrast, bees, as an essential component of the pollination system, can colonize the flowers with the BCA and achieve disease suppression naturally, via frequent pollination visits to each inflorescence at the proper time.

1.2 Pollinators in Biological Control Dissemination

The use of pollinating insects for the biological control of plant diseases and pests has its origins in the early 1990s (Peng et al., 1992), when honeybees were first used to disseminate biological control agents to strawberry flowers as a replacement for insecticides. Subsequently the concept was termed ‘entomovector technology’ by Hokkanen and Menzler-Hokkanen (2007), and a more systematic development of the pollinator-and-vector technology was established. This environmentally friendly control strategy, where control agents against plant pathogens and insect pests, are delivered directly onto crop flowers, while simultaneously fulfilling the pollination requirement, represented an innovative way of crop protection for organic as well as conventional cropping systems. Because the appropriate BCA is colonizing the flowers, natural disease suppression is achieved as a consequence of the frequent pollination visits at each inflorescence (Smagghe et al., 2012). The unique concept of entomovectoring incorporates several ecological components, including pollinators, biocontrol agents, and plant pathogens and/or insect pests (Kevan et al., 2008). However, its success is based on mutual and compatible interactions between the appropriate components of the vector, control agent, formulation, and dispenser, and the safety of the environment and human health, in particular the operator/manager at the farm.

One of the reasons which has led to the development of the entomovectoring technology as a biocontrol strategy was the need to reduce the application of environmentally harmful synthetic pesticides. Concerns regarding the impact of conventional chemical pesticides on human health and the environment, and the development of resistance by pests, have led to the search for alternative methods. Also, biological control methods, where BCAs have been used as conventional applications (e.g., biofungicides), often have resulted either in poor control, or in too high application costs, resulting in slow progress towards an ideal system. The entomovectoring technology represents a promising alternative, wherein pollinators achieve a dual role: control agents are directly delivered on the target location (i.e., the flowers), while the pollination needs are fulfilled (Mommaerts & Smagghe, 2011). In this way the BCA forms an effective disease and pest management tool during flowering of the crop, and during the development of fruits, since the flowers are the main location of infection by plant pathogens (e.g., *B. cinerea*) and insect pests (e.g., the western flower thrips *Frankliniella occidentalis*). Control of these infections by the entomovector technology can thus increase marketable fruit and berry yields (Mommaerts et al., 2011), and even play a role in controlling post-harvest diseases, such as *Alternaria alternata* (Nallathambi et al., 2009).

Despite the promising results of the first studies on the use of pollinating insects to spread the BCA to fruit flowers, the practical adoption of this approach by the growers has progressed slowly. The CORE ORGANIC 2 (EU ERA-NET) project BICOPOLL was designed to tackle this lack of uptake, and to provide a pan-European case study on protecting organic strawberry from its most important disease, the grey mold, by entomovectoring using the fungal antagonist *Gliocladium catenulatum* (Prestop® Mix). In addition, the project investigated possibilities of expanding the use of the concept into other berry and fruit growing systems. A pilot study for the control of the core rot of apple (*Fusarium avenaceum* and *B. cinerea*) was included in 2013-2014.

To our knowledge, this is the first time the entomovectoring technique has been tested on apple. The problem to be solved is a storage disease, core rot, which infects apples through the flowers. The symptoms may sometimes appear at harvest, but most often the disease occurs only after storage. Certain apple varieties, e.g., ‘Rubinola’, ‘Gala Schnitzel’ and ‘Santana’ are very susceptible to core rot. Appropriate chemical control of this disease is not available.

Figure 1. Core rot symptoms caused by *Fusarium avenaceum* on the apple variety ‘Santana’, which is sensitive to the disease

Photo: Marja-Leena Lahdenperä, Verdera Oy.

2. Methods

2.1 Case Study on Biocontrol of Grey Mold on Organic Strawberry and Raspberry

Targeted precision biocontrol and improved pollination were studied first in a pilot project in Finland (2006-2009), followed by the Europe-wide project BICOPOLL in 2011-2014. We chose to focus as a case study the control of strawberry grey mold, *Botrytis cinerea*, with the biocontrol fungus, *Gliocladium catenulatum*, vectored by honey bees or bumble bees. The joint trial targeted strawberry cultivations in the open field, and included four treatments: untreated control, chemical fungicide, entomovectored biocontrol (Prestop® Mix), and chemical and biocontrol combined. Wide variety of fungicides was involved, according to the regulatory approval and local practices in each country; typically 3-5 different fungicide treatments were used at 2-4 day intervals during flowering. Each active ingredient was used only once per season. In organic fields, no pesticide treatments were included. In 2010 and 2011, field trials were conducted in Estonia, and in 2012, in Italy – in addition to Finland, where large commercial farms used entomovectoring after the pilot study. In 2013, the experiments were expanded to Slovenia and Turkey, and were completed in 2014.

The biocontrol agent for all trials was the commercial preparation of *Gliocladium catenulatum*, “Prestop® Mix”, which was sent to all partners in sufficient quantity for the trials each year. Common parameters across all field trials are detailed in Table 1. As most trials were conducted on operational, commercial farms, local adjustments were made to the experimental plan as needed. In total, we report in this paper the results from 26 separate field experiments on strawberry in five countries between 2006 and 2014. In addition, the same experimental protocol was used on five raspberry fields in 2007 in Finland.

Table 1. Common parameters for strawberry entomovectoring field trials, and instructions to operators

Parameter	Preferred minimum set-up	Deviations if needed	Remarks
Type of field	Organic strawberry in a commercial farm setting	(i) test fields of a research farm, or (ii) conventionally grown strawberry with minimum pesticide use	If conventional growing is used, no fungicide spray is allowed on the assessment plots: cover these with plastic sheets during spraying if needed
Size of field	One hectare for the BICOPOLL project (two beehives per ha); sampling from 2 m x 2 m plots	Smaller area can be used, but then the ”bee” or ”hive density” per ha will be higher	If the total strawberry area is much larger, more hives and dispensers are needed
Surroundings of field	As little competing flowering plants close to the field as possible		Bee-attractive vegetation can be within the field, e.g. white clover between rows
Treatments	1) untreated control 2) entomovectored treatment using *Gliocladium catenulatum* (Prestop® Mix) and honey bees	Add “extra pollination only” (by honey bees) if possible: plots with exclusion cages, and daily dose of honey bee foragers without Prestop® Mix, added for pollination	Other treatments can be added as each project partner wishes. Untreated controls must be covered with light exclusion cages during the bee dissemination period.
Plot sizes	Minimum: 2 m x 2 m		For treatment 2 clearly marked plots in the open field are needed; treatment 1 plots must exclude bees
Number of replicates per treatment	4	More is better, if possible	
Placement of bee hives	At the edge of the strawberry field so that they can easily be operated; can be next to each other. Place them a little above the ground (10-30 cm min.)		Bring the hives there at the start of the experiment, not earlier if feasible.
Properties of hive	A “strong” but “relatively small” hive is preferred. Healthy colony with large brood area and low pollen stores.	Larger hives are also OK	“Small” hive = about 5000 adult workers and a 15000-worker brood at the start of flowering
Prestop® Mix dissemination	Start after the first flowers are open (about 5-10% of flowers); stop when the main flowering period is over		Place the exclusion cages over the control plots as you start the dissemination; first let the bees ’learn’ to use the dispenser without Prestop® Mix for 2-3 days, and then start to disseminate. REMOVE the exclusion cages as you stop the dissemination at the end of flowering.
Dosing and timing	Apply daily about 3-4 mm layer of Prestop® Mix in the dispenser (about 5 g), early in the morning; 200 g in total /		Train the grower to do this, if feasible. Use protective gear as a rule. Do not apply if the weather is very

	dispenser; 400 g/ha during the whole flowering period		rainy.
Data/samples to be collected	Map the vegetation, and in particular the flowering plants attractive to honey bees, within 1 km of the field	Smaller area is also OK	No detailed assessment is necessary (estimated size of ground cover of the most important plants; a rough 'map' is best)
	If possible, monitor occasionally flower visits of honey bees on the strawberry flowers; quantify for brief periods (10-20 minutes)		Not needed if not feasible to do
	Effect of treatment: measure (a) marketable yield and (b) moldy berry yield for each treatment plot and replicate. Collect berries from 1 m of strawberry row (or from a fixed number of consecutive berry bushes) from each plot into separate collection baskets (healthy, moldy) and weigh them immediately. Apply minimum size for acceptable berry (10-mm diameter). Collect every two days, or as customary at the farm. Finish data collection when the grower does not harvest any more strawberries	If you have time and resources, you can collect flower samples and try to study the amount of *Gliocladium* spores on them, from the different treatments. This has been difficult to do accurately (but see Mommaerts et al. 2011 for selective media and plating techniques).	As this trial is mostly for demonstration purposes, effect on marketable yield is the most relevant measure of success. If we at some study sites can separate the impact of improved pollination from the impact of disease control, even better (with a set of extra exclusion cages and using bees without Prestop® Mix).

2.2 Case Study on Apple Trees in Finland

The apple trial was carried out in 2013 in collaboration with the manufacturers of Prestop® Mix (Verdera Oy), the advisory service group Pro Agria Ålands Hushållningssällskap (Pernilla Gabrielsson), and Peter Sundin's & Margareta Björkén's commercial apple orchard in the Åland Islands, Finland. The orchard was managed by conventional methods (i.e., synthetic pesticides were used according to typical practices simultaneously with the biological control (Prestop® Mix entomovectoring). The synthetic pesticides were applied against other pests, such as apple scab (*Venturia inaequalis*).

2.2.1 Field Trial Arrangements 2013

Since the trial was carried out in a conventional orchard, the experimental arrangements included one area where the honeybee-disseminated biocontrol was used, and a similar area which served as the untreated control. These two areas, separated by a small forest, were located far enough apart that bees delivering *Gliocladium* were not likely to fly from the treated area to untreated apple trees. The test was carried out with the winter variety, 'Rubinola', which is sensitive to core rot. Two beehives equipped with a BeeTreat® dispenser (Aasatek Oy, Finland; see Smagghe et al., 2012) were placed at the edge of the apple orchard about 50m from the test apple tree rows. Upon exit from the hive, bees had to cross an inoculum field in the dispenser, thus picking up the biocontrol agent spores on their body hairs. Prestop® Mix powder was applied every day with a spoon onto the inoculum field, about 5 g at a time, and spread evenly over the field resulting in a 2-4 mm thick layer. This was done around 8 a.m. for the entire flowering period. Unfortunately, flower samples for *Gliocladium* analysis were not collected in the first test year.

2.2.2Apple Storage Trial in 2013-14

The field trial then continued as a test against storage disease: In the beginning of October, externally healthy apples were harvested into four boxes holding 5 kg each (about 30-35 apples per box), for storing until January and February. At the end of the storage period, final evaluation of apple quality and disease damage was conducted. The quality was assessed by grouping the apples in three categories: (i) Grade One (EVIRA, 2009), (ii) affected by core rot, and (iii) other damages. To be able to make observations on the internal core rot symptoms, the apples were cut in half. In addition, several pathogen identifications from diseased apples using standard agar-plate isolation techniques (Narayanasamy, 2011) to determine the causative agents of the core rot, were carried out in the laboratory of Verdera Oy, Espoo, Finland.

2.2.3 Apple Field Trial Arrangements in 2014

Based on the promising results obtained in 2013-14, the study was continued by establishing a new field trial in spring 2014 in the same apple orchard. The arrangements were similar to those in the previous year, but the winter variety, 'Zari', was used as the test fruit because this variety was growing closer to the beehives than 'Rubinola' (the previous year's variety). 'Zari' is also sensitive to core rot. There were five beehives placed at the edge of the orchard, but only two of them were equipped with a microbe dispenser. These two were located close to the apple tree rows (at 10-m distance). The other end of the rows was at a distance of 100 m. Daily filling of the dispenser with about 5 g of Prestop® Mix powder per day began on the 22nd of May, and continued until the end of the flowering period. Harvest was completed in early October.

2.2.3.1 Sampling of Flowers

Flower samples were taken at full bloom, i.e., 10 days after the beginning of honeybee-delivery of the biofungicide. Flowers were sampled in a laboratory analysis to assess the colonization by *G. catenulatum*. Flower samples of treated trees were taken at 3 distances from the hive, from 2 apple trees per distance and 10 flowers/tree, or 60 flowers in total. To ascertain that Prestop® Mix had not been carried by bees to the untreated reference area, 10 random flower samples were collected also from trees grown in the area where entomovectoring of Prestop® Mix had not been used. Flowers were collected at the fully open stage and samples were packed in small plastic tubes, 1 flower per tube. For the transport from the orchard to the lab at Verdera Oy, Espoo, Finland, the sample tubes were packed in a polystyrene box with an ice pack.

2.2.3.2 Laboratory Analysis

From each flower, 15 stamens were plated on water agar (Figure 2) and other flower organs (petals, pistils and calyx) on another plate (potato-dextrose agar) for the detection of *Gliocladium*. After 8 days incubation at room temperature, observations of *G. catenulatum* were made using a stereomicroscope. At the same time also fungal pathogens causing storage rot were observed by following procedures described above.

Figure 2. Stamens of apple flowers on water agar for microbial analysis

Photo: Marja-Leena Lahdenperä, Verdera Oy.

3. Results

3.1 Strawberry Results

Strawberry efficacy results showed crop protection equalling or exceeding that provided by a full chemical fungicide program, under all weather conditions and over a wide geographical range (from Finland to Italy and Turkey, Table 2). Under heavy disease pressure (>25% diseased berries in untreated controls), entomovectoring provided on average of 47% disease reduction, which is the same as obtained by multiple fungicide sprays. Under light disease pressure (0-10% diseased berries in untreated controls), biocontrol decreased grey mold on average by 66%, which was more than the reduction from using fungicide sprays (Table 2). Biocontrol significantly reduced grey mold incidence from that in the untreated control in 20 out of the 23 field trials (Table 2).

Table 2. Field trial results using bee-disseminated precision biocontrol for the control of strawberry grey mold (*Botrytis cinerea*) by the antagonist *Gliocladium catenulatum* (Prestop® Mix). Honeybees were used as vectors in all countries, but in Estonia both honey bees (HB) and bumble bees (BB) were used

			Grey mold proportion[1]				**% reduction**		
Country	**Site**	**Year**	**Untreated**	**Fungicide**	**Biocontrol**	**F:cide+Bio**	**by Biocontrol**	**Sign.**	**Citation**
Light mold attack									
Turkey	1	2013	2.6		0.8		69		1
Turkey	1	2014	3.5		0.9		74		1
Estonia	BB 1	2012	3.9		0.2		95		2
Finland	3	2006	5.8		3.2		45		3
Estonia	HB 1	2011	6.0		3.0		50		2
Finland	5	2007	8.5		3.0	1.8	65		3
Finland	2	2006	9.5	2.5		0.8			3
Average			5.7	2.5	1.8	1.3	66		
Moderate mold attack									
Finland	4	2007	11.9		7.8		34		3
Finland	2	2007	12.0	4.0	7.0	4.2	42		3
Estonia	BB 1	2013	14.5		6.5		55		2
Finland	3	2007	17.0		9.1		46		3
Estonia	BB 2	2012	17.5		5.5		69		2
Slovenia	1	2014	19.0		17.0		11	ns	4
Finland	1	2009	22.1	2.6	9.6	3.3	57		3
Estonia	HB 1	2012	23.0		15.0		35		2
Finland	3	2008	24.0	9.0	8.0	3.0	67		3
Finland	3	2009	24.2		14.9		38		3
Average			18.5	5.2	10.0	3.5	45		
Heavy mold attack									
Finland	1	2007	26.3	6.0	7.8	1.0	70		3
Finland	2	2009	38.5		19.6		49		3
Italy	1	2012	39.4	25.8	13.3	10.5	66		5
Finland	2	2008	40.0		20.0		50		3
Finland	1	2008	45.0	10.0	35.0	1.0	22	ns	3
Estonia	HB 1	2010	48.0		38.0		21	ns	2
Finland	4	2009	50.3	46.0					3
Slovenia	1	2013	55.0		27.0		51		4
Finland	1	2006			10.5	9.0			3
Average			42.8	22.0	21.4	5.4	47		

Citation: 1 = Eken, 2014; 2 = Mänd et al., 2014; 3 = Hokkanen et al., 2014; 4 = Bevk, 2014; 5 = Maccagnani, 2014

[1] Values represent the proportion of moldy berries at the time of berry-picking at the main harvest. The column "% reduction by Biocontrol" is the reduction in the proportion of moldy berries using entomovectored biocontrol, from that occurring in the untreated control. The reduction by Biocontrol was statistically significant in all but three trials, indicated as 'ns' in the Significance column.

3.2 Raspberry Results

Grey mold levels in the study year (2007) were moderate on raspberry, averaging 6% to 14%. Honey bee-vectored biocontrol reduced disease by 42%, on average, while the combined fungicide program together with bee-vectored biocontrol reduced the disease by 71% (Table 3). Unfortunately, no treatment with only fungicides was possible to arrange.

Table 3. Field trial overall results using bee-disseminated precision biocontrol for the control of the grey mold (*Botrytis cinerea*) by the antagonist *Gliocladium catenulatum* (Prestop® Mix) on raspberries in Finland in 2007

	Grey mold proportion[1]			
	Untreated	**Biocontrol**	**F:cide+Bio**	**% reduction by Biocontrol**
Farm 1	6.9	2.7	2.1	61
Farm 2	14	8.4	3.9	40
Farm 3	9.2	4.9		46
Farm 4	9.7	6.1		37
Farm 5	6.1	4.5	2.0	26
Average	**9.2**	**5.3**	**2.7**	**42.0**

[1] Values in the treatment columns are proportions of moldy berries of the total harvest. Last column gives the percent reduction in the proportion of moldy berries by biocontrol, compared with the untreated control. All reductions are statistically significant.

3.3 Results on Apple trees

3.3.1 Flower Analyses

Analyses of apple flowers from treated trees revealed that the delivery of Prestop® Mix with the help of honeybees was successful in maintaining disease levels below economic thresholds. The examination showed that 50-75% of the apple flowers were colonized by *Gliocladium*, depending on the distance from the hive (Table 4, Fig. 3). The antagonist was present in all flower organs (stamens, pistils, petals and calyx). No *Gliocladium* was detected in apple flowers collected from the untreated area.

In the flower analysis, the occurrence of the bio-control fungus, *Gliocladium,* and other pathogens were examined. No *Botrytis cinerea* was found on stamens, whereas *Fusarium avenaceum* occurred quite abundantly on stamens (Table 4, Figure 4). The percentage of *F. avenaceum* in the stamens was highest in the untreated reference flowers and lowest near the hive. When going further away from the hives, the amount of *Fusarium* increased approximately 2.5-fold (from 10.7% to 26.0%).

Table 4. The occurrence of *Gliocladium catenulatum* in apple flowers after Prestop® Mix entomovectoring, and the effect of entomovectoring and distance from hive on the occurrence of *Fusarium avenaceum* in apple flowers

Treatment/Distance from the hive	*Gliocladium* % in apple flowers			*Fusarium* in stamens	
	Stamens	Petals and pistils	Flowers	%	Relative
Untreated	0	0	0	26.0	100
Prestop Mix (10m)	18.3	22.0	75	4.0	15
Prestop Mix (50m)	5.3	13.5	60	7.3	28
Prestop Mix (100m)	5.7	9.5	50	10.7	41

3.3.2 Apple storage Results

The BCA, *G. catenulatum,* appeared to improve the shelf-life of apples. After *Gliocladium* treatment during flowering, apples were better preserved than fruits from the untreated reference (Table 5). After 3 months' storage (in January 2014), the Grade One yield was higher, and there was less core rot after the application of Prestop® Mix by entomovectoring, than in the controls. Also the proportion of apples in the category 'other damages' was reduced. Damages in question were mainly caused by unidentified diseases. One month later, in February 2014, the evaluation of the apples gave the same results, with greater differences between treated and untreated apple trees.

Table 5. The effect of Prestop® Mix entomovectoring on the quality of apples after 3-month (January 2014) and 4 month storage (February 2014)

	Proportions (in %) of apples after storage			
	Entomovectored Prestop® Mix		Untreated control	
	3 months	4 months	3 months	4 months
Grade One[1]	76	72	66	59
Botrytis	1	2	2	8
Fusarium	2	0	2	1
Other damage	22	26	30	32

[1] Determined after EVIRA (2009).

The isolation tests on stored apples showed that, in Finland, *Fusarium avenaceum* was the main pathogen penetrating the developing fruit via the flower. However, part of the damage in apples is caused by *Botrytis cinerea*.

Figure 3. *Gliocladium catenulatum* colonizing a stamen from an apple flower

Photo: Marja-Leena Lahdenperä, Verdera Oy

Figure 4. *Fusarium avenaceum* colonizing a stamen from an apple flower

Photo: Marja-Leena Lahdenperä, Verdera Oy.

4. Discussion

4.1 Strawberry and Raspberry Grey Mold Control

Peng et al. (1992) and Yu and Sutton (1997) reported good control of grey mold in raspberries and strawberries using *Gliocladium roseum*, reducing *B. cinerea* incidence from 90 to 68%, and from 64 to 48%, respectively. To our knowledge, results reported here represent the first successful use of entomovectoring by growers over large cropping areas. A review of entomovectoring (Mommaerts & Smagghe, 2011) provided a listing of numerous other studies with a wide variety of target diseases, pests, crops, and antagonistic BCA, but could not identify practical applications in crop protection – other than our case in Finland. In the ERA-NET CORE ORGANIC 2 project BICOPOLL the group provided evidence that the control of *B. cinerea* on strawberry by using entomovectoring is possible across Europe, and that control results are similar to chemical fungicides. Furthermore, our Finnish on-farm research results with raspberry, reported here, confirmed that grey mold can be controlled with entomovectoring in commercial production of that crop as well.

Our results show that good efficacy in grey mold control can be achieved with *Gliocladium catenulatum* at much lower doses than what is required for equal efficacy when applying the BCA by spray treatments, thus resulting in economically competitive control (Lahdenperä, 2006; Lahdenperä, unpublished data). Using entomovectoring, 400 g of Prestop® Mix is disseminated/ha/season, but to achieve the same level of control by spraying the product would require about 1-2 kg/ha applied in 3-5 spray treatments (Lahdenperä, 2006; Lahdenperä, unpublished data). We assume that at least two factors contribute to this result: (i) blanket spraying of the crop at economically feasible doses does not bring high enough numbers of antagonist spores to the strawberry flowers when needed to prevent *Botrytis* from developing; and (ii) as at least some 40,000 new flowers open every day in a typical strawberry field per hectare (own calculations), these remain without protection until the next spraying is carried out. Entomovectoring appears to remedy both factors: (i) bees bring high amounts of BCA spores directly to the flower (several hundred spores have typically been measured after a bee visit, e.g., Peng et al., 1992; Yu & Sutton, 1997) – enough to prevent the grey mold fungus from colonizing the flower; and (ii) bees are active every day, and visit flowers as soon as the weather conditions allow. This provides a continuous, targeted precision biocontrol to take place, and ensures thereby good protection against *B. cinerea*.

4.2 Apple Core Rot Control

Based on the first-year results of the apple trial, the biological efficacy and impact of Prestop® Mix applied through entomovectoring is considered successful for apple core rot management. The grower found it easy to deliver the microbial product with the dispenser attached to the beehive. Despite these promising results we have to keep in mind that core rot disease pressure was quite low due to the dry weather at the time of flowering. Therefore, conditions for fungal attack were not very favorable.

It is also interesting that the biocontrol method worked well while normal chemical pesticide programs were used on the experimental area. We can therefore indirectly conclude that with the bee-assisted Prestop® Mix treatment beneficial microbes have not been affected adversely. Chemical pesticides are usually sprayed early in the morning or late in the evening when bees are inside the hive, and not flying and spreading *Gliocladium*. Accordingly, this biological control is compatible with chemical treatments and can be used in integrated production.

Flower analysis showed reduced core rot. Apple flowers were colonized by *G. catenulatum*, so honeybees had successfully carried Prestop® Mix powder to the flowers. The antagonist was detected in stamens, pistils, petals and calyx.

The entomovectoring technique, i.e., a combination of Prestop® Mix and bees, is already commercially used for the control of grey mold (*B. cinerea*) on strawberry and raspberry. This part of the study shows that the bee-assisted system works also on apple against core rot (*Fusarium avenaceum* and *B. cinerea*). This indicates that the biocontrol method has potential to become an effective tool for the management of many other flower-transmitted diseases on various crops needing pollination by bees.

4.3 Honey Bees vs. Bumble Bees

In the literature there has been an unresolved debate concerning the relative merits of honey bees versus bumble bees as crop pollinators (e.g., Willmer et al., 1994), and this discussion refers also to entomovectoring situations. In the BICOPOLL project, we focused on the use of honey bees, but also investigated the potential of bumble bees and solitary bees for entomovectoring. We have established the reliability of honey bees, using the standard two-way dispenser BeeTreat® developed earlier in the pilot project. This system has been successfully used by some growers for nine years, and in recent years, by hundreds of other strawberry growers in Finland (Hokkanen, unpublished). In the BICOPOLL project, good control results in the open field using bumble bees were obtained in Estonia (Table 2), and in Finland, using Prestop® Mix delivered by bumble bees. However, at that time growers used self-made dispensers. In 2014, in Finland, some strawberry growers appear to have tested bumble bee hives with a new commercial dispenser for disseminating the BCA Prestop® Mix. A grower with 102 ha of strawberries purchased 150 bumble bee hives for entomovectoring, but unfortunately did not witness bee visits to his crop, nor dissemination of the antagonist (Koivistoinen, 2015; Taari, 2015). Due to cool weather the bumble bees apparently sealed the exits from their hive, and therefore did not disperse the BCA. The grower had used honey bee disseminated entomovectoring during the previous years, and had been satisfied with the result, but decided to test the application of bumble bees (Koivistoinen, 2015).

4.4 Adoption of Entomovectoring for Wide-Scale Use

Due to the successful results obtained in the BICOPOLL project, a significant shift is taking place in Finland that relates to the EU's Common Agricultural Policy (CAP) reform, and the associated legislation concerning environmental support to agriculture. In the new statutes, entomovectoring is specifically mentioned, under "Alternative crop protection in berry and fruit production" (Reskola, 2015). As of the 2015 growing season, conventional growers who commit to substituting chemical fungicide treatments with entomovectoring, for a minimum of 5 years, will receive 500 €/ha/year in environmental support (Reskola, 2015).

While we very much welcome this paradigm shift and the boost to environmental safety and entomovectoring, we would like to point out that all components of the system would need further research and development. This includes improved dispensers, BCA formulations, and the overall operations. Dispensers need to be improved to allow less frequent filling with the BCA. BCA formulations available for the moment have not been developed for entomovectoring, but for other uses, such as mixing into the soil. Although working adequately in practise, research in BICOPOLL has shown that formulations can be improved considerably for entomovectoring, allowing a better dispersal of the BCA in the target crop at a lower initial dose than what currently is used (Smagghe, 2014). More research needs to be carried out concerning the overall entomovectoring operation, such as placement and density of the bee hives, and hive conditioning allowing steering the foraging activity of the bees into our target crop. Conditioning possibilities include manipulation of the amount of pollen stored in the hive, and the number of open brood, which will determine whether the bees forage mainly for pollen, or for nectar. Strawberry cultivars vary in their attractiveness to bees (Ceuppens et al., 2015), but they all are primarily sources of pollen (protein), rather than nectar, to the bees. Furthermore, research in BICOPOLL showed that entomovectoring is enhanced if a diverse and abundant network of wild pollinators (e.g., Jedrzejewska-Szmek & Zych, 2013; Vaudo et al., 2014) is maintained close to the target crop (Maccagnani, 2014). Such a pollinator network facilitates secondary spread of the BCA, ensuring a more complete and even dissemination of the BCA in the crop.

In addition to these research and development needs, all parties involved must work together in order to make full use of the entomovectoring technique: for that the berry and fruit growers are recommended to (i) keep bees themselves, or to hire local beekeepers' services from entomovectoring; and (ii) manage vegetation within and around the target crop to support the activity of bees and other pollinators, which can help to disseminate the beneficial microbes within the crop. Beekeepers are recommended to (i) market pollination and biocontrol services to fruit and berry growers, and (ii) in the management of bees and the dissemination activity to ensure that all operations are effective in mananging bees and their microbe dissemination activity. Biocontrol product manufacturers are recommended to develop products and their formulations specifically for entomovectoring, and regulators are recommended to register, and to promote the registration of biocontrol products, which are needed for effective control of target diseases and pests amenable to entomovectoring. In all project countries we experienced that the lack of registered BCA products is a major bottleneck to adopting these techniques more widely.

What should be avoided, in particular in Finland as a pilot country officially supporting the adoption of entomovectoring, is an unguided and hasty uptake of the technology. Conventional crop protection using chemical pesticides is highly regulated and guided: operators need to be trained and have to take exams, machinery needs to be approved and inspected, and abundant advisory service help is offered so that the crop protection operations have the highest possible chance to be successful. Although the initial adoption of entomovectoring by the pioneering growers has taken place predominantly without problems, a wider uptake may face increasing crop protection failures unless more attention is paid to training all stakeholders.

Entomovectoring offers to organic growers for the first time an economically feasible tool to protect their berry crops against the grey mold disease, as well as an opportunity to manage diseases such as the core rot on apples.

This improves the competitiveness of organic berry and fruit growing, and provides a positive image, which can be utilized in marketing of the products, as already is happening in Finland (e.g. by using the slogan "Enjoy the fruits of entomovectoring pioneers", Aasatek Oy, Finland).

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The Role of Animals in Eco-functional Intensification of Organic Agriculture

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Abstract

Eco-functional intensification is understood as building synergies in multi-functional and resilient agricultural systems in harmony with their surrounding environment and human systems, to the benefit of diversified production of food and beyond, as in, for example, ecosystem services. Integration of animals into eco-functionally intensified agricultural systems to enhance agricultural, ecological and social systems, can contribute to driving a future sustainable development of organic agricultural and food systems. This approach may respond to challenges of an increasing industrialization of livestock in the global north, a process which has led to heavy reliance on external inputs, and, to a large extent, a detachment of animals from farming systems, especially in the global south. Animals are living sentient beings, but often not acknowledged as such. Complex, well-integrated systems can be organized so that they support the health and welfare of animals, and let these animals be valuable resources within the farming system. There must be an emphasis on diverse genetic inheritance and locally adapted species. Complex systems require complex knowledge which must be continuously developed to respond to current challenges in constantly changing environments, *e.g*., climate change. A necessary driver in transition towards more eco-functionally intensified agricultural and food systems is a governance system which protect the actors without a voice, *e.g*., ecosystems, pollinators, animals, and future generations through regulation of consumption patterns, flow of external inputs, and resource use. This requires a change in attitudes both acknowledgment of the importance of protecting the environment, consumption, resource use; and seeing agricultural systems as necessary and valuable contributors to nourishing both people and the earth.

Keywords: livestock, governance, agricultural systems, ecological intensification

1. Introduction

1.1 The Idea of Eco-Functional Intensification (EFI)

Intensification of agriculture is often understood as 'increasing the input intensive aspects of the agricultural systems to get a high output of a certain commodity', using more energy, nutrients and water but less labor input. Gamborg and Sandøe (2005) describe for example how animals have been bred to grow faster and produce more leading to a range of production based welfare problems, and as a part of intensification of agriculture since 1950s. Eco-functional intensification is quite different from this. There is no published and universally accepted definition of 'EFI'; however, Niggli et al. (2008) presented it as:

'first and foremost, activating more knowledge and achieving a higher degree of organization per land unit. It intensifies the beneficial effects of ecosystem functions including biodiversity, soil fertility and homeostasis. It uses the self-regulatory mechanisms of organisms and of biological or organizational systems in a highly intensive way. It closes material cycles in order to minimize losses (e.g. compost and manure). It searches for the best match between environmental variation and the genetic variability of plants and livestock'.

This will mean a higher degree of diversification within the system. Eco-functional intensification also increases the complexity of systems, utilizing the genetic variability and other resources and introducing clever use of low or no risk technologies. Eco-functional intensification of a system must happen in harmony with the surrounding nature, and in such a way that all resources involved are utilized and maximized within the system, irrespective of the scale we talk about. Eco-functional intensification of a given agricultural system is knowledge intensive in terms of contextually relevant knowledge. By increasing the complexity of a system, building on the synergistic effects among components and/or between levels within the system, one could claim that the full system appears ‘simpler’ because self-regulating mechanisms, as well as a number of mutual systems effects, are enhanced. On the other side, it requires immense knowledge and insight, which can be facilitated though communication and local community-based and context-specific knowledge generation.

Eco-functional intensification will in many ways stress the organic principles described by the International Federation of Organic Agriculture Movements - IFOAM (IFOAM, 2005), where the principle of ecology states that: *“Those who produce, process, trade, or consume organic products should protect and benefit the common environment including landscapes, climate, habitats, biodiversity, air and water.*” This requires systems approaches which are beyond many organic agriculture regulations. Organic regulations are generally concerned with how a production takes place, for example ensuring that chemical fertilizers and pesticides are not involved, but not requiring a certain way of organizing the system in terms of diversification.

Intensification towards more diversification can go beyond the agricultural system itself. Ideally, an agricultural system interacts with human, social and ecological systems in synergetic ways. Vanlauwe and co-authors (2014) used the example of sustainable intensification (SI), which in their paper was viewed as achievable only if diversity in agro-ecological conditions, farm household endowment, farming systems, and socio-economic conditions within the landscape were taken into account.

Eco-functional intensification can for example consider pollinators such as bees, which bridge the natural system with the agricultural system. This can include both wild bees (‘ecosystem service’), and domesticated farm animals, *Apis mellifica*. Tcharntke and co-authors (2012) argue for such land-sharing approaches, where agro-ecological intensification is the backbone for global food security, by, among other things, involving and inviting crucial ecosystem services as part of what they call ‘*planned and associated biodiversity*’, to benefit the agricultural system.

Another side of intensification is the interaction between human and social systems and farm animals within the framework of an agricultural system. An example of this is a system where animals’ ‘natural needs’ are met by allowing animal mothers to interact with their offspring during the milk feeding period. Such system requires in-depth insight into animals’ needs, behavioral patterns, health and welfare issues, as well as experience when observing and ‘reading’ animal signals. Furthermore, all this has to be a part of a wider system into which multiple functions of the farm also fit, in a knowledge intensive innovative system.

Finally, it can also be claimed that the idea of EFI plans for resilience by spreading risk over more elements in the production. This is in contrast to industrial intensification, which aims at a high yield of a commodity, often measured by man hours invested in the production. In other words, the idea of ‘EFI’ has wide perspectives, and animals can be involved in agricultural systems and can interact with their various components in multiple ways.

1.2 Rethinking the Notion of Performance in Food Producing Systems with Animals

In food production, ‘performance’ is often referred to as high yield. When considering EFI, it is relevant to consider other qualities related to performance, which does not necessarily exclude ‘high yield’, but merely encompasses a more holistic understanding of how animals can perform in the system. Highly diverse agricultural systems will include production of other things than tangible animal products (Tichit et al., 2011), such as eco-system improvements like improvement of soil, air, clean water, or biodiversity. When animals are well integrated into such systems, their performance can be described as ‘systems contributors’. These systems contributors manage land in a way which maximizes the synergy between the animals and different plants. For example, letting animals root on post-harvest-areas, contributes to agro-forestry systems, as with fruit and other food trees with poultry raising, or contributing to integrated or mixed land use *e.g.*, in rotations.

Organic animal farming should ideally build on ecological systems with closed nutrient cycles. An eco-functionally integrated animal farming system will not rely on high amounts of external inputs. On the contrary, the characteristics of the system will be determined by what is possible within the boundaries of a self-reliant system. As a mirror to the considerations related to planetary boundaries (as described by Röckstrom et al., 2011) it can be relevant to examine ‘which local system boundaries do we need to respect and build on to avoid trespassing planetary boundaries’? In the following, I will briefly examine some of the challenges of current organic livestock production systems, and use this to discuss relevant aims of an eco-functional integration process of organic animal farming.

2. The Setting: Challenges of Current Organic Livestock Production

Organic animal production is growing in some countries, and an increasing number of consumers choose organic animal products (Anonymous, 2014; Willer & Lenoud, 2015). At the same time, organic agriculture is also challenged by being part of a global, conventional food system in many parts of the world. The current global food system is operated by relatively few major corporations, produces huge amount of waste through the way in which it is organized, and, in many cases creates complete separation between producer and consumer. This is very far from the principles of organic agriculture, such as the closed nutrient cycles and the ideas of fairness. Organic animal based food products are basically competing on the same premises as all other food which is industrially produced, transported, packaged, stored, and processed in big quantities. In some cases, it stimulates consumption patterns which can also be questioned in terms of sustainability, for example 'organic fast food', and a generally high consumption of livestock products, some of which are not produced in well-balanced, integrated agricultural systems. In general, one can claim that the sustainability of any farming system can be questioned when it is part of an unsustainable food system (Vaarst et al., 2015).

In a discussion about how EFI of organic agriculture can help further development of organic animal agriculture towards a higher degree of sustainability in all its aspects, it is important to address the current challenges facing much organic agriculture. In the following, both the global north and south will be considered.

2.1 Challenges in the Global North

2.1.1 A Livestock Industry Relying on Multiple Inputs

Three types of inputs are especially relevant as inputs on which organic livestock production in the global north, especially in Europe, relies: imported feed, fossil fuels, and antibiotics.

One important thing that happened in the industrial agriculture was a more or less complete detachment between animals and land, promoted by introduction of feed which could be transported over large distances, e.g. from Brazil or China to Europe. This possibility of transporting both feed and live animals moved agriculture from being oriented towards systems designs and recycling of resources, being self-sufficient (on a certain scale ranging from farm to regional levels) towards a commodity-oriented production, allowing huge amounts of one product to be produced in specialized areas, and allowing a huge animal production in places requiring feed transportation, with animal products subsequently transported away from the production site. An estimated 34% of current global cereal production goes to animal feed (FAO, 2013), whilst livestock takes up to 70% of all agricultural land (Steinfeld, 2006). Ideally, manure is a valuable resource, and yet, it is often referred to as a source of pollution, in areas with a dense livestock population. Consequently, feed is transported into some areas and manure is transported out of the same areas, as a sign of a complete detachment between animals and land.

Organic farming should ideally be based on closed nutrient cycles, which means that feed should primarily be of local origin. The notion of 'local origin' of feed can be questioned: in some contexts it is understood as feed from the same farm on which animals live, as for example, when the Danish organic farmer organization included in their requirements that 50% of the feed should be produced on the farm or in cooperation with other farmers within a radius of 25 km (Mogensen, 2004). In other contexts it is understood as feed produced within a regional area, or wider, *e.g.*, in the European research project ICOPP it was defined as 'European feed' (http://www.organicresearchcentre.com/icopp/). However, 'local' should not be understood as feed brought over long distances. Some ingredients for organic concentrate feed are imported to USA and Europe, e.g. Chinese organic soy bean. This furthermore illustrates the detachment between land and animal production, on which huge parts of today's industrial agriculture is based, and which organic production should ideally not apply to. According to FAO, livestock production accounts for about a third of the global cropland production, and livestock production is increasingly managed in large-scale operations and involved in international trade (http://www.fao.org/ag/againfo/themes/en/animal_production.html; retrieved 21st Feb.2015). Schader et al. (2013) modelled the environmental impact of livestock in five different future scenarios, and compared among others the scenario of 'upscaling organic agriculture' (in its current form) versus 'banning concentrate feed', and found that the latter would be more environmentally friendly than upscaling organic agriculture in its current form. This could indicate that the ideas of EFI of organic agriculture with animals, is highly relevant. The use of freshwater is strongly connected to the land-use of livestock production. Livestock production accounts for about 20% of the world's freshwater use (Molden et al., 2010). Out of this, only 2% is estimated to go to their actual drinking, and the rest to the feed production (Peden et al., 2007). Depending on the type of production, freshwater is involved in other processes than feed production, such as washing of milking parlors and cooling of milk, in the dairy sector.

The issue of import and export of organic feed furthermore relates to the current reliance on fossil fuels, which is heavily involved in all aspects of organic animal production, from the on-farm feed production and transport, through farm operations using machinery and electricity to the transport of products. Tittonell (2013) gave the example of maize grains, where 70% of the energy comes from fossil fuels, and calls it the '*intensification trap*' because it creates dependency. Processing units are getting bigger and fewer, which means that milk, eggs and all other animal products, as well as live animals, must be transported over longer distances, sometimes between countries or even continents.

Whilst a complete prohibition of antibiotics exists in organic agriculture in the USA, it is permitted in Europe for treatment of diseases, and can only be administered by a veterinarian, or through the involvement of the veterinarian in one way or the other. The actual use of antibiotics varies extremely between sectors, countries, and even farms. Access to and availability of alternatives to antibiotics is quite high in parts of the USA and is relatively well spread among organic farmers, involving various ways of using them, and different results. In the EU (European Union) countries, legislation has almost blocked any use of for example homoeopathy, and partly also of phytotherapy. However, in many European countries, organic farmers have been leading in building up and ensuring animal health promoting strategies for organic livestock, which have led to significant reduction of antibiotic use in organic dairy cattle, in particular (Bennedsgaard et al., 2010; Ivemeyer et al., 2012 & 2015). Nevertheless, European organic animal farming has the possibility of treatment with antibiotics as a constant 'back-stopper', which still can be regarded as 'reliance' in many cases, because it potentially influences the whole herd management strategy.

2.1.2 Loss of Agro-Biodiversity and Genetic Inheritance

Humankind has domesticated at least 30 species of farm animals, accounting for over 8.000 registered breeds, of which many are locally adapted, multi-purpose and indigenous. Large parts of North European organic farming are single commodity-oriented and mono-cultural, that is, in the case of livestock production, farms with only one animal species, often with no other type of production than animal production and feed for the animals. The number of different breeds available for organic agriculture has become very low over the last decades particularly, in certain countries. The current breeds in industrial systems of today are almost exclusively single purpose breeds. For example, in today's broiler production, the very few existing genotypes are selected for excessive growth and very high feed efficiency, but they are more vulnerable in terms of immune competences (Rauw et al., 1998). Eradicating breeds means not only losing natural capital or 'wealth' in a colorful and diverse world, but also eradicating possibilities for adaptation to different environments and situations, *e.g*., climate changes or consumer choices (FAO, 2014).

In other words, the underlying systems theory and approach of organic agriculture is not met in practice in large parts of organic animal farming today. The emphasis on specialisation can have potential impact on the way in which we focus our breeding and our perception of which animal types are needed. When animals are viewed not as systems components with potentials for interaction with other elements within the system, but as 'the production focus on the farm', animals are bred and shaped to fit into these 'high production systems'. Poultry production represents one extreme of this, where layer hens and broilers are completely 'separated' by breed, meaning that millions of male chickens of layer hens are killed just after hatching, which can raise severe ethical concerns, and which is not in accordance with organic or ecological ways of thinking. The low degree of diversification within-farms can influence breeding aims and patterns, and vice versa.

2.2 Challenges in the Global South

Livestock contributes to the ecological and environmental sustainability of many tropical smallholder farming systems, *e.g*., in nutrient recycling (Hermansen, 2003; Powell et al., 2004). Livestock play a significant role in household food and income (Dreschemaeker et al., 2010; Funes-Monzote, 2008). Besides, they provide with many other materials. Tropical smallholder livestock keepers represent about 20% of the world population (McDermott et al., 2010).

2.2.1 Livestock Not Fully Included in the Idea of 'Organic'

Even though many smallholder farming systems in the global south are diversified, and some of them use agro-ecological practices, they are not considered 'organic'. 'Organic agriculture' is defined as organically certified in accordance with the organic standards of global north countries, and with the focus on producing organic high-value products (for example coffee, cocoa, spices, herbs and fruits). Most organic products are for export to countries in the global north, where approx. 95% of the global organic production is sold. In many cases, animals are part of the farms on which export products (for example vanilla or pineapples) are produced, but they are not thought of as 'organic', because their products only very rarely can be sold as organic. Odhong et al. (2014) and Nalubwama et al. (2014a & b) emphasized how the livestock herd and the farm seem to 'co-exist' but not as a fully integrated farming system. Many organic standards are not fully developed, for example the organic feeding standard (Kiggundu et al., 2015).

2.2.2 Utilizing Manure Efficiently Versus Letting Animals Meet Their Natural Needs

In many tropical smallholder farms, there is a need for arable land and manure. At the same time, the organic principles emphasize that animals should meet their natural needs. This is identified as a major dilemma in organic smallholder farms with scarce land in the tropics (Muwanga, 2010). The manure is needed for compost or other redistribution of nutrients, and at the same time, land is very scarce and must provide food for a whole family and in some cases also for cash crops. In many tropical smallholder farming systems with animals, the change from traditional farming to organic and agro-ecological farming has led to keeping animals indoors to a much higher degree because of new awareness of the value of manure (Muwanga et al., 2010). Araya and Edwards (2006) and Edwards et al. (2010) illustrate this well in their work, showing how severe land degradation problems in arid areas in Ethiopia were solved mainly by creating zero-grazing systems for the small ruminants in the area. This restricted the animals from grazing, and thereby many aspects of natural behavior while foraging, performing social behavior and moving around on grassland.

2.2.3 Endemic Diseases

Endemic diseases are a major challenge in many tropical countries in the global south (Rubaire-Akiiki et al., 2006; Vaarst et al., 2006). Rubaire-Akiiki et al. (2006) concluded that in the case of local and cross-bred cattle, most tick-borne diseases could be managed by regular hand-picking of ticks. This is not possible with so-called exotic cattle (e.g. Holstein-Friesians) which are much more vulnerable to infections (Rubaire-Akiiki, personal communication, 2014). In pastoralist herds with hundreds of cattle, this is obviously not possible. These animals are given the possibility of carrying out their natural grazing behavior and, depending on the climate and environment, they will get sufficient amounts of feed in accordance with their natural needs. However, they are in higher risk of endemic diseases, hence also of the use of acaricides and other medicines, especially when land areas are restricted, and they are exposed to ticks and other vectors. In the case of poultry, free-ranging life can be very challenging as well, and vaccinations can be one option, e.g., to overcome Newcastle disease in free ranging poultry.

3. Roles of Animals in Eco-Intensified Agricultural Systems

When researching and discussing the potential roles of animals in well integrated and eco-functionally intensified farms, it is relevant to see this both from the side of the animals and from the perspective of the systems. This will be done in the following, where I open up for a view on livestock as animals, and thus for a wider systems approach to 'animals'. However, this article is primarily focusing on the role of farmed animals in EFI of organic agriculture. The second section of this part of the article will be the systems view on integrating animals into the system, including examples and case studies.

3.1 Meeting Livestock's Common Global Challenge: They Are Animals

Various definitions of livestock exist. According to the Codex Alimentarius , livestock means 'any domestic or domesticated animal including bovine, ovine, porcine, caprine, equine, poultry and bees raised for food or in the production of food. The products of hunting or fishing of wild animals shall not be considered part of this definition' (Awada, 2011; http://www.fao.org/docrep/005/y2772e/y2772e04.htm). Others define it differently, for example the online dictionary Merriam-Webster (http://www.meriam-webster.com/dictionary/livestock) explicitly excludes poultry. FAO defines it broadly: 'The terms "livestock" and "poultry" are used in a very broad sense, covering all domestic animals irrespective of their age and location or the purpose of their breeding. Non-domestic animals are excluded from the terms unless they are kept or raised in captivity, in or outside agricultural holdings, including holdings without land' (FAO, 2011). The differences as well as the combination of these definitions may reflect a view which is very valid or even necessary to consider in the case of organic farming: the organic well-integrated farming system builds on mutual benefits and synergies between 'the system' and 'the animals', and this can include both domestic or wild animals, such as pollinators, earthworms, wild birds and mammals.

Animals have many different roles in human lives, as working partners and providers of multiple products like eggs, milk, wool, skin, bones, meat, honey and manure, just to mention some. They bear many cultural meanings, they are part of our history and have been domesticated and shaped and have helped us shaping our lives. In integrated agricultural systems they are systems partners: they are important partners in the nutrient cycle, interact with the soil (for example by stepping on and rooting in it, and providing it with nutrients), and with the surrounding nature if allowed, by, for example, choosing certain elements of the vegetation, browse trees and interact with the birds and other wild fauna. So, we can identify many ways in which animals are integrated into whole systems and interact both with the human and the ecological systems. According to its principles, organic farming incorporates a systemic view of humans and animals as part of the surrounding larger ecological system (Alrøe et al., 2001; Baars et al., 2004; Vaarst et al., 2004a). Animal health can be described within the framework of resilience (Döring et al., 2013), and the system of which animals are part, should be organized in ways which enable them to unfold as individuals and use their capabilities as part of their welfare (Cabaret et al., 2014). Animals are living sentient beings, which can feel pain, anxiety, happiness, frustration and fear. They are domesticated, but also have what can be characterized as 'natural needs', a characterization which is not only about their behavioral patterns, but equally about their need for species-specific feed. The organic principles as formulated by IFOAM acknowledge this aspect and emphasize in many ways the role of animals as partners in the system (the principle of ecology). However, the concept of naturalness is also included here. For the animals, this includes access to outdoor areas and freedom of choice that allows each animal to express its individual preferences (Lund, 2002, 2006; Verhoog et al., 2004; Verhoog et al., 2007; Waiblinger et al., 2004; Bracke & Spoolder, 2013). Their species specific needs can, for example, be having mother-offspring contact, dust bathing, space for natural laying down behavior, wallowing, grazing and social behavior), and to have species-specific feed, so that ruminants are fed 'ruminant feed', which is high amounts of roughage and grass based diets.

Lund and Olsson (2006) described animal agriculture as a form of living together between humans and animals that has evolved through a process over thousands of years. Lund (2002) and Lund et al. (2004) discussed the "ethical contract" between humans and farm animals in organic farming, farmed according to the organic principles. Humans have a moral obligation to take care of the animals for which they have taken responsibility. This care includes allowing them access to as much naturalness as is possible under farmed conditions, and caring for them at all times. An aspect of this care is to intervene when necessary. According to the ethical contract, humans are allowed to use animal products and take animals' lives, but they have the obligation to ensure that the animals in human households live a life in which they are allowed naturalness, and where they are taken care of when needed. Both "naturalness" and "care when needed" are vaguely expressed and seem unavoidably left to negotiation in practice (Vaarst et al., 2004b). Numerous 'animal welfare assessment models' have been developed, based on different views on animal welfare (Haynes, 2013; Fraser, 2010), and can provide a well-informed basis for discussion and negotiation about the animal welfare situation in a given herd. However, a negotiation about the understanding of animal welfare and the situation on a given farm will be based on individual perceptions and ethical choices, depending on humans' knowledge, insight, empathy, ability and willingness to relate to the animals and their needs (Vaarst et al., 2004b). According to Hendrickson and James (2005), group and self-identity are prime movers for ethical or moral behavior. They explained how a changing environment towards industrial farming can lead to what they call "erosion of farmer ethics", with severe structural and practical consequences for the way the farm is designed and organized, and the animals are managed. Organic agricultural systems must necessarily include care for and management of animals, as a part of thinking them into whole farming systems. Appleby (2005) formulated '*A collaborative approach to humane sustainable agriculture will benefit animals, people and the environment'*.

Changing focus from 'livestock' to 'animals' may lead the attention to also caring for and integrating non-domesticated animals into the farm. It can be argued that this is very much in accordance with the idea of a fully eco-functionally integrated farm, where, for example, animals categorized as so-called ecosystem service animals, such as earthworms and wild pollinators, are highly valued as components of the farm. Other animals, such as birds and wild mammals, can also have roles to the benefit for the whole agricultural system in its interaction with the surrounding nature.

3.2 Animals as Integrated Partners in Diversified Systems

The integration of domesticated animals into farming systems can give long term benefits in terms of circulation of nutrients, utilization and care of land areas, prevention of land degradation and erosion, and contribution to resilient and robust, diversified, and intensified farming systems (Funes-Monzote, 2008; Pretty, 2006; Halberg et al., 2009; Vaarst, 2010). To enable this, a balance between the capacity of the land area, the species, and the number of animals is paramount. Different animal species clearly contribute differently to the system. Bonaudo and co-authors (2014) emphasized how cattle in a moderate stocking rate and with a moderate milk production, could benefit the system in more ways by letting grass be the main fodder source reducing bought-in-feed. The photosynthetic capacities of the grasses optimize the conversion of carbon dioxide, water and minerals into biomass. Legumes fix nitrogen, and there is a synergy within the mixture of legumes and grasses. The cows harvest, fertilize and weed the field, fulfilling in this way at least three functions, and attempting to have a long grazing season cuts harvesting and distribution costs (Bonaudo et al., 2014). In many ways, this type of system is not a 'new invention' - rather a traditional cattle rotation system. Nevertheless, such a system represents an alternative to industrial cattle systems, and can furthermore include use of marginal land, which then contribute to the production of animal products. These systems can also help create farm areas where pollinators, earthworms and wild animals can find space. In many settings, dairy production is quite mono-cultural, but there are huge potentials that dairy cattle can be drivers and be part of a farm which follows a diversification strategy. Monogastric animals are often perceived as more challenging than ruminants. However, poultry fit into many different agro-forestry systems, where they keep away pest animals from fruits and berries, and benefit from the shelter and protection given by the vegetation (Pedersen et al., 2004). Synergy effects have been shown in farms with pigs working on land after harvest, or e.g. energy crops or Jerusalem artichokes (Kongsted et al., 2013). Integration of more animal species on a farm requires much human insight. The development over the past decades has gone more and more in the opposite direction, that is, towards specialization, monoculture and increased herd sizes on farms. This might explain why it is difficult to find recent research documenting benefits for animal health and welfare of multi-species animal integration in agricultural systems in the EU or the U.S., although a lot of recent and current projects also look at integrated production, for example the EU-funded projects Agforward (http://www.agforward.eu/index.php/en/) investigating different viable agroforestry strategies, and and 'CANtogether' (http://www.fp7cantogether.eu/index.php). Gliessman (2006) pointed to animals' role in shaping landscapes, ensuring energy flows and influencing the dynamics of plant population and species interaction. Bonaudo et al. (2014) analysed and discussed agro-ecological practices in a French and in an Amazonian system which shifted from systems with co-existence of crops and animals, to an integrated crop-livestock system, meaning that they created or re-created links between soil crops and animals through a diversified production, with the additional benefit of giving economic resilience to market shocks. They maximized ecological (predator-prey) or production-based interactions, *e.g.,* by improving complementarities between production cycles. These systems illustrated how elements of agro-ecological practices under two widely different sets of conditions, could contribute to robust and viable systems, and led to the conclusion that there are several paths to building more and more sustainable systems. In practice, they minimized losses and external inputs, optimized the nutrient availability for crops and animals through temporal management, and developed the collective management at the landscape level, including the semi-natural elements (Bonaudo et al., 2014).

Animals which are integrated into complex agro-ecological farming systems constitute a part of this system with its synergies and mutual benefits. Silvopastoral agroforestry systems seem to form one particularly promising approach to integrated systems throughout climatic zones, which is still relatively unexplored and unexploited in industrialised countries and the special conditions of temperate climatic zones.

4. Strengthening Systems Approach and Eco-Functional Integration in Animal Systems

Agricultural systems which benefit animals, humans and ecosystems, must necessarily be based on balance and connection between land, water, resources, humans and animals within the farming system. This will mean building up diversified systems, which are resilient in an ecological sense (different elements of the system supporting each other and creating buffers to shocks and events) and economic sense (for example risk diversification). An emphasis on complexity and diversification within agricultural systems will lead to a more diversified local production of food and other products, which can be mutually related to reduction of fossil-fuel-based transport. Diversified agricultural systems producing food for more local food systems will require e.g. a more seasonal food pattern, which is just one step towards fundamental changes in current consumptions patterns and food systems. Other changes will be efforts towards less food waste and lower consumption of animal products. This calls for an improved governance of agricultural systems. Moraine et al. (2014) emphasized the need for keeping flexible public policies to meet increased demands for preserving common assets in agricultural areas, rather than trying to meet the economic competitiveness of the agricultural sector. Hilimare (2013) reviewed possibilities for crop-livestock integration in North America, and mention the challenge of having regulatory frameworks which are better suited for large-scale farms. This is just some examples of regulations encouraging one type of farm enterprise, namely the more industrial model. All these issues of governance and institutional changes around our food systems are beyond the scope of this article, although closely connected in the call for a profound transformation of farming and food systems towards an eco-functional integration of human, social, institutional, ecological and agricultural aspects and systems elements.

Such an emphasis of larger agricultural systems can take different forms. Lemaire and co-authors (2014) emphasized the urgency of forming diversified, resilient systems and suggest that even if farms specialize, the collaboration and integration between farms in an area can form a coherent and large-scale ecologically intensified system. Moraine et al. (2014) presented and discussed collaboration between farms to create integrated crop-livestock farms in a European project 'CANTOGETHER' (http://ec.europa.eu/research/bioeconomy/agriculture/projects/cantogether_en.htm), and identified basically four different types or 'scales' of integration between farms, from exchange (type 1) to 'increased temporal and spatial interaction among the three spheres in a rationale of territory-level synergy', where it is organized so that resource allocation, knowledge sharing, and work as well as other types of collaboration is optimized (type 4). Based on three contrasting cases, they identified some common trends: all three cases were characterized by a certain level of diversity, either on cropland use, production systems or landscape. Grassland, cash crops and forage crops were present in all cases, and ecosystem service improvements could be identified in all cases, and obviously, all cases had some level of collaboration, sharing and development of social systems between involved farms and families, as well as in relation to the surrounding society.

Dumont et al. (2014) outlined different strategies to incorporate agro-ecological strategies to integrate crop and livestock systems better, among others adopt management strategies aiming at improving animal health (e.g. different plants strengthening immunity, preventing disease and giving better nutrition). The monogastric animals are particularly challenging to integrate, and strategies to reduce inputs and pollution are important in the process of eco-functional integration. Ruminants in particular have the ability to use roughage from areas where no food for potential human consumption can be grown and by-products which are not suitable for human consumption. An integrated system will use this ability and reduce competition between humans and animals regarding resources, including feed/food production.

It is well documented that even though farming according to the organic standards provide a framework which is more animal-friendly than industrial farming, it does not ensure that the practices live fully up to the organic principles, nor does it guarantee good animal welfare (Sundrum et al., 2006; Vaarst et al., 2008). In the process of creating systems that meet animals' needs, much knowledge and the ability to reflect and innovate is required. For example when managing organic calves, organic farmers need knowledge about disease risks and epidemiology as well as knowledge of ethology and natural behavior to design systems and act in these systems in ways that are appropriate to the animals that we have domesticated and taken into human care (Vaarst et al., 2001, 2004b), and they have to have the ability and willingness to develop such systems in their own farm context. When intensifying the systems towards better integrated ecological systems, learning and knowledge generation has to take place, and innovation is crucial for this process. We are often restricted to think of innovations only as technical solutions. A Danish action research project in collaboration between the Thise Dairy Company and Organic Denmark and Danish Institute of Agricultural Sciences (now merged into Aarhus University) developed the so-called 'stable schools', which employ a farmer owned, facilitated advisory method in farmer groups (Vaarst, 2007; Vaarst et al., 2007). This concept was developed in European projects to different farm and advisory contexts, and demonstrated the importance of farmer ownership in development of farm practices for lasting change on herd and farm levels (Vaarst, 2007; Ivemeyer et al., 2012, 2015; Vaarst et al., 2010, 2011a, 2011b; Bennedsgaard et al., 2010). MacMillan and Bennett (2014) involved farmers in innovation and research processes with interesting results. Padel and co-authors (2015) emphasized that it is important to think of innovation in terms of, for example, social or environmental innovation, where clever and context relevant solutions are developed for the organization of social systems-for example, farmers working together in new ways, or in new combinations of plants or ways of processing farm products.

Niggli et al. (2008) emphasized the importance of knowledge for the process of EFI in a vision paper for research in organic agriculture (see above): *'Knowledge is the key characteristic of eco-functional intensification'*. Approaches like Stable Schools or Farmer Field Labs as described above, could offer interesting approaches to common knowledge generation for further development of eco-functionally integrated agriculture. Similarly, a new mode of thinking in new ways is needed for scientific development. Tittonell (2013) urged the development of new scientific approaches to whole-farming systems analyses. Gonzales-Garcia and co-authors (2012) explained how complex multi-functional systems require research which includes the complexity and meets it with multidisciplinary and holistic approaches. In the same line of thinking, Moraine et al. (2014) proposed that multilevel and multi-disciplinary designs of research projects are developed to fully understand the ability of agro-ecology to enhance ecological processes as well as of humans to make collective action. This is strongly supported by Dumont et al. (2014), who suggested a wide range of relevant research focus areas directed towards enabling a transition to more resilient and sustainable agricultural and food systems, areas such as development of principles for systems design in various contexts, collective action initiatives, and interaction between different systems components.

Scientific development and research goes strongly hand in hand with the teaching of students. Rickerl and Francis (2004) pointed to the importance of including multidimensional thinking, systems understanding, as well as ethical, social and ecological dimensions of agriculture and food systems. They developed approaches to letting the students direct their learning themselves (Francis, 2003), since they – as much as farmers and everybody else - need context relevant and specific learning. Tittonell (2013) outlined how courses around farming systems ecology were organized in a university setting in ten steps, exploring all inter-linkages between elements and whole systems analysis.

5. Conclusion and Future Perspectives

This article presents and discusses a range of options and challenges for better integration of animals into organic agricultural systems, aiming at synergy between the animals and the other functions and productions of the farm. In many parts of EU and elsewhere, policies have to a large extent encouraged commodity oriented and rather mono-cultural, large-scale organic agriculture more than focused on eco-functional integrity, diversification and resilience of agricultural systems. To intensify organic agriculture in alternative ways, through EFI with a focus on synergies and harmonies within the agricultural systems, and between agricultural, natural and social systems, profound structural and social changes have to be developed regarding current agricultural and food systems, including consumption patterns, and directions of knowledge generation and innovation. A key to bringing about such changes is our governance of agricultural and food systems, strategies such as engagements in nature conservation as part of forming agro-ecological farming systems, and forming social communities to contribute to local food systems. Animals can become valuable and relevant partners of such systems, and numerous studies of agricultural systems in many different contexts, demonstrate multiple synergies within the systems, which also benefit animals' health and welfare.

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Soil Health and Related Ecosystem Services in Organic Agriculture

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Abstract

Soil health is dependent upon complex bio-physical and bio-chemical processes which interact in space and time. Microrganisms and fauna in soil comprise highly diverse and dynamic communities that contribute, over either short or long time frames, to the transformation of geological minerals and release of essential nutrients for plant growth. Certified organic soil management practices generally restrict the use of chemically-processed highly soluble plant nutrients, leading to dependence on nutrient sources that require microbial transformation of poorly soluble geological minerals. Consequently, slow release of nutrients controls their rate of uptake by plants and associated plant physiological processes. Microbial and faunal interactions influence soil structure at various scales, within and between crystalline mineral grains, creating complex soil pore networks that further influence soil function, including the nutrient release and uptake by roots. The incorporation of organic matter into soil, as either manure or compost in organic farming systems is controlled to avoid excessive release of soluble nutrients such as nitrogen and phosphorus, while simultaneously contributing an essential source of carbon for growth and activity of soil organisms. The interdependence of many soil physical and chemical processes contributing to soil health is strongly linked to activities of the organisms living in soil as well as to root structure and function. Capitalizing on these contributions to soil health cannot be achieved without holistic, multiscale approaches to nutrient management, an understanding of interactions between carbon pools, mineral complexes and soil mineralogy, and detailed examination of farm nutrient budgets.

Keywords: soil biological fertility, mineral nutrient sources, organic matter, soil biodiversity, local knowledge

1. Introduction

Organic agricultural practices are underpinned by soil biological processes that are influential in the supply of nutrients to plants as well as to the creation of beneficial soil structural conditions for plant growth (Mader et al., 2002; Bhadauria & Sazena, 2010). Both bio-physical and bio-chemical processes are central to the effectiveness of organic productive systems (Gomiero et al., 2011). Provision of an adequate supply of nutrients in certified organic farming systems can be challenging if they depend on sources of low solubility (Quilty & Cattle, 2011). Furthermore, the avoidance of loss of nutients into the surrounding environment, including loss to groundwater, is also a high priority for organic systems (Askegaard et al., 2011). The effectiveness of use of nutrients in organic farming systems depends on the rate of cycling of nutrients from both organic matter and allowable minerals, which differ in magnitude according to the soil's inherent fertility (Heitkamop et al., 2011) and mineralogical composition (van Straaten, 2002). Globally, soils used for organic agriculture range from deep, highly fertile soils to shallow, highly weathered and nutrient depleted soils (Chivenge et al., 2011). The nutrient amendments required in organic agriculture therefore vary considerably depending on the local soil and environmental conditions, and potential level of productivity at the location of the farm (French & Schultz, 1984).

1.1 Soil Biological Fertility

A major component of soil fertility in organic farming systems depends on biological processes that sit within the framework of organic certification (Fließbach et al., 2007). Soil biological fertility has been defined as "*the capacity of organisms living in soil (microorganisms, fauna and roots) to contribute to the nutritional requirements of plants and foraging animals for productivity, reproduction and quality (considered in terms of* *human and animal wellbeing) while maintaining biological processes that contribute positively to the physical and chemical state of soil*." (Abbott & Murphy, 2003). Organic certification emphasises agricultural management practices that support soil biological processes (Gomiero et al., 2011) contributing significantly to the nutritional status of soil. Supplying adequate levels of nutrients for plant growth in organic systems is complex where it depends on soil processes for nutrient release. Excessive nutrient concentrations in the soil solution can arise if high quantities of manure are added to soil (Foissy et al., 2013). Therefore, this needs to be managed carefully to avoid nutrient loss. Although soil structure is largely dependent on the parent material, enhancement of biological processes can improve soil aggregation (Pulleman et al., 2005; Six et al., 2004), access to water (Augé, 2001), and reduce hard setting when combined with an appropriate quantity of organic matter (Djajadi et al., 2012).

Agricultural practices such as tillage, crop rotation and organic amendments significantly influence soil chemical and physical fertility (Birkhofer et al., 2008). They alter the rate of release of nutrients for plant uptake and growth of roots leading to both direct and indirect effects on plant production and delivery of ecosystem services (Sandhu et al., 2010). Tillage can hasten soil structure deline (Conceicao et al., 2013) but it is difficult to avoid in organic systems although no-till organic options are being explored (Carr et al., 2011). There is evidence that negative effects of tillage on some beneficial biological processes such as the accumulation of soil microbial biomass, may be less marked in tilled organic sytems compared with conventionally tilled systems (Larsen et al., 2014).

In agricultural systems where large quantities of relatively soluble synthetic fertilisers are used, some soil biological processes (such as nitrogen fixation and colonisation of roots by arbuscular mycorrhizal fungi) can be over-ridden, and their contributions may not be fully realised for agricultural production (Richardson et al., 2011) or efficient resource use (Rice et al., 2002). On the other hand, the slow rate of release of nutrients from recalcitrant sources of minerals (Manning, 2008, 2010) or from plant residues (Damon et al., 2014) may restrict plant production in organic systems compared with conventional agricutural systems. While this is commonly viewed as a deficiency of organic systems, alignment of productivity at a particular site to that which is sustainable in the longer term, based on lower risk potential (Tiedemann & Latacz-Lohmann, 2013) is fundamental to organic agriculture. In some environments, organic production may lead to 'mining' or reduction of existing nutrient resources (Romanya & Rovira, 2009), some of which may have been added to soil prior to organic certification. Soil fertility in organic farming systems is complex, and needs to be considered locally according to (i) existing and previous soil conditions, (ii) environmental conditions, including environmental change, (iii) plant requirements at different stages of their growth cycles, (iv) quantify of nutrients removed in grain or consumption of forage, (v) rotational sequences, (vi) soil disturbance, and (vi) economic models employed by the farmer.

1.2 Soil Biodiversity

Soil biodiversity is important in effective management of organic farming systems for chemical and physical fertility. Soil organisms need to be managed to ensure they contribute at optimal levels within and between seasons. For many soil organisms, their collective contributions depend on the form and quantity of organic matter in the soil and on environmental conditions that occur at the scale of soil aggregates, roots and soil pores (Rillig & Mummey, 2006). For other organisms, such as those that are involved in nitrification (de Gannes et al., 2014), indirect relationships with mineralisation of organic matter can influence nitrogen cycling, including nitrogen loss. They may be significantly influenced by soil chemical conditions such as pH (Bramley and White 1990) and soil physical conditions such as compaction and water-logging (Engelaar et al., 2000).

The diversity of soil organisms varies within and among soils managed according to the guidelines of organic certification (Hartmann et al., 2014). Furthermore, there are dynamics in activity and relative abundance of soil organisms in response to availability of substrate or following nutrient application. The extreme diversity of soil organisms builds redundancy in function (Wolters, 2001; Chaer et al., 2009). Long-term reduction in organic inputs into soil can reduce the capacity of the community to mineralise some recalcitrant organic carbon fractions in soil (Paterson et al., 2011) and harsh conditions can minimise some functions (Liebich et al., 2007). It is likely that there are threshold levels of relative abundance and/or diversity for optimal function for some communities of soil organisms (Philippot et al., 2014). Soil biodiversity varies according to soil type, location and management practices (Paterson et al., 2011). However, the potential impact of changes in diversity, dominance and abundance of communities of soil organisms may or may not affect soil conditions for plant growth.

In addition to differences in the diversity, relative abundance and biomass of organisms in soil, there are considerable differences in their function (McGuire & Treseder, 2010). It is not easy to equate diversity patterns of soil microbial communities, levels of microbial biomass, or levels of soil microbial respiration to 'ideal' soil conditions for their growth because temporal dynamics in suitable carbon substrate (Hoyle & Murphy, 2011) or water deficit (Kakumanu & Williams, 2014) can influence their abundance and activity. Most organisms go through periods of inactivity because local conditions are temporarily unsuitable (Bardgett, 2002). There is evidence of increased diversity of some groups of soil organisms with conversion to organic farming practices. For example, the diversity of arbuscular mycorrhizal fungi was higher in organic fields, and similar to that of natural grassland, compared with conventional agricultural mangement (Verbruggen et al., 2010). In a comprehensive comparison of soil microbial diversity in the long term DOK Trial in Switzerland, diversity of both soil bacteria and fungi were markedly affected by organic farming practices (Hartmann et al., 2014). Five farming systems were examined, three of which had organic management. Application of nutrients had a larger impact on soil microbial communities compared with plant protection practices used. There were distinct microbial communities in the different farming systems and these differences were less affected by spatial heterogeneity or temporal change. The higher resolution of microbial communities identified in this study compared with previous studies at the same site showed that, most likely the application of farm yard manure had a significant influence on microbial community structure (Hartmann et al., 2014). The differences between microbial communities in the organic and conventionally managed land in this study were largely attributed to the form and amount of organic fertiliser. Hartmann et al. (2014) noted that despite the higher diversity of bacteria and fungi in organically managed soil, the functional significance of this finding is not well understood. In this case, the higher diversity was closely associated with application of organic fertiliser, rather than other organic practices such as integrated pest management. Differences in tillage practice were not specifically investigated here, but they could also be expected to have significant effects on microbial community structure in organic farming systems (Yang et al., 2013).

Levels of soil microbial biomass and gas fluxes in organic farming systems can be higher than in conventional systems and are commonly linked to levels of organic matter (Chirinda et al., 2010). However, soils differ widely in their potential to protect organic matter from mineralisation (Zimmermann et al., 2012). This in turn relects on differences in microbial activity associated with mineralisation. Therefore, although the level of microbial activity in soil may be higher in organic than in conventionally managed farming systems (Gunapala & Scow, 1998), it may not be indicative of plant productivity because many factors combine to define achievable levels of plant yield. On the other hand, higher microbial activity may contribute to greater loss of nutrients from soil for some combinations of organic management practices, including use of cover crops and tillage.

Differences in clay, loam or sand content of soil influence thresholds for 'ideal' levels of microbial biomass but benchmarks also depend on local conditions. A sandy soil may temporarily be highly biologically active leading to rapid depletion of organic matter because the organic resources are not well protected in soils with low structural stability. In constrast, a more clayey soil may display less marked peaks and troughs in microbial respiration than a sandy soil in response to mineralisation of organic matter because of its higher structural stability and greater capacity to protect organic matter (Djajadi et al., 2012). Overall, 'effective biological functioning' of soils under organic management differs widely according to soil type and location in the landscape, plant production practices, irrigation practices and nutrient inputs (Chirinda et al., 2010). Local benchmarking according to soil type, management practice and environmental condition is necessary because of the complexity of relationships between microbial activity, microbial diversity and plant response.

1.3 Bio-Physical and Bio-Chemical Processes

Bio-physical processes underlie structural configurations in soil and influence soil aggregation (Rillig & Mummey, 2006), mineral dissolution (DeJong et al., 2013), water and nutrient access by roots (Dunbabin et al. 2002), and resilience to intermittent drought stress (Thierfelder & Wall, 2010). Furthermore, these processes occur in the same or overlapping timeframes and some organisms may simulteously be involved in more than one process (Moore, 1994). Soil organisms involved in biological perturbation contribute to mineralisation of organic matter, while soil enzymes may be involved in mineralisation of organic matter or dissolution of geological minerals (Burns et al., 2013). Soil amendment with manure, commonly used in some but not all organic agricultural systems, alters both the soil physical and chemical environment. This has flow-on effects to biological processes in soil, and complex bio-physical and bio-chemical processes are also involved (Rillig & Mummey, 2006; Six et al., 2004). Arbuscular mycorrhizal fungi (Cavagnaro et al., 2012) are examples of a community of soil organisms that cross boundaries of chemical and physical fertility by contributing to nutrient use efficiency, soil structural development, access to water, and resistance to plant disease. Some of the bacteria and fungi involved in nutrient cycling also contribute to stabilising soil aggregates (Six et al., 2004). It is difficult to quanitify biological contributions to each of these process separately, and to identify their specific economic value (Abbott & Lumley, 2014).

Organic management practices seek to maximise contributions from specific groups of soil organisms such as those involved in symbiotic nitrogen fixation, microbial facilitation of nutrient uptake at root surfaces (Verbruggen et al., 2010), and disease suppression (Benitez et al., 2007). These functions are all influenced by the physical and chemical characteristics of soil to some extent. Earthworms have particularly important roles in altering soil structure (Versteegh et al., 2014) as well as in nutrient cycling, and while their contributions may be enhanced in organically managed systems, other considerations such as the length of time in pasture or cropping can override effects of organic compared with conventional management practices on their abundance (Pulleman et al., 2005). Selectivity in incorporation of organic matter into soil by earthworms further highlights the complexity of interactions between mineralisation and soil structural contributions of earthworms in organic farming systems (Pulleman et al., 2005). Organic practices can foster contributions of both mesofauna and macrofauna to soil ecosystem functioning (Dominguez et al., 2014). Furthermore, the abundance and diversity of larger soil fauna may be less influenced by organic farming practices than by conventional management practices based on observations of species richness (Postma-Blaaaw et al., 2010). In organic systems, effective functioning of soil communities may reduce disease risk associated with increased suppressiveness of soils (Yogef et al., 2011). Plant health is a complex issue (Doring et al., 2011), especially in the context of organic farming because the emphasis is not on completely eradicating pathogens or pests; maintaining soil ecosystem function is of high priority for building resilience against the development of disease or damage caused by pests.

2. Certification Requirements Define Nutrient Inputs

2.1 Examples of Allowable Mineral Sources of Nutrients

Certification requirements define allowable nutrient sources for use in organic farming systems, and include poorly soluble forms of minerals, including rock phosphate, dolomite, lime and milled silicate rocks (‘rock dust’) as well as a range of sources of organic matter including compost. Certification requirements restrict use of the most soluble forms of both phosphorus and potassium (permitting mined potash salts according to circumstances), so alternative sources need to be used. Allowable sources of phosphorus differ in solubility over time and in relation to soil pH (Manning, 2008). Other allowable rock-based nutrient sources, including feldspars, feldspathoids and micas, can provide a range of elements such as potassium, calcium, sodium and silica, with traces of other elements, but all are low in solubility (Harley & Gilkes, 2000). Potassium can be supplied from potassium silicate minerals containing feldspar, nepheline and mica (Manning, 2012). It is released during weathering of the rock-forming minerals, especially micas (Mohammed et al., 2014). Weathering processes are slow but depending on climate and soil properties, the quantities required for plant growth may be delivered during the season. Additionally, micas and clay minerals influence cation exchange reactions (Manning, 2012).

The rate of release of nutrients from mineral resources depends on the mineral crystal structure as well as the concentration of nutrient, and the rate of release may be increased through involvement of microorganisms by addition of composted organic matter (Manning et al., 2013). Clay minerals can form complex associations with organic matter that can influence its stability (Jundaluang et al., 2013). Humus adsorbed on clay minerals can affect the rate of release of potassium and silica when exposed to organic acids (Datta et al., 2009). For humus-depleted clay, an initial release of potassium triggered further release of potassium (Datta et al., 2009). This study showed that clay-humus complexes can restrict the release of potassium. However, there is also potential for microbial processes to increase mineral dissolution (DeJong et al., 2013).

It has been shown that individual minerals in close proximity on rock surfaces exposed to the environment can have distinctive bacterial communities (Hutchens et al., 2010). Specific bacterial isolates were found on feldspar, quartz and muscovite in the rocks studied. Fungal communities tended not to display the same level of specificity as bacterial communities (Gleeson et al., 2010). While these studies have been conducted on exposed rock surfaces, different forms of minerals were shown to influence microbial community structure when they are introduced into soil (Carson et al., 2009). In this study, mica, basalt and rock phosphate were incubated separately in soil with or without a legume. Bacterial communities on individual mineral fragments differed from those in the surrounding soil. Thus, addition of poorly soluble minerals to soil could create microhabitats and contribute to spatial variation in bacterial communities (Carson et al., 2009); this in turn may support highly diverse microbial communities in organic farming systems with specific rock-mineralising capabilities.

2.2 Examples of Sources of Nutrients From Organic Matter

Organic matter is the primary source of many nutrients in organic farming systems (Heitkamop et al., 2011). Retention of organic matter is essential for good management and provides other benefits to soil conditions for plant growth. Microbial processes are involved in effective recovery of nutrients from manure and composted organic matter resulting in the release of essential plant nutrients during interactions with soil fauna, including earthworms (Bhadauria & Sazena, 2010). Higher levels of microbial activity in soil under organic managment may not necessarily lead to increased access to stable forms of phosphorus in organic matter (Keller et al., 2012). Re-use of organic 'wastes' (e.g. manure), when permitted by organic cerification, can contribute valuable sources of nutrients in organic farming systems (Heitkamop et al., 2011; Fließbach et al., 2007). Combinations of composted organic matter and clay-based minerals can increase the rate of release of nutrients from rock minerals (Manning et al., 2013).

Stable isotope tracing is used to identify relationships between the nitrogen, phosphorus and carbon cycles in soil by tracking nutrients through the complex pathways (Dungait et al., 2012a). Near edge X-ray fine structure spectroscopy and scanning transmission X-ray microscopy have potential to provide new opportunities for three-dimensional investigation of molecules in soil (Schmidt et al., 2011). There are also opportunities for clarification of "recalcitrant" vs "protected" organic matter (Dungait et al., 2012b), and for identifying the roles of different microbial communities in connected and disconnected soil pores (Carson et al., 2010).

3. Delivery of Ecosystem Services in Organic Farming Systems

Organic farming systems have potential to deliver a wide range of ecosystem services associated with soil health if they (i) increase efficiency in use of nutrients from less soluble sources (Manning, 2012), (ii) minimise loss of nutrients to ground and surface water bodies (Ekholm et al., 2005), (iii) release nutrients according to plant requirement (Damon et al., 2014), (iv) budget for replacement of nutrients according to their removal (Dalgaard et al., 2002), (v) reduce the susceptibility of plants to disease (Postma et al., 2008), (vi) reduce erosion by minimising tillage (Peigné et al., 2014), and (vii) increase access to water during periods of low-rainfall (Thierfelder & Wall, 2010). Use of comprehensive whole-farm nutrient budgets (Dalgaard et al., 2002) increases the likelihood of maximising nutrient use efficiency. Successful delivery of ecosystem services attributed to organic management may be constrained by environmental conditions and soil type (including inherent levels of soil fertility based on the source of parent rock).

Interestingly, Adl et al. (2011) concluded that the conventional agricultural practice of using pesticides can provide benefits to organic systems if they lower the threshold of disease locally. For example, if the ratio of the area of organic to adjacent conventional farmland is kept below a threshold level, the pest population can remain low. If the area ratio exceeds the threshold, the pest population can increase in the organically managed area, increasing risk to the conventionally managed area. In this case, the area under organic agriculture could be a pest reservoir.

Organic agricultural practices related to soil health provide a model for addressing the challenging issue of maximizing beneficial soil biological processes in agriculture generally, not just in organic systems. Local conditions will constrain the extent to which biological processes can proceed effectively. Furthermore, the biological status of soil is dynamic, and differs in magnitude according to season, soil type and management history (Zelenev et al., 2006; Hoyle & Murphy, 2011; Le Guillou et al., 2012). Benchmarks are not easily attained for any of the soil parameters that could be measured because of this variability. An important aspect of organic systems is the simultaneous focus on phosphorus as well as nitrogen cycles, in contrast to many current conventional practices, but attention also needs to focus on potassium. Finally, organic systems are practiced on soils that vary widely in structure and inherent fertility, and they differ in their exposure to climatic and environmental conditions. Therefore, caution is required in generalising about issues related to soil health in organic farming systems because on-farm management efficiency differs. Nevertheless, there is a continual requirement to minimise detrimental environmental impacts, maximize nutrient use efficency, re-use waste, and manage the soil for sustainable agricultural production.

4. Conclusion

Organic farming practices have the potential to contribute significantly to ecosystem services in a number of ways. The health of soil is dependent upon complex bio-physical and bio-chemical processes which interact in space and time, and if they are managed effectively, they can make efficient use of nutrient resources and water for agricultural production. In doing so, loss of nutrients to surrounding land or water bodies or in wind erosion can be minimised. The availability of sources of phosphorus and potassium remain a significant issue for organic farms because of the requirement to use poorly soluble sources of these essential nutrients. Recent advances in microbial metagenomics and 3-D visualisation of the finest components of organic matter should lead to advances in understanding of processes that underpin transformations that support organic management. The interdependence of many soil physical and chemical processes that contribute to soil health is strongly linked to activities of organisms that live in soil as well as to root structure and function. An integrated approach is required to capitalize on these contributions to soil health and associated ecosystem services.

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Eco-functional Intensification and Food Security: Synergy or Compromise?

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Abstract

There is an increased understanding that the challenges of producing enough food and biomass while preserving soil, water and biodiversity necessary for ecosystem services can not be solved by prevalent types of conventional agriculture and that agro-ecological approaches and ecological intensification is fundamental for our future food production. FAO has stated that "Ecosystem services sustain agricultural productivity and resilience" and advocates production intensification through ecosystem management. Terminologies such as agro-ecology and ecological/ eco-functional/sustainable intensification are being proposed for agricultural development, which builds on higher input of knowledge, observation skills and management and improved use of agro-ecological methods. Contrary, increased global demand for food, and non-food biomass has increased the pressure for intensifying land use and increasing crop yields based on conventional inputs, while still aiming at reducing environmental impact. There is a battle of discourse between these approaches in competition for – among others – research and development funding. The examples of improved local food security from introducing agro-ecological and low external input agriculture practices among smallholder farmers are many. However, upscaling remains a challenge and the ability of such eco-functional intensification to feed the increased urban populations in emerging economies remains an open question. A broader view of what is organic and conventional farming is necessary and the use of new understandings from ecology and molecular biology will be needed to create and profit from synergies between preserving and building on eco-systems services and providing increased food and biomass.

Keywords: global food security, organic, agroecology, sustainable intensification

1. Introduction/Background

There is an increased understanding that the challenges of producing enough food and biomass while preserving soil, water and biodiversity necessary for ecosystem services cannot be solved by prevalent types of conventional agriculture and that agro-ecological approaches and ecological intensification is fundamental for our future food production. FAO has stated that "Ecosystem services sustain agricultural productivity and resilience" and advocates production intensification through ecosystem management. Terminologies such as agro-ecology, ecological, or eco-functional or sustainable intensification are being proposed for agricultural development, which builds on higher input of knowledge, observation skills and management and improved use of agro-ecological methods. Contrary, increased global demand for food, and non-food biomass has increased the pressure for intensifying land use and increasing crop yields based on conventional inputs, while still aiming at reducing environmental impact. There is a battle of discourse between these different approaches in competition for – among others – research and development funding.

The aim of this paper is to assess under which conditions and to what degree organic and agroecological approaches may be valuable pathways for improving food security in short and long term perspectives, respectively.

2. The Food Security Challenge: Trends and Competing Discourses

According to FAO there is a need to increase global agricultural output by 60% between 2010 and 2050 and the major part of this increase in agricultural output should come from developing countries, where agricultural biomass production should be doubled over the period (Alexandratos & Bruinsma, 2012). Tilman et al. (2011) found that extrapolating historical relations between per capita GDP and crop demand for feed and food to 2050 would result in a doubling of the need for crop calories and protein compared to 2005. This estimate was based on UN projections of population growth and on assumptions of average GDP per capita growth of app. 2.5% per year with higher rates for developing countries. Tilman et al. (2011) thus considered diet changes as extrinsic to developments of agriculture and population pressure and did not include options for reducing livestock food intake by high income consumers or options for reducing food waste (Smith, 2013). An important part of this challenge is linked to the increasing demand for livestock products and increasing use of crops for non-food purposes such as biofuels. Cassidy et al. (2013) estimated that 36 and 53% of crop yields measured in calories and protein, respectively were used as livestock feed around the year 2000. This proportion is growing and so is the proportion of biofuel crops, where the ethanol production in US and Brazil accounted for 4% of global calorie production in 2010.

Harwey and Pilgrim (2010) analysed the drivers for increased competition for land arising from the combination of increased food needs towards 2050 and increased demand for biomass to replace petrochemical products and concludes that the combined challenges of delivering both increased food and biomass while mitigating agriculture's contribution to climate change and other environmental impacts calls for a "long term political strategy driving forward the shift to a sustainable intensification of land use". Using the data from app. year 2000 in average 6 persons were fed per hectare of cropland which is a combination of yields, losses and feeding crops to livestock (Cassidy et al., 2013). This differs greatly from region to region. Theoretically, by reducing the proportion allocated to livestock feed and biofuels the global average could rise up to between 8-10 persons fed per hectare, with up to 16 person per ha in the US using the current crop yields.

As discussed in Halberg (2009) the food security challenge is aggravated by current non-sustainable trends in terms of undermining agricultural systems' functional integrity and the natural capital necessary for ecosystems services in general. Eco-systems services, which are important for agriculture and for other societal purposes are undermined by some agricultural practices due to wrong use of fertilizers and pesticides and lack of proper soil protection and soil fertility building (Lal, 2009; Nelleman et al., 2009; Beddington et al., 2011; Gomiero et al., 2011). The climate change represents yet another challenge for the improved food security currently and even more so in the perspective of the crop needs towards 2050 (Wheeler & Braun, 2013; Porter et al., 2014). All aspects of food security are potentially affected by climate change, including food access, utilization and price stability. The triple challenge of increasing food and biomass production while adapting to climate change and at the same time reducing the negative impacts on natural capital and environment is addressed under different discourses, which however partly use overlapping terms (Halberg, 2009). The terms and ideas of Ecological (Cassman, 2008; Bommarco et al., 2013; Tittonel, 2014) or eco-functional intensification (Niggli et al., 2008), sustainable intensification (Pretty & Bharucha, 2014; Garnett et al., 2013; Buckwell et al., 2014), climate smart agriculture (Lipper et al., 2014), organic agriculture (Halberg, 2009) and agro-ecology (Wezel, 2009; Altieri et al., 2012) may be seen as different discourses competing for hegemony (Howarth, 2010; Unger, 2012) in terms of defining the "right" development pathway for agriculture and thus gain political and economic support (development funding, research and innovation funding, subsidies, ..).

The term *sustainable intensification* (SI) is defined by FAO (2011) as a productive agriculture that conserves and enhances natural resources. It uses an ecosystem approach that draws on nature's contribution to crop growth and enhances soil organic matter, water flow regulation, pollination and natural predation of pests and applies appropriate external inputs at the right time, in the right amount. This approach according to FAO represents a major shift from the homogeneous model of crop production to knowledge-intensive, often location-specific, farming systems. Garnett et al. (2013) discuss four premises underlying the concept of SI and remarks that while an overall increase in food production is needed it should go hand in hand with reducing food waste and moderating demand for resource intensive livestock food products. Overall food production should be increased while reducing environmental impact and reflecting different balances in different contexts. This is in accordance with Buckwell et al. (2014), who moreover suggest that SI, especially in Europe, is not primarily about the use of more fertilizers, pesticides and machinery applied per hectare, but the development of much more knowledge intensive management including of the ecosystems services on which agriculture relies. They propose "more knowledge per hectare" as a shorthand for SI. While most discourses agree to this goal they differ in the assessment of the necessity of increasing external inputs and the most pertinent ones e.g. fertilisers, pesticides, seeds, ICT, … (Gianess, 2013; Pretty & Bharucha, 2014; Curtis & Halford, 2014).

Bommarco et al. (2013), defines *Ecological intensification* (EI) as an approach to agriculture which aims at integrating ecosystems services from managing biodiversity in crop production systems in order to secure and augment yields with low negative environmental impact (see also Kremen & Miles, 2012). Thus, these approaches differ from the wider definitions of SI and are more in line with the agroecology movement of especially Latin America (Altieri et al., 2012; De Abreu & Bellon, 2013) and with principles of organic agriculture.

Agroecology has several meanings as reviewed by Wezel et al. (2009) ranging from a scientific discipline which applies principles from ecology in the study of agricultural systems (a field, a farm, landscape, …) to a comprehensive action oriented and partly normative framework for development of a certain type of farming systems and to a movement of farmers and stakeholders applying these principles for the livelihood improvement of smallholder farmers (Altieri, 2002; Vandermeer & Perfecto; 2013; De Abreau & Bellon, 2013).

The East African standard for *Organic Agriculture* (OA) states that 1) Organic agriculture is a holistic production management system, which promotes and enhances agroecosystem health, including bio-diversity, biological cycles and soil biological activity, 2) It seeks to minimise the use of external inputs, avoiding the use of synthetic drugs, fertilizers and pesticides and aims at optimising the health and productivity of interdependent communities of soil life, plants, animals and people and 3) It builds on East Africa's rich heritage of indigenous knowledge combined with modern science, technologies and practices (East African Community, 2007). The regulation of organic agriculture of the European Union states as objectives for OA to respect nature's systems and cycles and sustain and enhance the health of soil, water, plants and animals and the balance between them; to contribute to a high level of biological diversity and to make responsible use of energy and the natural resources, such as water, soil, organic matter and air [European Commission (EC), 2007]. The Canadian organic regulation defines OA in a similar way and also emphasizes the main role of maintaining and benefitting from above and below ground biodiversity (Canadian General Standards Board, 2006).

Thus, Agro-ecological and organic agriculture aims at protecting and benefitting from ecosystems services by renewing and maintaining critical natural capital as a basis for agricultural production. Ideas of Intensification of organic agriculture builds on principles of recycling of organic matter and nutrients at field, farm and landscape levels and benefitting from sustaining biodiversity. The term "*eco-functional intensification*", was introduced in a research strategy for the improvement of organic agriculture in Europe: Intensification of land use and agriculture by means of improved knowledge and application of biological principles and agro-ecological methods and increased cooperation and synergy between different components of agro-eco systems and food systems (Niggli et al., 2008). While this overlaps with objectives stated in the broader definitions of SI and in some approaches to "climate smart agriculture" (Lipper et al., 2014) the deliberate minimal use of external chemically based inputs in agroecology and organic farming ideally enhances the focus on eco-functional intensification strategies.

Several of the mentioned discourses and schools of thought regarding the future of agriculture have their merit under different natural and sociocultural conditions and most likely organic/agroecological based systems will co-exist with different (improved) conventional systems and they will co-develop over the next decades. In the following we will focus on the perspectives of organic and agroecological practices for improving current food security and for securing and maintaining food security in a long term perspective and the challenges these systems face.

3. Yields in OA and potential for Eco-Functional Intensification

A wide number of comparisons of organic vs conventional crop yields have been produced over the last four decades based on long terms trials and on recorded yields in private farms. De Ponti et al. (2012) analysed 362 paired sets of organic-conventional yield data covering 67 crops from 43 countries and reported that on average organic yields are 80 % of those obtained under conventional agriculture. They also stated that relative yield differ across the region of the world; lowest in Northern Europe (70%) and highest in Asia (89%), relative yields differed between crops with soybean, some other pulses, rice and corn scoring higher than 80% and wheat, barley and potato scoring lower than 80%. Te Pas and Rees (2014) found on average 26% higher yields in organic farming in a review of organic vs conventional comparison studies specifically from Tropics and sub-tropics and with the largest yield difference in least developed countries and dry growing conditions.

In the largest and most recent meta-analysis of organic vs conventional yield comparisons Ponisio et al. (2014) found that across 1071 observations from a total of 115 comparison studies the organic yields were 15.5-22.9%

lower than conventional (95% interval and average 19.2%). Contrary to earlier studies they did not find significant differences in the yield gap for certain crops such as leguminous crops but for the categories perennials and roots/tubers, the variation in yield difference was larger than for annual crops as a whole. Similarly, this study did not demonstrate significant effects of nitrogen or phosphorus levels on the yield comparison. However, the results did show that yields in more diversified organic cropping systems with either diverse crop rotations or multi-cropping were only 9% and 8% lower on average, respectively when compared to conventional monocultures. Whether this is a relevant comparison depends on whether one considers organic crop production to be more diversified at field and farm level as a systemic function. In any case it demonstrates a yield potential of diversification practices which is an inherent principle of agroecology and organic agriculture and thus is part of eco-functional intensification strategies.

Critics of organic agriculture find that yields are too low and that options for improving total yields without being indirectly or directly dependent on conventional farming are limited (Kirchmann et al., 2008; Connor, 2008). Kirchmann et al. (2008) states that organic manure would not be available in sufficient amounts to allow a significant upscaling of organic agriculture with yields comparable to conventional. Therefore, organic crop rotations need to include green manure and if these crops are not harvested for feed then the total crop yield calculated from organic rotations should be discounted for the years with no crop export from the fields. On the other hand, organic systems with ruminants which may utilize large proportions of grass-clover or other leguminous forage crops often have sufficient and continuous N inputs to the soils which again may supply other crops with Nitrogen if grown in a rotation (Halberg et al., 1995; Kirchman et al., 2008).

Kremen and Miles (2012) presents evidence of significant advantages of biologically diversified farming systems in terms of biological regulation of agricultural pests (insects, weeds and diseases including soil pathogens), pollination and soil quality maintenance and water holding capacity. This enhances resilience and reduces the negative impact of farming on important ecosystems services. However, the degree to which this also supports high and increasing yields is less clear and is context dependent. Kremen and Miles mostly use organic vs conventional comparisons to discuss the yield potential of biologically diversified farming but stress that this is an insufficient test since most organic systems set up in comparison trials do not include intercropping or other diversification strategies. Moreover, there is a lack of yield assessments which go beyond single crops and integrate the total edible output harvested from diversified agriculture systems.

The potential of agroecological practices for improving and sustaining yields is better documented in tropical agricultural systems than in high input systems in temperate regions (Perfecto et al., 2009; Altieri et al., 2012). Examples include the Push Pull system of intercropping maize for the control of stem borer and Striga, which has proven higher yields than conventional maize growing in large parts of East Africa (Khan et al., 2011). Agroforestry systems where trees supply nutrients for annual crops through leaves incorporated into soils ("fertiliser trees") have proven to support yields of maize comparable to high fertilizer supply (Garrity et al., 2010; Akinnefesi et al., 2010). Akinnefesi et al. (2010) reports that when the fertiliser trees are used in combination with 50% additional kilograms of N and P fertiliser, Maize yields were higher than when using fertiliser alone. Moreover, fertiliser trees can reduce weed problems and improve soil properties such as water uptake and P-supply. A few examples of agroforestry and other types of intercropping in Europe demonstrates potential for improved total yield and resource use, which however is not widely used in practice (Malézieux et al., 2009).

Most of the options and practices described in the previous paragraphs would be in accordance with the principles of organic farming and agroecology. In conclusion, there is evidence of well-functioning organic and agroecological farming systems with yields comparable to conventional or with relatively small yield differences. On the other hand, in high input areas yield differences can be larger and strategies for EI needs to be significantly improved in light of the triple challenge (increased biomass demand, preservation of ecosystems services, climate change).

4. Short to Medium Term Perspective

The examples of improved local food security from introducing agro-ecological and low external input agriculture practices among smallholder farmers are many (FAO, 2013). In a widely cited study Pretty et al. (2006) collected and interpreted self-reported data from a large sample of 208 development projects in Africa and Asia. They documented success in increasing food production per hectare by 50-120 percent using a number of improvements and interventions which the authors classified in four strategies: A. Intensifying the "kitchengarden", B. Introduction of new elements in the farming system (e.g. fishponds or multipurpose trees), C. Better exploitation of soil, water and organic material (e.g. mulching), D. yield increase in staple foods (e.g.

pulses, better seeds). Altieri et al. (2012) report similar successes in improving yields and food security by development and utilization of agroecological practices in Cuba, Brazil and the Philippines.

While most – but not all - of the interventions described in the survey by Pretty et al. (2006) fall within the definitions of agroecology and organic agriculture few were certified organic schemes. The effects of increasing poor farmers' production capacity using organic agriculture and agroecological practices partly depends on whether a project aims at supplying *certified organic products* to a high value market or aims at increasing production and quality by *informal use of organic principles* and agroecological practices. While the certified approach often links smallholder farmers to a high value market and thus improves their income and livelihood including food security this type of project does not necessarily create holistic improvements in the overall farming system if the focus of intensification is limited to a single cash crop (Panneerselvam et al., 2013b). Also, the total effect of higher prices on cash crops from small areas can be modest (Pannerselvam et al., 2012; Ayuya et al., 2015). Contrary, projects like the majority of the cases in Pretty et al. (2006) which focus on agroecological methods, may be closer aligned with organic principles and express a holistic approach to integration of local and scientific knowledge for farm level intensification and building of natural, human and social capital (also called informal organic systems, Pannerselvam et al., 2013b).

In three linked case studies in India Panneerselvam et al. (2011) studied the impact of conversion to organic agriculture on the food security of small holding farmers in relation to market orientation and local conditions. The study found examples of both certified and informal organic agriculture with similar differences in the main effects. One case study in Madhya Pradesh (Central part of India) farmers were linked with a company focusing on introducing organic cotton production for export and farmers were trained by training institute, BioRe Association, in agroecological methods such as composting of local manure and growing pigeon peas as intercrops. Main results were that the families improved their food security mainly by the combined effects of reduced debts (due to the reduced need for borrowing cash at high interest rates for fertilizer and pesticides against the harvest sales) and increased self-sufficiency of protein food from the intercrops. Moreover, the price premium on organic cotton compensated for the lower yields. In two case studies the market orientation was less prominent due to NGOs promoting informal organic farming for improving the households' food security. In Tamil Nadu the local NGO Center for Indian Knowledge System (CIKS) provides training programs for organic farmers on soil conservation, vermicompost production, and managing pest and disease organically. CIKS facilitated farmers association for marketing the non-certified organic products with 10 percent price premium. The surveyed conventional farms in Tamil Nadu were high-input systems and the organic were in a conversion period, hence low yield was the biggest challenge for organic farmers. Nevertheless the study found that organic farmers improved their food and nutritional security by increasing net income (by 34% reduction in input costs) and increasing pulses production by 26% even though total farm production decreased by 5% (no price premium was incorporated in this estimation).

There is a need for more thorough and systematic investigations into the potential for EI or eco-functional intensification based on agroecological principles and practices in light of future increasing crop production and food needs (Malézieux et al., 2009; Doré et al., 2011; Caron et al., 2014; Maraux et al., 2013). The linkage between the following two approaches could be improved: One, a coordinated effort recording developments in crop and livestock production and food security across a wide set of development projects (NGO's, Governments, market driven) using mutually agreed standard recording and assessment methods at field, farm and landscape levels of scale (see also Shennan, 2008). Second, a set of coordinated research sites for testing of agroecological practices complemented with in-depth research into biological and bio-physical processes to support the interpretation of results in terms of yield trends, variation and resilience and the development in other ecosystems services related to changes in natural and human capital in the research site.

In conclusion, there is abundant evidence that food security may be improved in resource poor rural environments by agroecological and organic approaches where principles of eco-functional intensification are applied in participatory processes of co-development and learning to jointly build human, social and natural capital (Halberg & Muller, 2013). Two main questions remain, however. First, how to outscale these knowledge intensive methods and practices (which at the least requires significantly higher investments in agricultural research and development for EI) and second, whether eco-functional approaches to intensification will be sufficient for the further EI/SI in order to meet the growing food demands towards 2050? This is the focus of the next section.

5. Upscaling and the Long Term Perspective

Some examples exist of scenarios testing consequences for food security of upscaling of OA or agro-ecological farming to larger areas with or without considering population growth and/or diet changes.

Bagdley et al. (2007) modelled the effects of upscaling organic agriculture to global level based on a review of conventional to organic yield differences and assumptions regarding availability of organic manure in combination with legumes for Nitrogen fixation. They estimated that the global food production after conversion would be sufficient to cover current needs for calories and protein with 2600-2700 kcal per capita per day. And given optimistic assumption of doubling yields in developing countries after conversion to organic they estimated a food availability of 4800 kcal per capita and day. However, the assumptions made by Bagley et al. (2007) were disputed especially as concerns the high relative organic yields in developing countries (Kirchmann et al., 2008; Kremen & Miles, 2012) and the assumptions regarding availability and redistribution of Nitrogen from Biological Nitrogen Fixation (Connor, 2008).

The findings from three case studies in India cited above were used as a basis for testing food security consequences in scenarios for upscaling organic agriculture to large areas in Tamil Nadu. On a regional basis Panneerselvam et al. (2013a) assessed the economic situation of marginal and small farm types under a large-scale organic scenario and the consequences for regional food production in two states of India -Tamil Nadu and Madhya Pradesh. Marginal and small farms cultivates 3.4 million ha (60% of area of all farm types) in Tamil Nadu and 4.8 million ha (27% of area of all farm types) in Madhya Pradesh. Conversion of these farms into organic based on current relative organic yields would lead to lower food production at state level, 5% in Tamil Nadu (Figure 1a) and 3% in Madhya Pradesh (not shown) over baseline. However, conversion of rainfed areas exclusively was beneficial by producing 13 and 4% more food in Tamil Nadu (Figure 1a) and Madhya Pradesh (not shown), respectively, compared to their rainfed baseline, whereas conversion of irrigated areas exclusively had a negative impact on regional food production. Large-scale conversion of marginal and small farm types improved their income due to reduction in costs of production and price premium for organic products (Figure 1b). The Gross margin calculated as crop value (harvest yields times market prices) minus variable costs A was 26% higher in the organic scenario and was partly dependant on the organic price premium. However, the conventional farmers (baseline) have specific government support in terms of fertiliser subsidies, currently not available to organic farmers.

Modelling a situation where such subsidies were equalised between different types of fertiliser (chemical vs organic/green manure) demonstrated the potential for improving further the Gross Margin of organic farmers, which could be twice as high as in the baseline . Organic farms would have higher net income in the hypothetical situation of no fertilizer subsidy (Figure 1B, Gross Margin B), and this did not include the likely outcome of improved organic yields over current scenarios if fertiliser subsidies were diverted also to cover green manures. The large-scale organic scenario has potential to improve the food security by increasing the income and reducing the debt (80% of the food insecure people in India suffer mainly from low purchasing power), and would play a major role in improving their nutritional security (50% of Indians suffer from protein malnutrition) by producing more protein rich pulses by intercropping, mostly consumed locally. India has been a net exporter of cereals and a net importer of pulses, the traditional protein source. The scenario changed rural food production to a higher degree of protein self-sufficiency, but without improvement in organic yields this could induce a (limited) reduction in food calories, unless the organic yields were improved for example by diverting subsidies or include green manures.

The upscaling by Badgley et al. (2007) and Pannerselvam et al. (2013a) used current yields and yield differences and known crop cultivation technologies to assess food production and security. However, in forecasting the consequences of different agricultural development pathways towards the predicted growth in food needs it would be necessary to include other assumptions regarding technological improvement, knowledge uptake and thus possible yield gains through e.g. eco-functional intensification. However, in a long term perspective it is pertinent to consider how different forms of EI or SI may reverse this trend, improve agriculture's relation with other ecosystems services and at the same time be resilient to climate change.

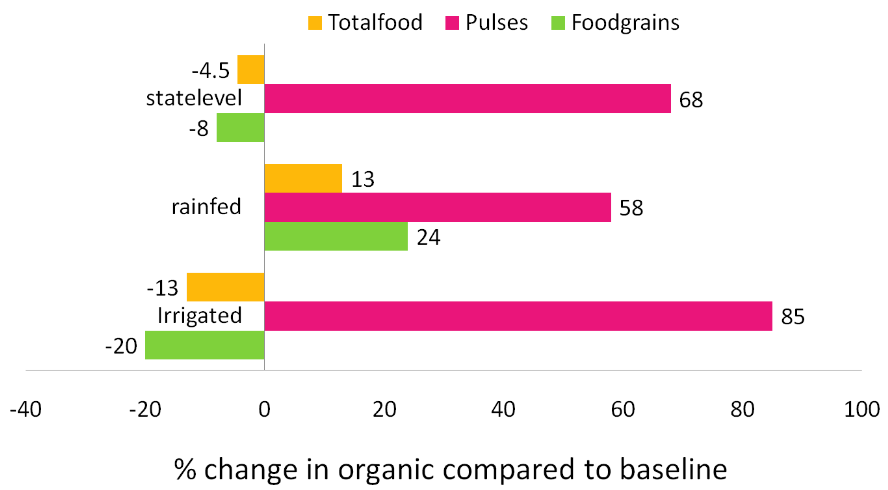

Figure 1a. Food production % change in Tamil Nadu

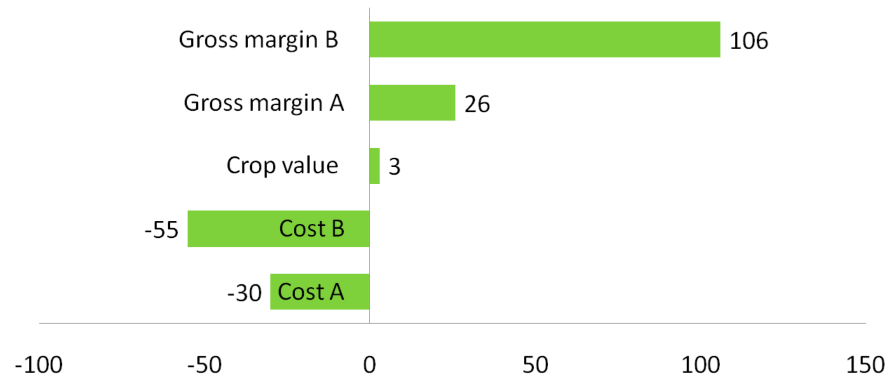

Figure 1b. Economic comparison % change in OA compared to baseline (Tamil Nadu)

Cost A = variable cost.

Cost B = Cost A+ cost of fertilizer subsidy (simulating "flexible subsidy").

Crop value = yield*market price+10 % premium for organic products.

Grossmargin A = Crop value – Cost A.

Grossmargin B = Crop value – Cost B.

A few macro level and global level scenarios have compared conventional intensification with eco-functional intensification and agro-ecological pathways. In the so called "Agrimonde study" Paillard et al. (2011) compared a business as usual scenario, relying on conventional agriculture, with an alternative scenario, relying on agroecological intensification (AEI). The Agrimonde AEI scenario shows that global food needs can be met even with low productivity increase assumptions, but partly because this alternative scenario also goes with more fundamental changes in animal production systems and in food consumption patterns. Thus, assumptions of reduced livestock based food in wealthier consumers' diets are intrinsic to this modelling. Therefore, the capacity of agroecological systems to produce enough food globally in 2050 still remains questionable in this scenario, due to the difficulty to change food consumption patterns over the same period, but such a scenario does not seem more questionable or less credible than the business as usual scenario. Common assumptions of the business as usual scenario can be considered as too optimistic, particularly with a very high level of increases of yields in regions where yields are already very high or even saturating, like in South and East Asia. This is also the case for North Africa and Sub-Sahara Africa, where the assumed yield increases seem very high compared to the potential very high impacts of climate change in these regions (Lipper et al., 2014; Porter et al., 2014). The business as usual scenario developed by Agrimonde with reference to the most common assumptions present in other scenarios from the literature therefore shows that conventional agriculture scenarios generally rely on very optimistic assumptions of technological progress in increasing yields, which seems very questionable in a context of degraded soils and increasing climate change.

On the other hand, the AEI scenario relied on very prudent, minimal assumptions of yield increases, taking into account potential extreme events due to climate change. In particular, based on more recent studies discussed here above, the productivity assumptions for agroecological systems in Africa could be made much higher in the agroecological scenario, showing a much better capacity of sub-Saharan Africa to feed itself, measured in terms of food availability for the continent. The improved access, stability or diversity in uses provided by agroecological systems then also adds to the conclusion of the Agrimonde study that agroecological innovation pathways can be a very good candidate for ensuring global food security in 2050.

The results of the Agrimonde scenarios converge with the study by Erb et al. (2009), where a variety of combinations of changes in food diets and in agricultural production systems was computed to test their capacity to rely on the cropping potential of the planet to feed humanity without damaging land to be preserved for biodiversity. This study develops scenarios where a convergence of diets towards the current western diet are not compatible with a conversion to an agroecological/organic pathway for agricultural systems, but a solution space does exist for an organic transition pathway if a lower consumption of animal products is assumed, and with an increase of cropped area of around 20% over the next 40 years. Such a scenario is questionable with regard to its consequences on biodiversity, through the expansion of cropped area it entails, but the FAO business as usual scenario also relies on increases in cropped area.

All these scenario exercises cannot represent, for the moment, the changes in supply chains, markets, linked to the diversification of crops in an agroecological scenario. They are therefore still weak in their capacity to discuss the feasibility and the performance of such a future development. The combination of different crops in the same rotation, on the same plot, or of different productions in the same production system is one of the key characteristics that make agroecological systems more resilient to climate or market shocks, more interesting in terms of nutrition, and also more productive than if measured only through the lens of the productivity of only one of the crops as discussed above. Including such a perspective in global modelling exercises is thus one of the key challenges for future research.

Kirchmann et al. (2008) considers current organic yield differences to conventional in the long term perspective and finds it unlikely that organic agriculture may feed the growing populations towards 2050 without drastic increases in cropped land, which they find unrealistic and problematic due to habitat loss and other environmental consequences. They do not, however, discuss options for increasing yield trends in organic agriculture or other means of limiting crop needs, such as diet changes or reduced waste. In this light, an important question is to what extent yields in organic agriculture may improve over the next decades, for example due to more research and innovation and better application of knowledge and good practices by farmers.

Halberg et al. (2006) used the “Impact” model to estimate the consequences of large scale conversion to OA in high input (Intensive) regions (Europe, North America (ENA)) and in low input regions (Sub-Saharan Africa (SSA)) under different assumptions of relative yield trends in organic and conventional crops towards 2020 compared with a baseline. Organic yields across 19 different crop commodities were estimated to be 60-100% of conventional yields in high input regions and 80-120% in low input regions. They tested different assumptions in separate model runs converting 50% of agriculture to organic in either high input regions or low input regions. An important assumption was the yearly yield growth rates from technological improvements in organic relative to baseline (conventional) yield gains over the 25 year modelling time span. Relative yield growth rates tested were 125, 150 and 200% higher yield growth rates in organic, Table 1. One assumption for this was that due to a previous lack of investment in research and development aimed at organic agriculture it would be possible to improve yields more in the future compared to conventional agriculture given the sufficient allocation of funding and resources. The Impact model uses this type of input to estimate yearly land allocation per crop/commodity type by region forming a global coverage and comparing this to regional and global food needs estimated from population numbers and economic indicators, for example purchasing power. The model was calibrated to the year 1995 and simulations of baseline scenario and organic scenarios were performed as a series of yearly simulations integrating assumptions, such as population growth, economic development and technological development by region. In each of five different scenario model runs only ENA or SSA was converted to 50% organic agriculture and for all scenarios the outcome was presented in the form of World prices for selected food crops, the economic food demand (not to be confused with food needs) in SSA and the resulting food security in

SSA, Table 1. Surplus and deficit of commodities were assumed to be traded between regions using purchasing power as an important driver, thus reflecting that food is traded globally. Therefore, reduced yields in ENA might increase global crop prices on the world market and potentially impact negatively on food security in poor regions (e.g. SSA) if there is not sufficient locally produced food. The results demonstrated that a large scale conversion of 50% of the land into organic agriculture in ENA would not impact the food security in SSA significantly (Table 1). However, the model also projected that economic demand for cereals and soybean, which are the main commodities traded globally, could be reduced in SSA as a consequence of higher world market prices. The reduced demand for cereals and soybean in SSA might result in small reductions in food availability (1-2% less kcal per capita) and subsequent increases in malnourished children (used as a proxy indicator for food security in the model). Increases in relative yield growth rate in organic crops in ENA resulted in lower impacts on world prices and food security in SSA (Table 1). The percent malnourished children are predicted to be slightly negatively influenced by higher world prices under these scenarios unless the organic yields grow more than conventional or food needs in SSA are better covered by increased local production and consumption of crops not included in the modelled commodities.

The two scenarios for conversion of 50% of SSA land to organic agriculture demonstrated a potential benefit if the yield growth rate was similar or slightly higher than the baseline (Table 1, right side). The baseline scenario projected an increase in imports of cereals to SSA because the expected conventional yield increases would not be sufficient for domestic food to compensate for population growth over the 25 years. This reduced self-reliance of food in SSA is a serious threat to food security because world market prices might become more volatile. This could be reversed in the organic scenarios for SSA, pointing to a higher degree of food security based on local food access. The assumptions of higher organic yields resulted in a lower projected import of cereals compared to baseline scenario, especially for the category "Other coarse grains" (millet, sorghum the local staple food in poorer regions) whereas the assumed lower organic yields in soy beans would lead to increased import needs (Table 1).

The Impact model was not entirely suitable for more in-depth studies of the consequences of organic agriculture or EI for food security because the commodities are treated separately and not as part of integrated farming systems and because synergies from, for example crop diversification and other agroecological practices, could only be simulated with rather coarse assumptions built into the factor for “relative yield growth rates”. On the other hand, the simulation exercise demonstrated the challenge of increasing the yields over time in organic agriculture for this to be a relevant strategy for EI and improving global food security in light of growth in populations and in economic prosperity. This is even more so, since the modelling did not account for the more recent knowledge of the possible impact of climate change and erosion of soil and ecosystems services on local food production in SSA or the impact of the growing allocation of crops for non-food purposes on global food prices.

As mentioned there are several discourses of agricultural development and linked with this also different opinions of the way to address changes in food demands. There is a difference between seeing the question of people’s diet choices as either extrinsic or intrinsic characteristics of food systems. Or put in simplistic terms: Should development ideas of future agriculture take the predicted increases in food consumption (especially of livestock products) for granted or should ideas of improved and changed diets and/or reduced waste be integrated in the agricultural development scenarios? Garnett et al. (2013) stress that the aim for sustainable intensification should not narrow dietary options, especially for poor consumers, by e.g. standardizing food choices to few high yielding commodities, which might risk aggravating micronutrient and protein deficiencies. Thus, SI farming strategies need to take nutrition into account and should also build on improved understanding of the role of wild food and indigenous crops in diets.

Table 1. Relative production after 50% conversion to organic farming in Europe and North America (ENA) and in Sub Saharan Africa (SSA) respectively for five separate model runs. Resulting world prices, and food demand in SSA modelled over a 25 year period. Results presented as percent of projected results of IFPRI's baseline scenario for 1995 (After Halberg et al., 2006)

Conversion Scenario	**ENA**	**ENA**	**ENA**	**SSA**	**SSA**
Relative Yield Growth Rate (% of baseline)	100	150	200	100	125
Production in region where conversion is modelled					
Wheat	92	95	97	89	92
Maize	90	92	94	105	108
Other Coarse Grain	92	95	97	106	109
Sweet Potato and yam				104	107
Cassava				105	105
Soybean	87	89	92	95	98
World Prices					
Wheat	111	107	103	100	100
Maize	112	109	106	99	98
Other Coarse Grain	113	109	105	98	96
Sweet Potato & Yam	114	110	106	96	94
Cassava	109	106	103	92	89
Soybean	108	106	104	100	100
Food Demand in SSA					
Wheat	94	96	98	100	100
Maize	97	97	98	100	100
Other Coarse Grain	96	97	98	101	101
Sweet Potato & Yam	100	100	100	100	100
Cassava	101	101	100	100	100
Soybean	95	95	96	100	100
Food Security in SSA					
Food Availability (Kcal/capita)	98	99	99	100	100
Total Malnourished Children	101	101	101	100	100
Net imports to SSA					
Wheat				100	100
Maize				98	97
Other Coarse Grain				90	84
Soybean				104	102

6. Conclusions

Eco-functional intensification for improved local food security has been documented in practice in poor rural regions and increasingly research is backing the development of agroecological methods for smallholder farmers in developing countries mainly in tropical areas. However, little documentation exists of the actual potential for upscaling to cover urban food demand now and in future. Foresight scenarios suggest that yields will have to be raised significantly in organic and similar agroecologically based farming systems for these to play an important role in satisfying the increasing crop needs towards 2050. The consequences of upscaling organic and agroecologically based farming based on eco-functional intensification in high intensive areas without changes in diets towards less animal products per capital are unclear. There is still a need for better foresights and scenarios for global and regional food security based on eco-functional intensification and development. Diet choice must necessarily be considered an endogenous factor in global food security scenarios. Moreover, for such scenarios to be useful more evidence based knowledge on the potential yield increments from eco-functional or Ecological intensification strategies is required.

The paradigms and research areas of agroecology, ecological and eco-functional intensification are promising in terms of building synergies between agriculture and other ecosystems services for improved yields, natural capital and resilience. Organic agriculture and the agroecology movement are the most prominent examples of ecological intensification strategies that have developed into sustainable systems based on low or no chemical inputs with lower but comparable yields to conventional agriculture. An increased effort of research and innovation in these systems using combinations of agronomy, biology and molecular sciences will most probably allow for improving yields of organic and agroecological farming while maintaining or improving sustainability and resilience. Part of this should be attempt at further "systems re-design" where agriculture would be adapted to a wider landscape approach using insights from biodiversity and agroforestry and coordinated land use for purposes of food and other biomass.

There is a need for more thorough and systematic investigations into the potential for eco-functional intensification based on agroecological principles and practices in light of future increasing crop production and food needs linking systematic recordings of improvements in different development projects and a network of coordinated research sites. Continuous results coming from such linked efforts would give more precise interpretations of the necessary improvements in production and potential improvements based on ecofunctional intensification and agroecology and synergies with other ecosystems services including consequences for sustainability and resilience.

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Keeping the Actors in the Organic System Learning: The Role of Organic Farmers' Experiments

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Abstract

The creative process that leads to farmers' innovations is rarely studied or described precisely in agricultural sciences. For academic scientists, obvious limitations of farmers' experiments are e.g. precision, reliability, robustness, accuracy, validity or the correct analysis of cause and effect. Nevertheless, we propose that 'farmers' experiments' underpin innovations that keep organic farming locally tuned for sustainability and adaptable to changing economic, social and ecological conditions. We first researched the structure and role of farmers' experiments by conducting semi-structured interviews of 47 organic farmers in Austria and 72 organic/agroecology farmers in Cuba in 2007 and 2008. Seventysix more structured interviews explored the topics and methods used by Austrian farmers that were 'trying something'. Farmers engaged in activities that can be labelled as farmers experiments because these activities include considerable planning, manipulating variables, monitoring effects and communicating results. In Austria and Cuba 487 and 370 individual topics, respectively, were mentioned for experimenting by the respondents. These included topics like the introduction of new species or varieties, testing various ways of commercialization or the testing of alternative remedies. Two thirds (Austria) and one third (Cuba) of the farmers who experimented had an explicit mental or written plan before starting. In both countries, the majority of the farmers stated that they set up their experiments first on a small scale and expanded them if the outcome of the experiments was satisfactory. Repetitions were done by running experiments in subsequent years and the majority of the farmers monitored the experiments regularly. In both countries, many experiments were not discrete actions but nested in time and space. For further research on learning and innovation in organic farming we propose an explicit appreciation of farmers' experiments, encouraging further in-depth research on the details of the farmers' experimental process and encouraging the inclusion of farmers' experiments in strategies for innovation in organic and non organic farming. Strategic research and innovation agendas for organic farming would benefit from including organic farmers as co-researchers in all steps of the research process in order to encourage co-learning between academic scientists and organic farmers.

Keywords: organic agriculture, innovation partnership, collective action, co-research, participatory research, co-enquiry, collaborative learning

1. Introduction

1.1 The Importance of Innovation

The performance of agriculture worldwide clearly shows that the current mainstream agricultural pathway is not sustainable, causing a diversity of ecological, social and economic problems (McIntyre et al., 2009). Currently, *innovation* (e.g. Smits et al., 2010; EU SCAR, 2012) is seen as the buzzword and the key concept for supporting the urgently needed pathways or transition towards sustainability (van de Kerkhof & Wieczorek, 2005) or towards resilient societies (Folke et al., 2010; Leach et al., 2012), particularly in organic farming. Organic farming has contributed to multiple aspects of sustainability, especially concerning (new/innovative) on-farm production methods (Darnhofer, 2014a, Moeskops et al., 2014).

For a long period of time the term 'innovating' was mainly associated with science or commercial enterprisess. Recently the focus has shifted and clear evidence has been presented, that innovation is a dynamic social multi-stakeholder process that implies the participation of a diversity of stakeholders (Smits et al., 2010). Today, participatory action research (McIntyre, 2007; Chevalier & Buckles, 2013), citizen science (Tulloch et al., 2013) or transdisciplinary research (Tress et al., 2005; Mittelstraß, 2011) are state of the art approaches for ensuring that not only local knowledge, but also creativity and enthusiasm from all stakeholders linked to a certain topic are involved and taken seriously in the related research and innovation pathways.

In the agricultural sciences sector the debate on the role of stakeholders in providing information, sharing knowledge and supporting innovation is far advanced and has been framed in various models like e.g. in the Agricultural Knowledge and Information System or the Agricultural Innovation System, i.e. AKIS or AIS (e.g. Rivera et al., 2005; Spielmann, 2008). Nevertheless, the creative process that leads to farmers' innovations is rarely studied nor described precisely in agricultural sciences e.g. in syntheses on Agricultural Knowledge and Innovation Systems (EU SCAR, 2012) and in policy papers on innovation in organic farming (Moeskops et al., 2014).

The concepts currently used for describing what leads to farmers innovations are e.g. 'problem solving', 'innovating' or 'self help' (Moeskops et al., 2014). These terms are however used ambiguously and imprecisely, which might easily lead to ignoring the complexity of the processes involved. A lack of knowledge of this genuine creative process of 'innovating' might also lead to ignoring the intervening factors, misplacing the key incentives and thus not sufficiently taking into account the opportunities for encouraging farmers' innovations especially in organic farming.

1.2 Farmers' Experiments

In this paper we pick up and propose the concept of farmers' experiments as one option for describing the creative process that might lead to farmers' innovations. Yet, an experiment in general is defined as 'a course of action tentatively adopted without being sure of the outcome' (ODO, 2010) or 'a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response' (Montgomery, 2009). Farmers' experimentation is the process by which farmers informally conduct trials or tests that can result in new knowledge and innovative management systems suitable for their specific agro-ecological, socio-cultural and economic conditions (Rajasekaran, 1999). Sumberg and Okali (1997), who did pioneer work on farmers' experiments, consider two conditions necessary for an activity to be labelled an experiment: the creation and initial observation of conditions, and the observation or monitoring of subsequent results.

1.3 Links to Organic Farming

There are two reasons why it is particularly interesting to explore farmers' experiments in the context of organic farming.

First, sustainable land use practices are more knowledge-intensive (Röling & Brouwers, 1999). While conventional farmers can use external inputs such as synthetic pesticides and synthetic fertilisers to handle adverse dynamics in their agro-ecosystem, organic farmers need to develop knowledge about the agro-ecosystem to a larger extent to be able to manage their farms successfully without these inputs.

Second, organic agriculture was developed by farmers and farmers' grassroots organisations. Academic science and research only played a minor role in the historical development of organic agriculture (Padel, 2001), and organic farming was developed by practical experiments and trials of farmers and practical researchers. The lack of advice and formal research in the pioneer phase of organic agriculture leads to the assumption that organic farmers have nurtured a culture of experimentation. Organic farmers in the pioneer phase can be referred to as active experimenters and practical researchers (Gerber et al., 1996).

To our assumption it was not only the pioneers of organic agriculture who experimented; many organic and non-organic farmers worldwide are presumably still actively trying and experimenting to answer questions and solve problems that emerge continuously. We were interested in addressing this assumption in field sites that are very different from each other and assessing if and to which extent organic farmers realize activities that can be called farmers' experiments. We focus on experiments carried out by farmers on their own initiative, and we explicitly avoid referring to on-farm research.

We want to contribute to the current debate on the elements needed for encouraging innovation in organic farming. We do so by presenting empirical evidence from Austria and Cuba that farmers' experiments are a key element of innovating at farm level and by discussing the potential role of farmers' experiments in the innovation process.

2. Case Studies and Method

Austria and Cuba were selected for field research (together with Israel; Data on Isreael not presented here) due to various criteria that cause variation between the study sites. Austria has a long history of third party certified organic farming under a formal regulatory and policy framework and is an industrialized country in a temperate climate with high availability of farm inputs and formal advisory on organic farming; Cuba counts with a well organized but relatively young agroecology movement, which is the national interpretation of organic farming, and is a tropical country with limited availability of farm inputs (Kummer et al., 2012) in prep; Leitgeb et al., 2011, 2014).

Field research in Austria and Cuba started with semi-structured interviews (Austria: n = 47; Cuba n = 72; both in 2007 and 2008) based on samples of farmers with maximum variation (criteria for variation e.g.: region, different production types) for learning the terminology and aspects related to the topic of 'changes at farm level' and 'trying something'). Semi-structured interviews were digitally recorded, transcribed with the software ExpressScribe, and processed with the software Atlas.ti. We used qualitative content analysis, employing a combination of deductive and inductive coding for learning on such aspects as the topics, methods, outcomes, attitudes and beliefs related to the process of trying, testing, changing 'something' at farm level. We expected that the term 'experiment' might be loaded with the connotation of a scientific procedure (Sumberg & Okali, 1997, p. 58). It was therefore agreed not to use that term during the semi-structured interviews to prevent narrowing the research field with this specific, technical connotation. The terms we used to refer to experimentation activities during interviews were 'to try, to try something, to try something new' (the terms we used in German were 'etwas probieren' or 'etwas ausprobieren', in Spanish: 'probar algo').

Based on insights from these semi-structured interviews a structured questionnaire was set up with pre-defined answer categories on all elements of experimentation identified. In the structured interviews, in contrast to the semi-structured interviews before, the conversation was started with the purposeful introduction of the term 'experiment', including a definition that was based on the results of the semi-structured interviews. The structured interviews were applied in Austria with 76 organic farmers in 2008 and 2012 and in Cuba with 34 farmers from the Cuban Agroecology Movement and the Cuban Urban agriculture movement in 2007 and 2008. Structured interviews from Austria were digitally recorded, data inserted into a Microsoft-Access database, and later descriptively analyzed with Microsoft-Excel and SPSS, from Cuba this data set has not yet been analyzed.

Here selected qualitative descriptive data is presented summarizing the results from Kummer et al. (2012, 2015 in prep) and Leitgeb et al. (2011, 2014).

3. Results

In Austria the interviewees in semi-structured and structured interviews (together n=123) mentioned 487 individual topics for experimenting and only eight interviewed farmers stated that they had never carried out any activity that they would define as 'trying something'. In Cuba 370 individual topics were mentioned by all farmers in semi-structured interviews.

Aspects in crop production (e.g. introduction of new species or varieties) were the most frequently mentioned topics in Austria and Cuba, but literally all aspects are to be found, and even commerzialization, construction, testing of alternative remedies or the influence of the lunar cycle, or social organisation were under the topics mentioned by the Austrian and Cuban farmers for doing experiments.

The most frequently mentioned motives for doing experiments were in both countries personal reasons and overcoming challenges or problems. Challenges frequently cited in Cuba were e.g. increasing productivity or achieving independence from external resources. Personal reasons included a general interest in a specific topic or curiosity about how something could work or not, and also the opinion that implementing a specific practice on the farm would be meaningful and desirable for the respective person. Farmers in both countries mentioned most frequently other farmers as sources for information needed for the experiment and also as sources for ideas, together with literature or advisors.

In Austria, two thirds of the farmers who experimented had an explicit mental or written plan before starting. In Cuba one third of the respondents had precise plans, partly in a written way based upon detailed criteria. In both countries, the majority of the farmers stated that they set up their experiments first on a small scale and enlarged them if the outcome of the experiments was satisfactory. Repetitions were done by running experiments in subsequent years between two and five years long, partly longer but without documenting the duration by our respondents.

In both countries the majority of the farmers monitored the experiments regularly, mostly through observation and comparisons (e.g. with previous experiences, with other farmers, with another unit at the own farm, etc.). Only a small proportion of farmers did measurements. Documentation strategies included taking notes, pictures, samples or videos.

In both countries, many experiments were not discrete actions but nested in time and space: One specific experiment can be the source of information or motivation for another specific experiment, experiments can be carried out simultaneously and a 'smaller' topic under experimentation can be part of a 'bigger' topic under experimentation.

In Austria farmers most frequently reported as outcomes of their trials having obtained more knowledge, having learned and increased satisfaction, but also having reduced the work load, increased production, gained reputation or increased income. Increased productivity, increased self sufficiency and better work efficiency were the most frequently mentioned outcomes in Cuba. First addresses for disseminating outcomes were other farmers in both countries. Having learned was attributed by the farmers even to failures or flops in experimenting.

In Cuba, *experimentar* (experimenting) and *experimento* (experiment) were terms frequently used by farmers when answering to our questions about 'trying something'. This was different from Austria where *etwas ausprobieren* (to try something) was the most common phrase used. In Cuba, *experimentación campesina* (farmers' experiments) was an integral part of the Cuban agroecology movement and therefore understood by most of the respondents as a concept and as a practical daily activity. Experimentation, innovation and inventions at farm level are part of the Cuban discourse on rural development and encouraged explicitely e.g. through competitions for the best innovation or invention at municipal, provincial and national level, including awarding them for innovations or supporting the negotiations for achieving a patent for promising inventions. In Austria, a formal discourse on farmers' experiments in the organic farming movement or under organic farmers, even when talking about 'to try something' could not be observed during the study period.

4. Discussion

With data from Austria and Cuba we can empirically confirm findings of e.g. Sumberg and Okali (1997) that farmers engage in activities of 'trying something'. These activities can be called *farmers' experiments* as they include to a considerable proportion planning, implementing variables of unknown consequences in search for their effects, monitoring the effects, and communicating results.

Various authors draw diverse conclusions about the significance of farmers' experiments, but most of the authors agree that all farmers have experimental capacity (e.g. Rhoades & Bebbington, 1991; Chambers, 1999; Quiroz, 1999; Critchley & Mutunga, 2003; Bentley, 2006, 2010), and that experiments are an integral part of farming activities (Sumberg et al., 2003). The experimental capability of farmers, similarly to the resilience of farms, cannot be regarded simply as an automatic response being deducted from the farms' characteristics, but it is rather the ability to identify opportunities, implement options and to 'learn as part of an iterative, reflexive process' (Darnhofer, 2014b).

However, this does not mean that all farmers are innovative (Quiroz, 1999). Experimenting farmers are rarely a homogeneous group. They have been found to be both resource-rich and resource-poor (Saad, 2002), both men and women, both outsiders and well-integrated, and both highly educated and less educated (Reij & Waters-Bayer, 2001). Farmers conduct experiments to test their ideas in their own way (Rajasekaran, 1999). Experimentation can be induced by intuition, curiosity or by an explicit desire to learn (Stolzenbach, 1999). Farmers can be driven by economic motives as well as by a concern for production, and saving labour or capital (Critchley, 2000; Bentley, 2006). While new ideas and changes spark creativity and induce experiments, the capacity to experiment and learn also depends on prior knowledge and experiences. The source of farmers' experiments is therefore a combination of prior local/traditional knowledge of the farmer and new information the farmer aquires from elsewhere (Bentley, 2006).

Based on our findings and literature, we propose a theoretical model of the experimentation process (Figure 1) that helps elucidating what usually just has been vaguely called 'problem solving', 'innovating' or 'self help (Moeskops, 2014). When a certain problem or topic arises, a farmer can decide to adopt an available solution to deal with the situation (Wortmann, 2005), without entering an experimentation process. If the farmer decides to start an experiment, he or she can adapt a common solution that is already known to him or her (Wortmann, 2005; Pretty, 1995), or can decide to try something new. The experimentation process can be defined as a research process that involves a specific methodological approach, including setup, monitoring of the process and evaluation of the results. Different factors, such as environmental, economic or social conditions influence the experimentation process (Sumberg & Okali, 1997), and have an effect on the experiment. Interrelations also exist with regard to the communication system in which the farmer is involved: farmers use local knowledge from their own farm in combination with knowledge from other sources, such as other farmers, media, science or advisory services (Stolzenbach, 1999; Bentley, 2006; Sturdy et al., 2008; Leitgeb et al., 2011). The results of an experimentation process can be classified into innovations, inventions or ‘failures’ (the later being learning experiences but not involving any change at farm level). These results are usually communicated to the social network of the farmers, such as e.g. family, neighbors or advisors. They are also fed back into the planning and implementation of new experiments to be realized by the farmer.

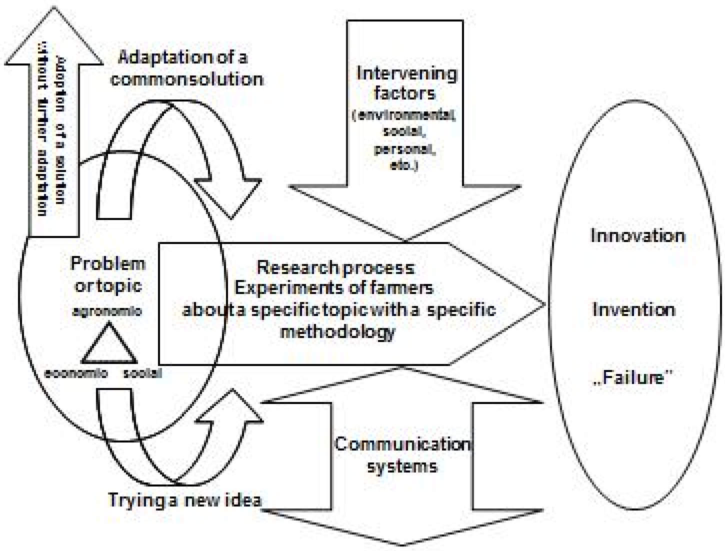

Figure 1. Model adapted from Ninio and Vogl (2006) for operationalizing the topic of farmers’ experiments

Farmers, at least in Austria, themselves hardly use the term ‘experiment’ to refer to their practical on-farm experiments, but relate this term more to a scientific and formal procedure. In various empirical studies on the topic, using the term ‘trying’ instead of ‘experimenting’ in interviews has been seen as being more expedient (Sumberg & Okali, 1997), while in other cases local terms are used to address the subject in the field (Stolzenbach, 1999). Other terms used in literature are i) ‘farmer research’, which refers to ‘research conducted by farmers for discovery or production of information’ (Wortmann et al., 2005) and ii) ‘on-farm research’, which means research conducted, and usually also controlled, by scientists on farms, involving the farmer more or less actively (Lawrence et al., 2007).

The topic of this paper was discussed during various oral presentations and poster presentations with peer scientists. In such discussions we often observed that scientists can be quite reluctant in accepting that the term *experiment* may be used also by actors not affiliated to academic science, and that e.g. farmers carry out their own experiments. For academic scientists, obvious limitations of farmers’ experiments are e.g. precision, reliability, robustness, accuracy, validity or the correct analysis of cause and effect. To our assessment based on our results, but also confirmed e.g. by Moller (Henrik Moller, personal communication, November 2nd, 2014), comparative weakness of the farmers’ experiments compared to the formal science experiments often include:

a) Lack of or poor spatial and temporal replication;

b) Few treatments, usually one at a time;

c) Reliance on a ‘Before-After’ comparison for detection of an experimental effect. Many farmer’s experiments reject or accept an innovation/change if it works/doesn’t work after a year or two – whereas ecological systems often display time-treatment interaction effects (what works now may not work in a different year and vice versa).

d) Poor quantification.

Most formal science is expensive, often aimed at a more general level of question, integrates and tries to find truth over a wide spatial scale (synchronic strength) over short investigation spans (diachronic weakness). In contrast, for farmers limitations of academic experiments might be the appropriateness of the design or the applicability of the results to the site specific conditions of a certain farm, and the lack of assessment under the complexity of annually changing farm conditions. Farmers' experiments are referenced against a long and culturally transmitted knowledge of how their local farm performed before the innovation was tried (diachronic strength) but may be less applicable to other farms, even ones nearby (synchronic weakness). Despite these weaknesses discussed in academia, for farmers their site specific experiments allows:

a) Local tuning of farmers' practice to the opportunities, threats and conditions of:

- Ecology and biophysical features of the land and landscape (soil, climate, environmental history);
- Social needs and capacity for change (what works for the farmers' view and values);
- Economic resilience (financial capacity and equity, resilience to experiment and ride through failed experiments, financial drivers to improve a weak part of their economic performance);
- Governance-constraints (policy, regulations, view of their co-owners or sector co-operative).

b) Building resilience by increasing adaptability in a changing world – the keys to capturing new opportunities and counteracting new threats.

c) Immediate uptake – because the practitioners act as free agents to initiate and conduct the experiments, we know them to be relevant, of keen interest and likely to be immediately heeded by the main decision makers on the farmer – this removes the main barrier to external expert driven research actually being used.

For further research and theory building on learning and innovation in organic farming we propose to avoid replacing academic experiments with farmers' experiments, or putting higher values on farmers' experiments than on academic experiments. First, we call for an explicit appreciation of farmers' experiments and encourage further in-depth research on the details of the experimental process and the related intervening variables of farmers' experiments. Second, we want to encourage the inclusion of farmers' experiments in strategies for innovation in organic farming. Strategies could be on-farm research or participatory research as proposed by Moeskops and Cuoco (2014).

Nevertheless, intensity and kind of participation can vary significantly (Pretty, 1999). On-farm research might also be called as such when farmers simply provide land to academic scientists for academic experiments, and the degree of 'participation' might vary considerably. Both on-farm research as well as participatory research have the potential that the role of farmers remains quite passive and ignoring their experimental capacity.

Strategic research and innovation agendas for organic farming and food (Moeskops & Cuoco, 2014) must see organic farmers not only as actors providing the land for academic research, but farmers shall be included as co-researchers in various steps of the research process such as analyzing literature and empirical experiences, formulating research questions, developing the research design, monitoring, analysis and dissemination of results. Here farmers can learn about aspects such as accuracy and validity of research designs, while scientists might benefit e.g. from a holistic research design and monitoring that can include factors beyond measuring controlled variables, and in doing so learning from farmers how to deal with complexity (comp. Hoffmann et al., 2007). The usefulness of stakeholder participation in agricultural research was highlighted before and comprehensive participation frameworks were suggested to guide the participation process through self-reflection, informed discussion, and decision-making between project participants. These frameworks help to decide upon strengths and weaknesses of stakeholder inclusion in the steps of the research process and transcend common perceptions of the more participation the better (Neef & Neubert, 2011). Research done by Sewell et al. (2014) showed that farmers' learning can be highly promoted when farmers participate in a learning community with scientists and become part of a shared inquiry, because 'dialogue is not only a means of communication, but it is also a means to generate new ideas, negotiate understandings and build knowledge' (Sewell et al., 2014). Care has to be taken by the organic movement that standards and regulations encourage, but do not hamper farmers' experiments (Vogl et al., 2005).

Co-learning and co-production of knowledge (Akpo et al., 2014; Sewell et al., 2014) between organic farmers and academic scientists do have a yet underestimated and underused potential in opening the creative potential for innovations in organic farming. The potential might even increase by opening the scope from the farm perspective to a perspective on the whole supply chain of certain products or to a regional perspective and involving the stakeholders along the chain or in the region.

Organic farmers should not only be perceived as beneficiaries of innovations through cutting edge basic science or scientific experiments, or as hosts for on-farm experimentation, but also be explicitely supported in their capacity of being experimenters and perceived as genuine co-researchers. 'Farmers cannot resist tinkering with new techniques. They will do this whether outsiders tell them to do so or not, regardless of any project or agency's philosophy. Farmers are experimenters, no matter what happens, even if outsiders do not encourage them to do so' (Bentley et al., 2010).

We believe that more sustainable and resilient farming can emerge from better listening and integration of the practitioners' ways of knowing with the structured experiments of agronomists. Complementarity between farmers' and academics' experiments forms a strong partnership of approaches that collectively opens a wider choice set for farming practice options and local tuning. Together the most robust and lasting knowledge will emerge, but at the moment the two types of expert rarely communicate with each other.

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Incorporating Agroecology Into Organic Research –An Ongoing Challenge

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Abstract

Agroecology – as a scientific discipline and as an approach to sustainable farming practice – has objectives similar to those of organic agriculture. The paper sharpens the profile of both concepts and identifies strengths and weaknesses. The overarching challenge of both is to minimize trade-offs between food and fiber production on the one hand and non-commodity ecosystem services on the other hand. A comparison of the two approaches may well be inspiring, especially for the future development of organic food systems.

Best use of human, social and natural capital characterizes organic farmers, especially in developing countries, as documented by many case studies from sub-Saharan Africa. That also applies to organic farms in temperate zones, although usually more external inputs are used in organic farming there. While the profitability of organic farms is comparable to or slightly higher than that of conventional ones, per area food production is lower by an average of 20 to 25 percent in temperate zones. Overly restrictive production standards are often mentioned as the cause, but also a lag in production techniques. One of the main approaches of organic agriculture to augment productivity is ecological or eco-functional intensification. Thereby, the goal is to maintain the ecological and social qualities of the farms and to increase food output. The future development of organic agriculture can be characterized by a comprehensive culture of innovation embracing social, ecological and technological innovations. Such a concept of innovation includes dynamic interactions between farmers and scientists in order to strengthen system resilience and make better use of basic research from a wide range of scientific disciplines.

Keywords: agroecology, organic agriculture, eco-functional intensification, innovation

1. Introduction

The former UN Special Rapporteur on the Right to Food, Olivier De Schutter, made strong recommendations in his final report in favor of agroecology (De Schutter, 2014). Productivity could be doubled in regions where the hungry live if agroecological methods are adopted. De Schutter saw agroecological science and practice as the most favorable way to boost future food production. Although he identified similarities between organic agriculture and agroecology, De Schutter did not emphasize organic agriculture in particular. To cope with the grand challenges of humanity ahead, ‘we urgently need to adopt the most efficient farming techniques available’ he wrote. In this article, the concepts of organic agriculture as part of agroecology and the respective farming practices are discussed. Furthermore, the consequences for future innovation in organic agriculture are deduced.

2. Organic Agriculture at a Crossroads

The history of organic agriculture reaches back to the early 20th century. It was one of the very first social movements in agriculture, food and nutrition with strong roots in Europe and the United States of America (Vogt, 2007). Many farmers, scientists and consumers perceived organic farming as a paradigm shift in agriculture (Wynen, 1996; Beus & Dunlap, 1991).

Table 1. Description of organic agriculture as a new paradigm (Beus & Dunlap, 1991)

Conventional farming	Organic farming
Dependence	Independence
Competition	Community
Domination of nature	Harmony with nature
Specialization	Diversity
Exploitation	Restraint

A paradigm shift in society finally leads to the adoption of new ideas by the respective mainstream activity or context (Kuhn, 1970). This has occurred in the case of agriculture as well; a multitude of “sustainable” farming systems have emerged in the last 30 years, at least partly inspired by organic agriculture. These include conservation tillage, integrated pest management, integrated production, precision farming, low input agriculture, low external input, sustainable agriculture, agroecological farming, permaculture and agroforestry systems. On the other hand, organic agriculture has developed into a highly standardized food production protocol regulated by 80 national laws (Huber et al., 2015). As a consequence of the growth in organic food trade, bilateral negotiations on equivalence or even compliance have become an important aspect of the sector (Huber et al., 2015; ITF, 2008). Eighty percent of organic food is consumed in the US and EU markets, while seventy-five percent of the producers produce outside of these two major domestic markets (Willer & Lernoud, 2015). In most European countries, conversion rates of farmers to organic agriculture are low although market demand is huge and direct payment schemes support conversion (Willer & Lernoud, 2015). In export-oriented countries, the growing trade threatens the regionalization and contextualization of organic agriculture because the standards of the EU and US markets are the dominant requirements (Oelofse, 2010). It was mainly the strenuous work of organic pioneer organizations in the 1970s to agree on the global standard of the International Federation of Organic Agriculture Movements (IFOAM) which enabled a prosperous global trade in organic commodities 30 years later (Geier, 2007; Schmid, 2007).

Two opposing developments can currently be identified: Conventional agriculture is adopting ecological and social elements of sustainability while organic agriculture is becoming globally standardized, potentially losing part of its diversity and becoming more business oriented. Questions thus arise on the positioning and unique profile of organic agriculture compared to the fast growing number of currently 435 labels with sustainability claims (COSA, 2013) such as Rainforest Alliance, UTZ, Fair Trade and others. Most of them apply one or several farm practices typical of agroecology (see the listing of agroecological approaches in Parmentier, 2014 and Wezel et al., 2014).

These discussions are especially intense in Europe, where support for organic agriculture is part of the political schemes for rural development and part of the agri-environment regulation EU 2078/92 (Council of the European Communities, 1992), which seeks to raise awareness among farmers of environment-friendly farm practices. Ensuring best farm practice and a high level of ecological, social and economic sustainability is an important issue in this context – equally important as meeting the quality expectations of consumers. Such concepts of best practice are part of the discussion under the slogan “Organic 3.0”. The term was first introduced by Braun et al. in 2010. In 2014, it was launched as an international campaign by IFOAM (Arbenz, 2015; Rützler and Reiter, 2014).

3. The Development of Agroecology

Agroecology as introduced by Altieri (1995) was a scientific discipline concerned with the application of ecology to agricultural systems. Since then, it has become the overarching concept of a growing number of agricultural universities and state research institutes. The German Research Fund, which finances fundamental science across all disciplines, qualified agricultural research as a system approach (DFG memorandum, 2005): Due to the paradigm shift in society, agricultural research addresses “interdependencies with environmental and social sciences, and ecology gains in importance as a source of relevant theories” the DFG memorandum wrote.

In Latin America, smallholder farmers have increasingly taken up the findings of agroecological research and have developed farm practice accordingly (Altieri et al., 2015; Altieri & Nicholls, 2005). The goal is to optimize productivity with best use of natural capital and to reduce dependence on costly inputs such as fertilizers and pesticides. Such practices encompass local breeding programs aiming at improving the quality and yield of locally adapted species and cultivars (Koohafkan et al., 2011). These programs take up the experience of farmers, especially women who are often responsible for the maintenance of seeds and tubers.

Most recently, the government of France has defined agroecology as the general principle of agricultural practice with consequences for the orientation of future research by the French National Institute for Agricultural Research (INRA) with 8500 full-tenure staff members (Ministère de l'algriculture, de l'agroalimentaire et de la forêt, 2013). In Switzerland, all state support schemes have been addressed exclusively to farms which apply several agroecological practices since 2006 (BLW, 2015). With the new Common Agricultural Policy (CAP), the European Commission established in 2014 a policy of 'greening' and required a few agroecological practices for all direct payments. These practices encompass hedgerows and other diverse habitats on five percent of the agricultural land, a more diversified crop rotation and restricted ploughing of permanent grassland (European Commission, 2013).

Finally, agroecology is a social movement and is strongly linked to the food sovereignty movement in Latin America and similar movements across the entire world (Wezel et al., 2009). A politically very active organization is Via Campesina which advocates for small-holder farmers, agroecological farming and food sovereignty (Via Campesina, 2015). In regions where agroecological initiatives and projects have become durable and farmers have not relapsed to unsustainable practices, it was the result of farmers and civil society organisations having become organized as a movement (Tittonell, 2014).

The principles and characteristics of both agroecological research and farm practices (Table 2) are almost identical with those of organic agriculture. Therefore, co-operation between the two concepts is fruitful and should be expanded greatly.

Table 2. Characteristics of agroecology (Altieri et al., 2015, Levidow et al., 2014)

Agroecological research	**Agroecological farm practices (principles)**
Develops more autonomous, participatory ways of producing knowledge that is ecologically literate, socially just and relevant in the context.	Less dependence on monoculture systems, input substitution, external input markets and costly biotechnology packages.
More responsibility and decision making power to farmers and citizens.	Integrated agroecosystems (based on functional biodiversity and on eco-functional intensification).
More significant roles of farmers, food workers, citizens-consumers in the production and validation of agroecological knowledge.	Resource availability from local agro-ecosystems (recycling).
	Protect environment and produce public goods.
	Local or regional market structures (circular economy models).
	Territorial development strategies (also food sovereignty) and interventions by social movements.

Agroecological research started from pest prevention, where biodiversity plays an important role (Altieri et al., 2015). Organic research in contrast was first very focused on soil fertility and on the specific methods which were introduced by biodynamic farming (Vogt, 2007). In this day and age, the research agendas for and with organic and agroecological farmers are similarly comprehensive, which delivers synergies for both farming practices (Lutzeyer & Kovacs, 2012; Stinner, 2007; Niggli, 2007 a; Niggli 2007b; Lange et al., 2006.; Wezel et al., 2009; Wezel et al., 2014).

While the principles of agroecological farming are almost identical to organic principles, the techniques and requirements on farms exhibit relevant differences. Because agroecological farming is not market-driven, clear entry thresholds are absent (Table 3). In contrast, organic farming has clear and rigorous restrictions and bans (e.g., no synthetic pesticides, fertilizers and processing aids and additives, no genetically modified organisms or products thereof) and farms are decertified and lose access to markets when they violate the restrictions (Table 3). Certification is an integral part of the requirements for an organic farm and is prominently regulated by both state systems and private labels. There is a certain flexibility in the choice of certification methods: Third-party audits according to ISO standards are most commonly used. For groups of smallholder producers, group certification is also applied, again supervised by a third-party audit. Some countries like Brazil allow

Participatory Guarantee Systems (PGS) where the proximity of farmers, consumers and trade replace an external control (Table 3).

Agroecological farms on the other hand are more flexible in many ways. Some of their techniques are not compatible with organic standards, like combined fertilization with organic manure and mineral fertilizers (including nitrate) or the spraying of herbicides and pesticides in order to prevent yield losses (Parmentier, 2014).

Table 3. Practices and techniques of organic and agroecological farms

Level	**Agroecological farms**	**Organic farms**
Principles	Many excellent principles and recommendations, comparable to organic farming; not codified (Altieri et al, 2015).	The four principles of health, ecology, fairness and care, worded in the same spirit as agroecology but codified (national and international law) (IFOAM, 2015; Huber et al., 2015).
System redesign and prevention	On both farm types, preventive techniques prevail which strengthen the farm system and make it more resilient. They include landscape management, habitat enrichment, crop rotation, polyculture, catch and cover crops, agroforestry systems and mixed farms (crop/livestock) (Wezel et al., 2014; Zehnder et al., 2007, Lampkin, 1990).	
Off-farm input	Reduction of off-farm inputs by prevention, nutrient cycling, biological N fixation, natural regulation of pests and natural amendments and biological pest control is paramount for both organic and agroecological farm practice (Wezel et al, 2014; Lampkin, 1990).	
Input regulation and GMOs	No general bans on inputs. No positive lists of accepted inputs. Agroecology does not exclude synthetic and chemical pesticides and fertilizers on “ideological grounds” (Parmentier, 2014). If a technology improves productivity for farmers and does not cause undue harm to the environment, it can be applied (Wezel et al., 2014; Parmentier, 2014; Pretty, 2008). GMOs are incompatible with agroecology as they increase peasants’ dependence on agro-industry, have harmful impacts on the environment and biodiversity, reduce soil fertility, increase economic costs for farmers and increase criminalization of peasants as a result of the patents (Parmentier, 2014).	Off-farm inputs are strictly regulated in positive lists. Everything not listed is banned and leads to suspension of certification. Inputs accepted on organic farms are registered according to clear criteria such as derivatives from natural compounds and living organisms. A few traditional chemical inputs like copper fungicides are used with restrictions. Bans on synthetic pesticides, mineral fertilizers and GMOs. Genetic engineering and many other breeding techniques are “excluded methods” (NOSB, 2013). The concept of the integrity of plants entails the genotypic integrity or the intact genome (Lammerts van Bueren et al., 2003). As consequences, cell fusion is forbidden in organic breeding (yet not for seed propagation) and substances derived from genetically engineered bacteria such as synthetic amino-acids are banned.
Standards, regulation and certification	No mandatory standards, inspection and certification. No standards for food processing, storage, packaging and trade are in place.	Organic standards are mandatory for farmers and include processing and distribution. A third-party audit (pursuant to ISO standards) is in place and a law is in force in more than 80 countries. In departure from ISO standards, group certification is possible in some countries and the participatory guarantee system (PGS) under which no independent audits are enforced is applied for local markets in a few countries (Huber et al., 2015; Kirchner, 2015).
Adoption	Farmers often start with using a few	Organic farmers comply with all elements of

	agroecological practices. Learning from other farmers is important as they become confident with further practices so that they abandon conventional techniques step by step. When farmers begin with agroecological practices, they already have the status agroecology. Convergence with all principles is the final goal.	the standards from the 1st day on they convert. Therefore, the entry threshold is high and challenging. Applying only a few organic practices is not an option. As long as full compliance is not achieved, farms remain conventional.

Agroecological practices include already well established farming systems like Low External Input Sustainable Agriculture (LEISA), Organic Farming, Permaculture and (Successional) Agroforestry Systems. Most recently, the concept of agroecology is also being taken over by industrial agriculture by subsuming Low Input Agriculture (LIA), Precision Farming, Integrated Pest Management and Integrated Production as well as Conservation Tillage under agroecological farm practices, a development criticized by smallholder farmers (Via Campesina, 2015).

4. Discussion of the Consequences for the Future Development of Organic Agriculture

The comparison of organic agriculture and agroecology, both as a concept for research and for farming practice, is used in the following discussion for reflecting on potential consequences for the future development of organic agriculture. Several concept papers addressing the future of organic agriculture are in *statu nascendi* and will conceptualize "Organic 3.0". The discussion in this paper reflects the ideas of the author who is involved in the concept papers of IFOAM (not yet published) and the German-speaking organic associations (not yet published).

The need for innovation in organic agriculture is one of the main drivers of the current discussions. Organic farms have become highly differentiated in terms of size, complexity or specialization, labor input, level of intensity, mechanization, profitability and marketing. Consequently, the pathways for innovations are manifold and in parts even contradictory (e.g. between organic pastoralists and organic greenhouse vegetable growers). Although the future innovation strategies are held together by the principles of organic agriculture (IFOAM, 2015), amendments of the standards and regulations may become needed. Unlike organic agriculture, agroecology uses a wider range of technological innovations, especially in developed economies (Table 3). Agroecology also fosters social innovation among smallholder farmers in developing countries.

What could be learnt from agroecological farm practices and how could it be effectuated in the context of organic agriculture? The most important conclusion is that organic agriculture has to implement more rigorously a comprehensive culture of social, ecological and technological innovation.

Firstly, social innovation is a powerful tool and can contribute to local food sovereignty and improved livelihoods in an organic setting. Subsistence farms in sub-Saharan Africa or pastoralists, for example, can considerably improve their crop or meat/milk yields and profitability by using state-of the-art organic techniques (Hine et al., 2008). The better use of human and social capital e.g. by farmer-to-farmer learning or by extension work and on-farm experimenting are the first and important steps to take, reducing not only food insecurity but also dependence on expensive off-farm inputs and therefore also indebtedness (Hine et al., 2008 report case studies of 1.9 million organic and subsistence farmers in sub-Saharan Africa where yields were doubled with good organic practice). While many more independent and non-business facilitators of knowledge on best practices are needed, a better understanding of the factors which restrict the adoption of best practices by farmers or rural societies is also relevant. Socio-economic research can provide these analyses. Social innovations are also supportive of farmer livelihoods in developed economies, especially through farmer-consumer partnerships such as community supported agriculture (CSA), direct marketing with Internet-based media and box schemes (Zahnder & Hamm, 2009).

Farmer-driven innovation also encompasses technical aspects of farming. Such fields of applied research (or of unraveling existing knowledge) can concern site-specific techniques, knowledge bound to local cultivars, botanicals used in plant protection and veterinary treatments, as well as agroforestry, rainwater harvesting and soil erosion prevention techniques. Interviews with a few hundred organic farmers in Switzerland, for instance, have resulted in well over 1000 prescriptions of botanicals practiced by farmers and verified by pharmaceutical and veterinarian scientists (Disler et al., 2013). The most important aspect of listening to farmers therefore is to systematically extract, evaluate and preserve indigenous or tacit knowledge of farmers and farm communities.

Secondly, similar to social innovation, ecological innovation is not yet fully exploited. On that point, the concept of "eco-functional intensification" as it was proposed for the EU-Research Framework by the European organic farmers stands for making better use of supporting and regulating services (like soil fertility, carbon sequestration, biodiversity) for higher and more stable yields (Niggli et al., 2008). Part of this innovation concept is to use natural capital better for productivity increases. The concept of eco-functional intensification only works when non-commodity ecosystems services are not lessened nor degraded by the farmers. Such an intensification strategy also strives to increase productivity while safeguarding the ecological advantages of organic farming (Niggli, 2014).

Eco-functional intensification means to generate productivity gains by activating ecosystem services and functions. This is in most cases the result of redesigning crop rotations, natural and semi-natural habitats and consequently the entire farm. The use of biocontrol organisms and botanicals in plant and animal strengthening and disease and pest control are other examples of eco-functional intensification. They are emerging technologies and are increasingly adopted by the industry (see their strong interest in the Annual Biocontrol Industry Meeting in Basel, Switzerland (ABIM, 2015)).

As synthetic pest control agents will never be an option for organic agriculture (see Table 3), well selected techniques which mimic natural mechanisms might be helpful for organic horticultural production. So far, organic regulations have a rather conservative approach to such innovations pursued, for example, by the interdisciplinary research field of bionics, where experts in the fields of biology, technology, engineering and design work together, identifying possible applications for solutions that nature has created in the course of evolution (Von Gleich et al., 2007). It would be worthwhile for organic farmers to look into this kind of innovation as well, especially when critical bottlenecks of organic farming still require borderline interventions like Copper, Sulphur or mineral oil sprays or chemical veterinary medications.

Thirdly, technological innovation has always played a role in the development of organic agriculture and will do so also in the future. For some technologies such as mechanical and thermal weeding, organic agriculture has been a leader of innovation (Niggli, 2007b). Novel developments in precision agriculture will become more prominent on organic farms in general but especially on broad-acre farms. A good example is a combination of contour farming with strip cropping which enables farmers to establish crop rotations in time and in space so that crops can profit from effects from the precedent crops as well as from adjacent ones. Precision farming might also play a role for the application of sprays compliant with organic regulations, for the application and dispersion of organic fertilizers and for the precise control of mechanical and thermal weeding devices.

Plant and animal breeding techniques such as genome-wide selection, an advanced application of marker-assisted breeding, have potential to accelerate the breeding progress for quantitative trait loci, which are often important for organic agriculture (Desta & Ortiz, 2014). They might be both contradicting and synergistic with the more holistic approach of organic breeding where phenotypic selection plays an important role (the "breeder's eye"). Some scientists even regard the latest molecular breeding techniques (precision breeding or genome editing) as compatible with the principles of IFOAM (Andersen et al., 2015).

Many of the examples given for future innovation on organic farms demonstrate the necessity of a custodian platform enabling a critical discourse on progress which is in compliance with the organic principles and on the modernization pathways organic agriculture will adopt. Stronger than in the past, innovation will become an area of tension between a bottom-up, farmer-driven and top-down, science-driven approach (Levidow, 2011; Marsden, 2013).

Future research requires explicit interdisciplinary cooperation and an improved dialogue with farmers and an involvement of these actors as co-researchers and as co-facilitators of knowledge. On the one hand, this integration of farmers increases the cost efficiency of research and the results are multiplied effectively among fellow farmers. Interdisciplinary and transdisciplinary research on a high scientific level will lead to the next stage of organic agriculture development and is indispensable.

Fourthly, a shift towards impacts and outcomes will be needed in order to increase both transparency and credibility for policy makers, environmentalists and consumers. Organic agriculture regulations focus with their minimum requirements on inputs and on general bans of technologies (see Table 3). A comprehensive set of indicators such as the Sustainability Assessment of Food and Agriculture Systems (SAFA) guidelines by FAO or the Best Practice Guideline for Agriculture and Value Chains of the Sustainable Organic Agriculture Action Network (SOAAN) of IFOAM will increase the sustainability of organic agriculture and help to identify unsuitable developments of organic farm practices (FAO, 2015; SOAAN, 2013).

Therefore, "Organic Agriculture 3.0" also means constantly striving for best practice. This can be learnt from agroecology as well.

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Are Organic Standards Sufficient to Ensure Sustainable Agriculture? Lessons From New Zealand's *ARGOS* and *Sustainability Dashboard* Projects

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Abstract

Our review concludes that organic standards need to account for a broader set of criteria in order to retain claims to 'sustainability'. Measurements of the ecological, economic and social outcomes from over 96 kiwifruit, sheep/beef and dairy farms in New Zealand between 2004 and 2012 by The *Agricultural Research Group on Sustainability* (ARGOS) project showed some enhanced ecosystem services from organic agriculture that will assist a "land-sharing" approach for sustainable land management. However, the efficiency of provisioning services is reduced in organic systems and this potentially undermines a "land-sparing" strategy to secure food security and ecosystem services. Other aspects of the farm operation that are not considered in the organic standards sometimes had just as much or even a greater effect on ecosystem services than restriction of chemical inputs and synthetic fertilisers. An organic farming version of the *New Zealand Sustainability Dashboard* will integrate organic standards and wider agricultural best practice into a broad and multidimensional sustainability assessment framework and package of learning tools. There is huge variation in performance of farms within a given farming system. Therefore improving ecosystem services depends as much on locally tuned learning and adjustments of farm practice on individual farms as on uptake of organic or Integrated Management farming system protocols.

Keywords: ecosystem services, integrated management, organic farming, sustainability indicators

1. Introduction

Maintaining biodiversity and other ecosystem services to sustain efficient food and fibre production is one of the greatest challenges facing humanity (Millennium Ecosystem Assessment, 2005). Efficient industrialised agriculture, powered by energy and nutrient subsidies and technology, helps secure human wellbeing by providing "provisioning services" (efficient and sustainable production of food and fibre). However it has also weakened nature's ability to deliver other key regulating and supporting ecosystem services, e.g. purification of air and water, protection from disasters, and nutrient cycling. "Cultural ecosystem services" underpin connection to place, community support, land stewardship values, local economies, transfer of knowledge, and the identity of farmers. These cultural services provide the incentives and enhance capacity to sustain and adapt coupled social and ecological systems. All types of ecosystem services are required to capture new opportunities and counteract challenges such as climate change, peak oil, globalisation of markets, biosecurity risks and transgenic organisms (Darnhofer et al., 2011; Pretty et al., 2010).

Market assurance and certification schemes have emerged as a global response to encourage and reward sustainable agriculture and inform consumers (Campbell et al., 2012b). Such schemes often stipulate best farming practices and many establish explicit standards, sustainability assessments, monitoring and audits that seek to future-proof ecosystem services in production landscapes. They are designed to assure consumers and regulators that the food and fibre has been produced in an ethical and sustainable way, and that foods are safe and nutritious to eat. "Organic Agriculture" is one of the very earliest and well recognised of such market accreditation schemes. There are now scores of other frameworks, standards and certification schemes that purport to enhance the economic resilience and sustainability of production. Some adopt elements of Integrated Pest Management, or more broadly 'Integrated Management', that seek to reduce and optimise the chemical applications and farm inputs in general and include whole farm management systems that promote efficient use of resources and land. They increasingly incorporate social and governance dimensions of ethical farming (e.g. good labour relations, animal welfare, and broader biodiversity care). For instance, the United Nations Food and Agriculture Organisation has recently promulgated the Sustainability Assessment of Food & Agriculture (SAFA) in an attempt to harmonise this growing and diverse range of sustainability assessment schemes (FAO, 2013). This raises an important question that we examine in this paper: Are organic standards sufficient to secure ecosystem services in the broader way that SAFA and other frameworks are now promulgating as necessary to ensure sustainability and resilience of farming?

This paper begins by briefly reviewing some of the results of the ARGOS project, a nine-year longitudinal study of organic and other farms in New Zealand. Next we present a broad 'gap analysis' between the Organic standards and principles and the new dimensions of sustainability incorporated into the SAFA. Then we describe the *New Zealand Sustainability Dashboard* project as an example of a tool that could close the gaps between organic standards and IM frameworks like SAFA. We conclude by examining options for the organic movement to better protect and enhance ecosystem services and secure its premiere market position for delivering sustainable and ethical food and fibre production.

2. Does Organic Farming Deliver More, Fewer or Different Ecosystem Services?

The Agriculture Research Group on Sustainability (ARGOS) was a transdisciplinary project measuring the ecological, economic and social outcomes from over 96 farms in New Zealand between 2004 and 2012. The project sought well-replicated and long-term research of whole working farms from different land use intensities. It compared economic, social, environmental and farming practice outcomes between Organic, "integrated management" (IM) and "conventional" orchards and farms (Campbell et al., 2012a, b). The Organic panels were certified as following organic standards. The IM panels had adopted a market assurance scheme that incorporated several principles of best farming practice, including elements of integrated pest management and optimisation of farm inputs. The "conventional" farmers did not adhere to any collective market assurance protocols. Examination of several hundred parameters tested an overarching null hypothesis of the study: H_o: *economic, social and environmental outcomes are the same for organic, integrated management and conventional farming systems.*

One commercial farm or orchard from each available farming system was chosen in each of 12 clusters for each sector ('kiwifruit, 'sheep/beef' and 'dairy') spread throughout New Zealand (Campbell et al., 2012a). Clustering ensured that soils, topography, climate, ecological constraints and rural community drivers were similar for each farming approach in a given vicinity. Spreading the clusters ensured a more representative test of the null hypothesis across several regions of New Zealand. There are no IM dairy farms and all conventional kiwifruit orchards have converted to IM in New Zealand, so only the sheep/beef sector had all three farming systems available for comparison. General Linear Modelling used a blocked design to remove the effects of cluster from statistical tests of the main effects of farming system on outcomes. The dairy farm panels were monitored before conversion of half of them to organic farming, so in that case we could use a Before-After-Control-Impact approach to test whether adoption of certified organic standards causes changes in outcomes. Sheep/beef and kiwifruit farms had converted to organic or IM farming systems long before the ARGOS study began, so any observed differences in current performance of the farms will only reflect their farming system practices if we can safely assume that sustainability indicators and performance were about the same before their conversion to organic or IM methods occurred. ARGOS therefore provided a well-replicated and relatively long-term comparison of outcomes on real working farms following different market assurance protocols with outcomes on a reference group of non-assured ("conventional") farms.

2.1 Provisioning Services Are Reduced on Organic Farms

Farmers primarily tune production landscapes for efficient production of food and fibre: the key provisioning service. A consistent finding of the ARGOS project was that production per hectare of land was much reduced in organic farming. For example, dairy farms converting to organic showed a consistent decline in production (milk solids/ha) relative to conventional dairy farms over a five year period (Figure 1). The largest difference in production was observed once converting farms became certified as organic growers, with organic farms producing only 69% of that of their conventional counterparts. Milk production was already lower on converting farms before they sought organic certification. This suggests that there was something about those farming families, their land or their existing farm practices before they actually formally adopted certified organic methods that resulted in lower production. This serves a clear warning that many organic vs non-organic farm outcome comparisons may provide only quasi-experimental evidence that changes in ecosystem services including yields are caused by the organic farming practices themselves. A formal experiment would require random allocation of families and land to each panel, whereas in real life the existing orientation of the farmers or even characteristics of their land or economy may have predisposed some to go organic or IM, and others to remain conventional. Our results demonstrated that a mix of both predetermined and causally driven organic farming practice effects caused lower production because initial differences from conventional colleagues greatly increased as dairy practices consolidated and certification was conferred.

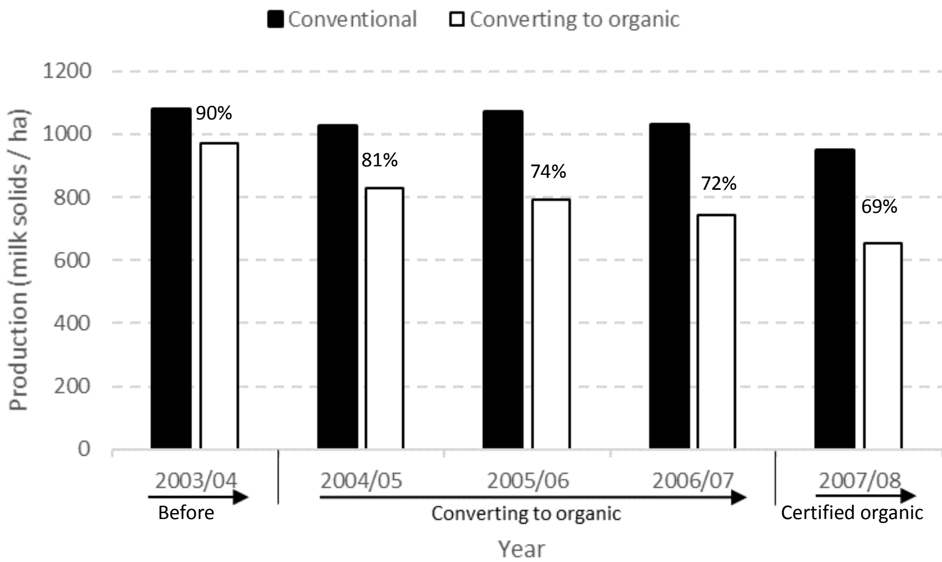

Figure 1. Annual production of dairy farms (milk solids / ha) for conventional farms and farms converting to organic, from the ARGOS project. Percentages of organic (converting to) production relative to conventional production is indicated for each year (Campbell et al., 2012a). Production measures have not been adjusted for land used to produce feed supplements imported from other farms

Comparative provisioning efficiency between sectors can best be summarised by comparing the gross energy outputs and inputs per hectare of production land. A 24.5% reduction in energy production per hectare was observed on ARGOS organic green kiwifruit orchards compared to IM counterparts, and organic sheep and beef farmers produced on average 17.5% and 29.1% less energy than their IM and conventional counterparts respectively (Norton et al., 2010). The same general pattern for reduced production per hectare has been observed in organic systems across the board when compared with more intensive agricultural systems that drive increased production by imports of ecological and energy subsidies (e.g. Sato et al., 2005; Rozzi et al., 2007). However, energy inputs (from fertilisers, pesticides, supplementary stock feed and electricity) to organic ARGOS farms were also much reduced compared to IM and conventional farms, so they rely less on ecological and energy subsidies for production. The net efficiencies of production from an energy point of view ("Energy Return on Investment", EROI) were therefore remarkably similar between all farming systems within the sheep/beef sector; but 13.4% less efficient on organic compared to conventional dairy farms; and 12.5% less efficient on organic compared to IM green kiwifruit. From an overall energy systems efficiency point of view then, organic ARGOS farms were of similar or slightly reduced in efficiency. However, if efficiency is calculated purely as production per hectare of land used, organic farming would be judged as a far less efficient way of delivering provisioning services.

Two broad 'land allocation' paradigms have been promulgated for provisioning a growing world human population without undermining ecosystem services: a "land-sparing" approach promotes more intensive farming of land that is tuned for maximum productivity so that more land can be protected (often reserved) for other services such as biodiversity conservation (Lindenmayer et al., 2012); a "land-sharing" approach promotes farming practices that maintain natural capital and all the ecosystem services from the same land that produces food and fibre. Along this continuum, organic agriculture is potentially less effective in a land-sparing strategy because reduced productivity on farmland may trigger more conversion of ecosystem service refuge areas to farmland or forestry. However organic farming will enhance land-sharing outcomes if it enhances regulating, supporting and cultural services in the production spaces (fields) of farming landscapes. This underscores that judgements about net benefits of organic production compared to non-organic approaches are scale dependent and coupled to an underlying land allocation model for maintenance of ecosystem services. More research is needed to test whether lower production on organic farms indeed reduces land-sparing, or whether any such environmental deficit is more than made up for in biodiversity benefits from land-sharing .

2.2 Enhancing Biodiversity for Supporting and Regulating Cultural Services

Organic farming standards traditionally concentrated on: prohibiting the use of xenobiocides and xenobiotic chemicals as inputs into food; only allowing naturally occurring (eobiotic) fertilisers (synthetic nitrogen fertilisers are thus prohibited) and other "inputs"; banning transgenic and similar technologies and their products; increasingly restricting nanotechnology, within a framework that is focused on enhancing soil health and maintaining the 'wholeness' of food thus produced. There is now a substantial body of research showing that this can affect the abundance of pests, weeds and beneficial biodiversity in direct ways. ARGOS found a greater variety of plants growing under shelterbelts (Moller et al., 2007) and higher species richness and abundance of invertebrates within the production areas (eg. Todd et al., 2011) of Organic compared to IM Kiwifruit orchards. Higher numbers of predators, parasitoids, herbivores, fungivores and omnivores in the organic orchards compared with those under IM are expected to result in more resilient ecosystem services in the organic orchards. The emergence of indirect effects in ecological food webs is of particular interest: might enhanced biodiversity or other ecosystem changes sufficiently substitute for the regulation services normally provided by chemical applications on conventional and IM farms? If so, more biologically efficient, inexpensive, practical and safe production can be expected from organic farming.

Biodiversity makes ecological systems adaptable and resilient to biophysical changes in production landscapes by supporting and regulating ecological processes needed for production of food and fibre. Community ecology has repeatedly emphasised that some species ('keystone species') have inordinate effects on other species in food webs, and some ('ecosystem engineers') are pivotal in creating habitat for whole new foodwebs and ecological processes. For example, earthworms comprise a major component of the animal biomass (non microbial) in soils and contribute to a range of ecosystem services through pedogenesis, development of soil structure, water regulation, nutrient cycling, assisting primary production, climate regulation, pollution remediation and cultural services (Kopke, 2015, this volume). The ARGOS study revealed higher earthworm density in organic kiwifruit orchards, but there was no evidence of them differing between farming systems for the dairy or sheep & beef sectors (Figure 2).

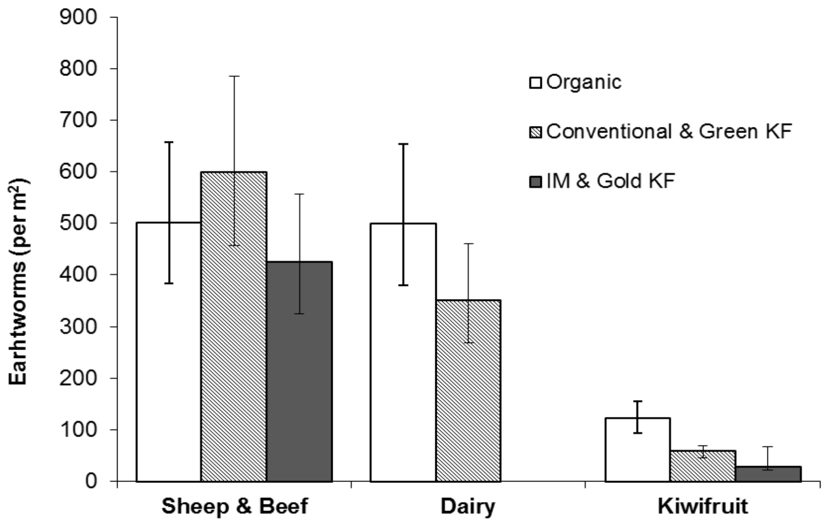

Figure 2. Earthworm density under different management systems for 36 sheep/beef, 24 dairy and 36 kiwifruit farms. Note that 'integrated management' was not available for the dairy farming sector and both Green and Gold Kiwifruit were grown under IM protocols. The error bars depict ± 1 standard error (Sources: after Carey et al., 2010)

The ARGOS project assessed whether orchards managed under an organic system supported higher bird density and diversity than those under two different IM systems (Gold and Green Kiwifruit). Birds were researched because they are often 'top predators' in food chains (and thereby sensitive to ecosystem change), relatively easy to monitor, conspicuous and loved by many consumers. This makes them potential "Market Flagship" species for promoting sustainable farming practices and ethical purchasing by consumers (Meadows, 2012). Higher densities of all New Zealand native bird species (insectivores and nectar-feeders) were detected on orchards managed under organic systems, relative to IM orchards (MacLeod et al., 2012). This lends support to the hypothesis that organic farming systems sustain enhanced biodiversity compared to non-organic counterparts (Bengtsson, Ahnstrom & Weibell, 2005; Hole et al., 2005). However the introduced bird species were an order of magnitude more abundant on the orchards than native species and there was no evidence that their abundance differed between farming systems. The New Zealand public have an overwhelming preference for conserving native and endemic species rather than introduced ones, mainly because the native biota are closely embraced as part of New Zealand's national identity and conservation responsibilities. However European consumers of New Zealand produce may be most concerned by the support of their own threatened farmland species that have been introduced to New Zealand and flourish there. This demonstrates a need for a more nuanced focus on particular biodiversity that might have particular functional roles or particular biocultural significance in agriecosystems rather than a simple binary expectation that organic agriculture enhances biodiversity across the board.

2.3 A Need to Manage More Than Farming Inputs

The above examples from the ARGOS project lead us to emphatically endorse the calls by Barberi (2015, this volume) and Niggli (2015, this volume) to focus on functional biodiversity. But we go much further to stress that further enhancement of sustainability of organic agriculture depends on finding and then managing the drivers of variation in those important animals and plants and key social-ecological systems processes. For example, pesticide loadings and woody vegetation cover proved to be more influential predictors of native bird densities than 'management systems' on New Zealand kiwifruit orchards: native bird density was lower where more pesticides were applied and higher on orchards with more woody vegetation (MacLeod et al., 2012). The presence of woody vegetation, while not considered in organic standards, provide vital ecological refuges and habitat for native New Zealand biota (Moller et al., 2008). We expect a synergistic interaction where the benefits of low toxicity of farm inputs will lift the average native bird abundance all the more above that of its non-organic counterparts if diverse and extensive woody vegetation is also retained. If organic farming actively promoted or even required provision of more woody vegetation on farms and orchards, we predict even higher density of birds would be found on organic farms. Another ARGOS example concerned spiders and beetles that provide important ecosystem services on dairy farms. Organic dairy farms and fenced shelterbelts supported 40% and 67% higher densities of spiders than conventional dairy farms and unfenced shelterbelts, respectively (Fukuda et al., 2011). Shelterbelts of native plant species supported higher species richness of native spiders and beetles than shelterbelts of exotic plants. So conversion to organics lifts biodiversity to some degree, but a combination of organic methods, fencing off shelterbelts and planting more native tree species in shelterbelts will provide all the more ecosystem services and biodiversity conservation on New Zealand dairy farms.

2.4 Sustainable Intensification: Might Organic Farming Be Particularly Beneficial in More Intensive Agriculture?

There is a clear need to transcend research from simple tests for significant differences in outcomes from organic, IM and conventional farming to testing larger scale hypotheses about the size, direction and reason for differences in ecosystem services between farming systems. An example is to test whether aspects of organic farming ameliorate the unwanted effects of landuse intensification. The ARGOS team proposed a second meta-hypothesis H_1*: Differences in economic, social and environmental outcomes between organic, integrated management and conventional farming are greater for more intensive farming sectors and farms.* This emerged from ecological first principles – the higher the rate of application of ecological subsidies (i.e. anthropogenic subsidies of materials from outside an ecosystem's boundary, Pilati et al., 2009) such as artificial fertilisers and suplementaty feed for livestock, the greater the alteration of local ecology through immediate and direct ecological disturbance effects. Organic restrictions might lessen the force of such subsidies partly by their more benign nature and partly indirectly because organic farms are generally less intensive operations (reduced stocking rates, less extraction of nutrients and materials, lower productivity as seen in Figure 1 and EROI comparisons).

We had insufficient replication of sectors to fully test this intensification hypothesis, but preliminary observations are consistent with it. For example, the relative effect of farming system on earthworm abundance was much greater in the most intensive sector (Kiwifruit) than the next most intensive farming (dairy), and there was no evidence of a difference between systems in the least intensive sector (sheep & beef). Similar interactions between sector intensity and soil structure and its macronutrients were observed (Carey et al., 2010). Rudimentary binary comparisons of organic and non-organic outcomes abound in the literature, but so far they have not led on to testing higher order drivers why these differences occur, or why they are larger in some agriecosystems than in others. Halberg (2015, this volume),Vaarst (2015, this volume) and Heckman (2015 this volume) have all empahsised the need for 'eco-functional intensification'. If the ARGOS intensification meta-hypothesis is true, organics has special value in supporting ongoing intensification of agriculture without damaging ecosystem services.

2.5 Organic Agriculture As an Agent for Change: A Role for Cultural Services

Our analysis thus far has mainly concerned ecological dimensions of ecosystem services. However discovery of the social and economic drivers of farming practice are also fundamentally important for sustaining coupled social-ecological systems (e.g, Rosin et al., 2008, Campbell et al., 2012b). The long term resilience and sustainability of agriculture depends on learning and adapatability (Vogl 2015, this volume). Transformation of agriculture to protect and enhance ecosystem services will depend on direction, motivation, "opportunity to perform" and ability (Tuuli, 2012; CEO Group, 2015). This means that farmers and policy makers will need an awareness of the need to change, the values and motivation to act in beneficial directions, and the capacity to make the required changes. Cultural ecosystem services include the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Millenium Ecosystem Assessment, 2005). We consider cultural services as potentially crucial for underpinning adaptability by building a sense of place and responsibility to other places and people, knowledge of the need and options for change, and forming core values to motivate change or strike balances and trade-offs between short term economic rewards and land care.

The ARGOS researchers used both formal Qualitative Analysis methods of semi-structured interviews and nationwide questionaniares (Fairweather et al., 2009a) to explore individual farmers' economic, social and environmental orientations (Table 1). Organic farmers displayed a much broader social and environmental 'breadth of view', were more likely to innovate, and were less focussed on economic success than their non-organic counterparts (Table 1). All these differences will make organic growers more aware of threats and opportunities for sustainability, and perhaps more ready to change when needed.

Table 1. Relative orientations of organic and non-organic farmers to four aspects of farming. A score between +1 (strong support) to – 1 (strong aversion) was determined by a Factor Analysis of each farmers' answers to a nationwide survey. (Sourced from Hunt et al., 2011).

Orientation	**Non-organic (n= 338)**	**Organic (n = 157)**	**t-Test significance**
Economic Focus (relative importance of economic success of their farm)	+0.07	-0.15	0.034
Social Breadth of View (relative contribution of their farming to wider society benefits)	-0.17	+0.37	<0.001
Environmental Breadth of View (relative importance to consider effects of their farming beyond their own land)	-0.16	+0.35	<0.001
Innovation Likelihood (relative willingness to experiment with their farming practice)	-0.21	+0.45	<0.001

3. What Should Organic Farming Be Compared Against?

Much of the literature on organic agriculture presents binary comparisons of organic farming outcomes and their provision of ecosystem services compared to non-organic farming. The ARGOS results that we briefly summarised above emphasise the danger in such simplified binary comparisons: a rapidly growing group of IM farmers are adopting market accreditation and monitoring schemes to fine-tune their farming practice in ways that purport to be more sustainable. Outcomes from these IM growers are sometimes quite different from so-called "conventional' farmers. For example, in the ARGOS project, macoinvertebrate communities and ecosystem functioning were negatively impacted in streams running through conventional sheep/beef farms, but there was no evidence of them being different in Organic and IM farms (Magbanua et al., 2010).

The results of qualitative analysis of interviews (Campbell et al., 2012b) and the responses of IM, Organic and Conventional growers in a nationwide survey to questions about environmental, social and economic dimensions of farming sustainability (Figure 3) both emphasised that IM growers are different from conventional ones. The IM growers were not just intermediate between organic and conventional (had they been, the multidimensional scaling diagram would have approximated E in Figure 3). Instead they viewed farming in very different ways from both conventional and organic growers. Differences between the panels were relatively less for financial and social orientations (the same conclusion is demonstrated in Table 1), but organic farmers were particularly distinct in orientation to environmental and production concerns. We do not know what drives the differences already evident nor, potentially more crucially, how they might change in future because of the engagement of IM farmers in the market accreditation and sustainability best practice monitoring frameworks. Clearly there are many clusters of "greeness" in orientation within all types of farming approaches and the way these are influenced by market accreditation and reward is an important dynamic for guiding the way the organic movement positions itself in markets and as environmental friendly farming advocacy (Fairweather et al., 2009b; Campbell et al., 2012b). In the meantime we urge researchers and market advocates of organic agriculture to not simply lump all non-organic farmers into one pool, especially since the eco-verification and wider sustainability claims of the IM farmers could undermine the premiere and historical monopoly of market assertions that organic agriculture certification gaurantees sustainable and ethical production.

4. On What Basis Should Stakeholders Compare Sustainability of Farming Systems?

In view of the rapidly rising prominance of the IM and market assurance farming protocols that are making sustainability claims, we sought to measure the degree of congruence and divergence between their tenets for ensuring sustainability and those incorporated into organic farming. The organic 'brand' is now synonymous with the organic standards, i.e., the 'rules' of organic farming systems. Traditionally organic sustainability claims are therefore based primarily around assumption that restricting the nature of farm inputs will protect and enhance ecosystem services and produce safer and higher quality food and fibre within a more ethical production system. More recently the standards have been mapped to and endorse four core 'IFOAM principles' (IFOAM, 2005): *Health* - Organic agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible; *Ecology* - Organic agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them; *Fairness* - Organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities, and; *Care* - Organic agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment. A comprehensive summary of the standards and principles (which we will henceforth collectively refer to as 'organic norms') is found in the Common Objectives and Requirements of Organic Standards (COROS). We chose to compare organic standards and principles with the FAO's SAFA framework because the latter is a recent, comprehensive and broadly applicable set of sustainability principles that attempts to integrate the features of a large number of IM and market assurance approaches.

4.1 How Many of SAFA's Sustainability Criteria Are Covered by Organic Principles?

We searched for a match between each SAFA indicator and its description with the IFOAM 2014 and BioGro New Zealand organic standards. A five point mark ranging from 0% (no correspondence), 25%, 50%, 75%, to 100% (complete correspondence) was scored for each SAFA indicator. Scoring was conducted by the lead author who has 24 years' experience of working with organic standards internationally to help make it as consistent and accurate as possible.

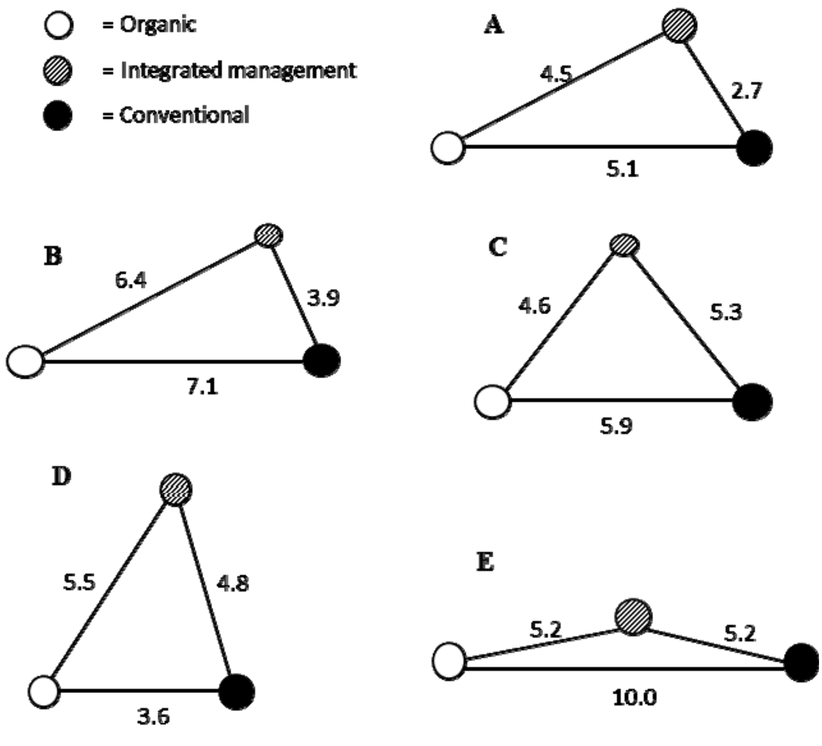

Figure 3. Multidimensional scaling to measure differences in the way New Zealand organic, IM and conventional farmers answered questions about different dimensions of farming. The numbers on each diagram are 'multivariate distances', a measure of how distinct the farmers from each farming system were in the responses to the same questions **A**: Production performance (9 questions), **B**: Environmental performance (17 questions), **C**: Social indicators (14 questions), **D**: Financial indicators (11 questions). **E**: a hypothetical example of IM as an intermediary between organic and conventional farming systems. (Source: The questionaire results are described by Fairweather et al. 2009a, and the multidimensional scaling is an unpublished analysis by Lesley Hunt)

Figure 4 replicates the radar charts that are commonly used by SAFA to depict performance at each spoke of a "wagon wheel" that depicts a family of criteria required for sustainability. The inner red zone represents failure of compliance when used in real SAFA assessments, but in our case we use it to show 0% congruence of the organic standards with SAFA requirements. We equate the inner and outer margins of the next amber zone with

25% and 49% congruence, and so on outwards until 100% congruence is plotted against the outer margin of the deep green zone around the wheel's perimeter. The dark line in Figure 4 represents average congruence of organic standards for several indicators within each SAFA sustainability dimension.

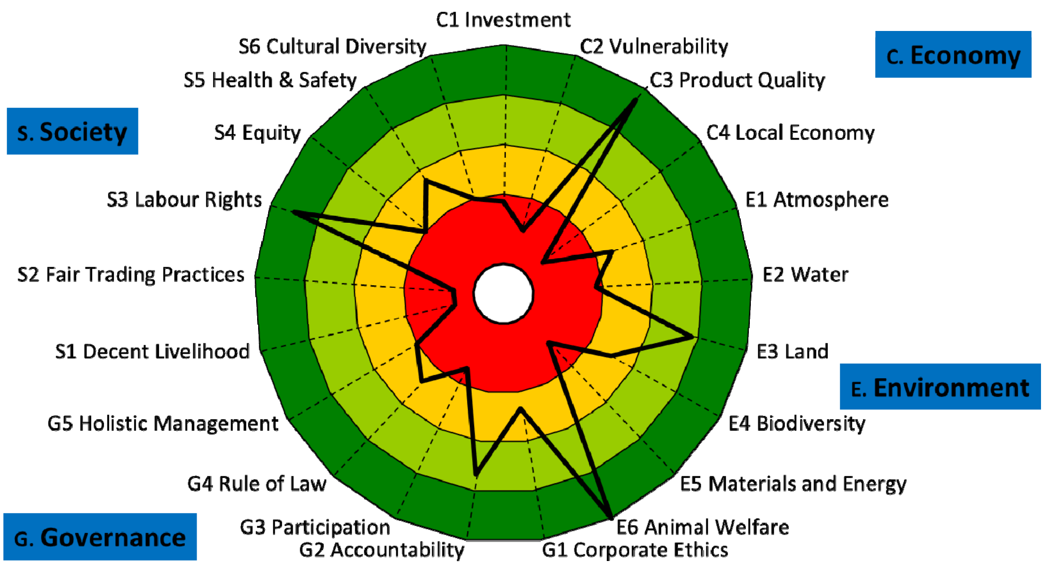

Figure 4. Sustainability scores of the organic standards when using FAO's SAFA criteria for sustainable food and fibre production. The black line indicates the degree of congruence between organic and SAFA sustainability criteria (the further the black line is from the centre the greater the congruence). Successive zones indicate grades of sustainability performance from deep green (most sustainable) around the outside to red (least sustainable) in the inner core. The SAFA framework has been customised to better meet New Zealand conditions by the Sustainability Dashboard

The organic standards are almost completely in agreement with SAFA on issues of Product quality & information, Animal welfare and Labour rights; but organic standards are virtually silent on the need for Fair Trade, providing a decent livelihood, contributing to local economy and minimising reliance on materials and energy. Even aspects of environmental and land care (like biodiversity, water and atmosphere) that are explicitly required in SAFA assessments are only partially embraced by the organic standards.

Our overall average score for congruence (the average distance of the dark line from the centre of Figure 4) was 36%. It is important to remember that just because the organic standards do not fully cover a given sustainability criterion (and so score 0% or 25% if partially covered), many of the organic farms may nevertheless be performing very well on that dimension of sustainability (indeed our ARGOS examples in Figures 1-3 and Table 1 above suggest this is the case). Our aggregated score would only measure performance if the organic farm was fully achieving the explicit requirements of organic standards and no more. The comparatively low overall score simply emphasises that SAFA and many similar sustainability assessments are including a much wider set of necessary and quite explicit conditions than those required for meeting organic standards and principles.

There is a remaining emphasis on organic input restrictions: 47% of 90 COROS standards are framed in terms of farming input restrictions, 35% concern more general principles and outcomes, and 18% regulate internal consistency of the organic standards. The IFOAM principles are cast in such general and abstract terms that they are difficult to interpret and judge in terms of day-to-day farming decisions, whereas rules on organic farm input restrictions are precise, measureable and voluminous. For example, BioGro NZ, one of the two New Zealand export organic certifiers, covers the six COROS items on fairness, respect and justice, equal opportunities and non-discrimination in just a third of a page (132 words) of its 2011 certification standards, yet the "Directory of BioGro Certified inputs for producers" 2011 for facility management, dairy, crops, bee keeping, livestock soil and seeds, lists 251 different types of inputs, with some inputs having multiple individual approved suppliers, e.g., fish fertilisers list 88 different fish fertiliser products, with the directories covering 26 pages. AsureQuality, the other organic certifier in New Zealand, did not include a section on social justice until its 2013 (No 5) version of its standards and devotes just 317 (0.7%) words out of 43,782 to social justice.

4.2 How Many of the Organic Standards *Are Covered by the SAFA Sustainability Criteria?*

We then used the same scoring methods to perform the reverse comparison: how well would a farmer that is fully meeting SAFA performance criteria score if judged against organic standards? Standards do not have the equivalent of SAFA indicators. Instead they are more akin to a legal document with a large number of specific details. Therefore the COROS were used to undertake the comparison. COROS, also called the "The IFOAM Standards Requirements", is designed for use in international equivalence assessments of organic standards and technical regulations and provides the basis for assessing equivalence of standards for inclusion in the IFOAM Family of Standards.

For each 'Objectives and Requirements' in COROS we estimated that a fully compliant SAFA farmer would on average meet 74% of the organic norm requirements. An excellent non-organic farmer, according to SAFA criteria, performs well in terms of the requirements for organic farmers to be systems oriented, minimise pollution and land degradation, protect animal welfare and health, and act with fairness and respect (Figure 5). However, more stringent requirements on organic farmers for long-term and biologically-based soil management, avoiding synthetic inputs, and especially in avoiding unproven and unnatural technologies remain as points of difference in organic farming (Figure 5). These points of difference are reflected in very specific requirements for organic growers to avoid transgenic organisms, irradiation, certain breeding technologies and nanotechnology (Figure 6).

5. A Need for Integrated Sustainability Assessments of Organic Farming

In 2012, the ARGOS project received funding from the NZ Government Ministry of Business, Innovation and Employment (MBIE) and several industry co-funders to develop a *New Zealand Sustainability Dashboard* for primary sectors (Manhire et al., 2013). This change of direction was to assist New Zealand farmers to measure and report across a rapidly expanding set of sustainability criteria incorporated into market assurance and monitoring schemes, and partly to bridge the gap between organic standards and such schemes (Figure 4-6). However, our change of emphasis was also driven by realisation that no one farming system would deliver hugely advanced sustainability or ecosystem services compared to any other. We were more struck by the large variation in sustainability outcomes between individual ARGOS farms within the same farming system panel than in relatively slight shifts in the average performance of each panel. Lifting the overall sustainability and resilience of New Zealand agriculture will depend more on assisting all farmers to do better, not from advocacy of a single farming system approach as a one-size-fits-all solution to the challenges and opportunities for future farming. Our goal was to create a practical, locally and globally relevant package of tools to turn compliance and auditing requirements into a learning opportunity for farmers and agricultural processors.

Internationally recognised frameworks and their key generic sustainability performance indicators have been co-opted to ensure that overseas consumers can benchmark and verify the sustainability credentials of New Zealand exported products. It is a participatory, industry-led approach to measuring and reporting sustainability allowing farmers to log mainly self-assessed sustainability measures into an online network. The Sustainability Dashboard will allow for instant benchmarking, trend analysis, progress towards targets and provide warnings when trigger points indicate a need for intervention. The Dashboard will also be equipped with an automated reporting system to benchmark a participating farmer's performance with that of others producing similar goods, or using similar farming technologies (eg. irrigation). The overarching framework developed in this project closely aligns with the SAFA sustainability goals and criteria but the emphasis of different parts of the assessment is adjusted to tune to New Zealand ecological, social, economic, and governance constraints and opportunities. Relatively standardised measures of farming performance will be shared between farmers, industry advocates, policy makers and consumers. A basic version of the dashboard is currently being customised and extended to meet the needs of New Zealand organic growers in particular so that organic producers can formally measure and demonstrate their performance against many of the sustainability criteria demanded by competing market assurance programmes as well as those needed for BioGro organic certification.

6. Conclusions: Are Organic Standards Sufficient to Ensure Sustainable Agriculture?

Organic agriculture often leads to enhanced ecosystem services, as emphasised by several papers in this special journal issue (Delate et al., 2015; Abbott, 2015; Cambardella, 2015) and our selection of examples from the ARGOS project (Figure 2, Table 1). This will assist land-sharing approaches to multifunctional agriculture which can be safely assumed to promote sustainability and agricultural systems resilience. However, productivity of organic farming is often reduced compared to IM and conventional farming and this could undermine land-sparing approaches to achieving global food security while conserving ecosystem services over larger spatial scales. Some indicators of ecosystem service were relatively unchanged between farming systems, probably in part because other ecological, social, economic or governance constraints trump the effects of organic input restrictions. Provision of ecological refuges, reduced reliance on ecological subsidies, specific farming decisions like fencing shelterbelts or planting native rather than introduced trees have strong positive impacts on ecological ecosystem services, but are not part of the standards and specific requirements of organic certification. More generally, our gap analysis emphasises that organic standards only cover less than half of the broader social, economic and governance criteria for sustainability of any food and fibre production system. In contrast, farmers performing well according to accepted sustainability criteria (i.e. SAFA) would cover the majority of the organic farming requirements. Agriculture is a complex and adaptive system that responds to coupled social, ecological, economic, and governance feedbacks. It seems obvious that simple adherence to organic input restrictions and standards cannot possibly be sufficient in itself to secure sustainability and resilience. Input restrictions remain the predominant tenets of the organic standards, but wider organic principles have recently been incorporated. Current developments of the concept of Organic 3.0, which includes an attempt to demand that organic farms should demonstrate a degree of continuous development vis-à-vis the principles and goals rather than just comply with rules (IFOAM 2015), is a valuable step in this direction. We encourage strenuous promulgation of these valuable general organic principles to dispel a general and outdated notion amongst growers, policy makers and customers that organic farming is simply about restriction of certain types of potentially dangerous farm inputs. We are not advocating that organic farmers become entirely like their IM counterparts – it is vital that the organic movement retains its certified points of difference that underpin price premiums and philosophy – but we do urge organic growers to adopt the best of the IM approaches that do not compromise organic principles.

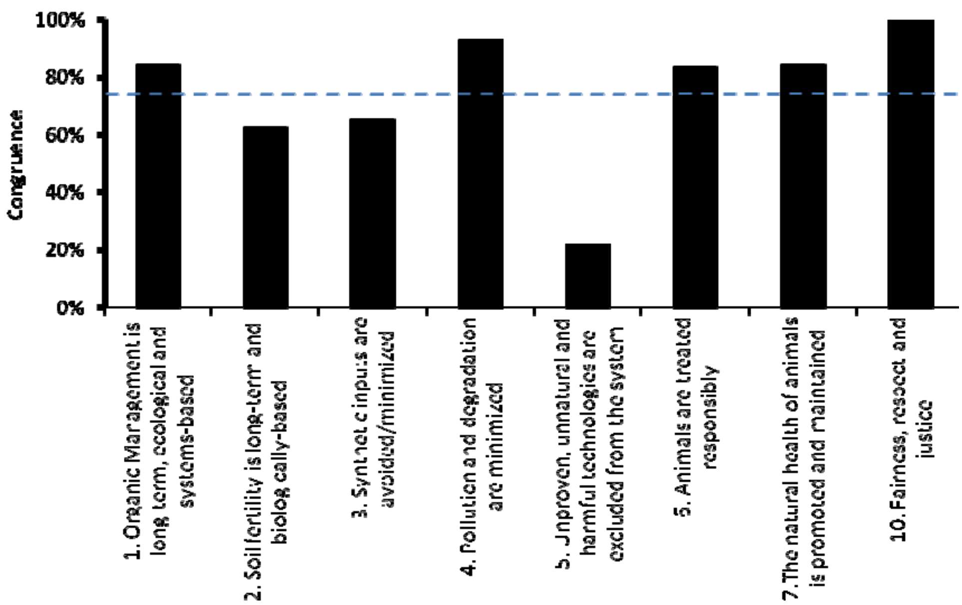

Figure 5. Congruence scores in higher order themes of a producer that is fully compliant with FAO's SAFA when judged against the IFOAM organic standards. The dashed line indicates the average degree of congruence (74%) for 78 specific requirements of organic production

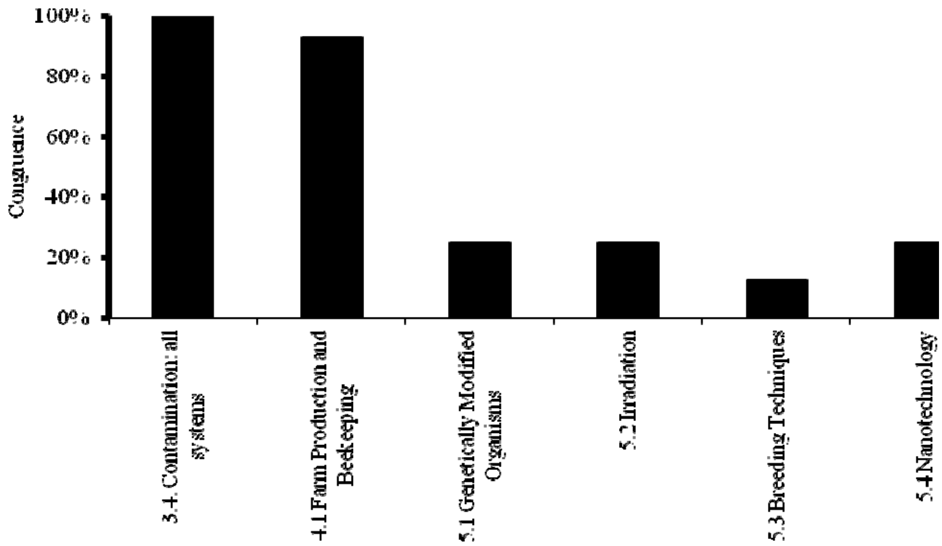

Figure 6. Congruence in some selected detailed criteria of a producer that is fully compliant with FAO's SAFA when judged against the IFOAM organic standards

This broadening of emphasis and an organic market share defence strategy could direct best farming practice, monitoring and reporting across a wider set of sustainability criteria than simply compliance with the existing organic standards. Many of the broader criteria that are now being included in general agricultural sustainability and resilience assessments will support, and be supported by, the organic principles, even though they are not explicitly codified in the standards. Some form of 'Organics Plus' eco-verification to match the claims of green market assurance programmes could help organic growers challenge and learn from IM approaches. Each version of the New Zealand Sustainability Dashboard is hosted by a particular agricultural sector that will adjust their emphasis and investment in measuring performance to match their own particular opportunities and challenges. An organic production dashboard could therefore emphasise points of difference in organic farming methods, especially strategy to minimise risk by restricting the nature of farm inputs, while still measuring the comparative performance of organic farming on the additional dimensions demanded by other market competitors. We conclude that adherence to organic standards undoubtedly promises some gains in ecosystem services, including the crucial cultural ones that assist systems adaptability and learning – but we also assert that organic standards will need to be combined with more targeted farming systems interventions across multiple criteria to maximise sustainability of organic farming.

Until detailed measurement of the comparative performance of IM and organic farming over this wider set of criteria are tabled, it is impossible to judge whether the beneficial effects of restriction to organic inputs more than outweighs the benefits of applying a wider range of sustainability interventions while still allowing chemical inputs and similar technologies on IM farms. However, we are not advocating just another round of binary comparisons of outcomes from organic and IM farming, nor from IM and conventional farming. A safer and globally more effective approach is to find local solutions for raising ecosystem services of all farms, be they organic, IM or conventional. Systematic and targeted measurement of key agricultural ecosystem drivers, will provide feedback to enable individual farming families to locally tune their farming practices for efficient and profitable production while leaving the land fit for future generations' survival and enjoyment.

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Organic Research and Development in Denmark (1996-2010) – Effects on the Organic Sector and Society

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Abstract

The ICROFS (International Centre for Research in Organic Food Systems) has conducted an analysis of the effects of organic research in Denmark (1996-2010) on the Danish organic sector and on society in general. Over these 15 years, three national programs and one program with European collaboration have been implemented in Denmark, financed via special government grants that amounted to just over 500 million DKK (approx. € 67 million—or approximately $ 80 million). The analysis itself was carried out as a compilation of information from three perspectives, each of which has been independently documented:

- Interviews with (representatives of) end-users of results from research and development (R&D) investigating their assessment of the challenges in the sector and solutions developed from 1996-2010
- Assessment of the R&D endeavours in different thematic areas (dairy/milk, pigs, crops, etc.) as they related to end-users and the stated challenges at that time
- Documentation of the dissemination of R&D results in relation to themes and challenges in the sector

The results showed very good correspondence between end-users' perceptions of the challenges overcome in the sector, the R&D initiated in the research programmes, and the dissemination of research results and other forms of knowledge transfer. The analysis documented direct effects of the research initiatives targetting the challenges in the sector such as higher yields, weed and pest control, animal health and welfare, the potential for phasing out the use of antibiotics in Danish dairy herds and reducing the problems caused by seedborne diseases. It also describes where research did not contribute as much to overcoming challenges. In contrast, the analysis showed that the effects of the research in the organic processing industry and among relevant governmental and non-governmental organisations were of a more indirect character. Research has helped stabilize the supply and quality of raw materials at a time of growing demand and sales. Organic research also generates new knowledge and leads to new opportunities that can provide inspiration for a green conversion, product diversification and growth also in conventional agriculture. The analysis showed that research under the national research programs overall have been very applied and directed at the barriers in the sector in order to support the general market and growth conditions for the organic sector. Having laid a solid foundation, the private sector has been able to take advantage of commercial opportunities when demand grew, while adhering to the organic policy objectives of the market-driven growth in the organic sector.

Keywords: organic research, analysis, effect, impact analysis, food production, organic sector, organic growth, Denmark

1. Introduction

1.1 The organic Sector in Denmark

Since the mid-1980s organic farming in Denmark has been promoted through political initiatives in order to respond to consumers' demand for organic products. The policies of governments during the past decades have included financial support for the conversion of conventional farms, regulation and control, advisory services, information campaigns, and education and research in organic farming (Halberg et al., 2012). At the end of the 1980s and start of the 1990s Danish research in organic farming was primarily carried out on private farms and in long-term crop rotations at research stations around the country (Halberg et al., 2012). With the first action plan [Action Plan I (Det økologiske Fødevareråd, 1995)] for the promotion of organic food production prepared by the Ministry of Agriculture and Fisheries in 1995 and followed by Action Plan II (Det økologiske Fødevareråd, 1999) in 1999, research in organic farming was given a higher priority than earlier times, which resulted in the development of a national research program and the establishment of the Danish Research Centre for Organic Farming (DARCOF) [now the International Centre for Research in Organic Food Systems (ICROFS)] – a 'centre without walls' to coordinate these programs as research continued within existing research environments throughout the EU.

From 1996-2010 Denmark had four research programs in organic farming and foods financed via special government grants (one of them with European collaboration). While the first program primarily addressed issues related to the primary production (Halberg et al., 2012) the following programs also included issues related to industry (including processing), society (including environment and health) and the consumer level (including credibility of the sector) (Halberg et al., 2012). In these programs funds were allocated to coordination, communication and dissemination, as well as to knowledge synthesis, research methodology and to research education (PhDs at universities and research centres involved in the research) (Halberg et al., 2012). The centre was able to establish and maintain close contact to the players in the sector via user groups and extensive meeting and dissemination activities in order to ensure the continued relevance of research efforts and applicability of results.

In the same period the organic sector has undergone a strong development from its beginning as a niche market and has become an important part of the Danish food sector. The area under organic farming, including the area under conversion in 2010, was 6.4 % of total farmed area (Statistics Denmark, 2012). Of the total food sales in 2010, 7.2 % was certified organic (Statistics Denmark, 2012) after a dramatic increase in sales from 0.5 billion DKK (approx. € 67 million —or approximately $ 80 million) in 1996 to 5.1 billion DKK (approx. € 684 million—or approximately $ 821 million) in 2010 (Organic Denmark, 2012). Nearly all supermarket chains had a large assortment of organic products and for some product groups, such as eggs and milk, the organic market share was 20-30% of retail sales (Statistics Denmark, 2012).

It is the view of ICROFS that several important factors have contributed to the positive development of the organic sector in Denmark, including support for marketing and the regulatory framework from public and private sectors; establishment of strong institutions in organic farming; entrepreneurs and pioneers in the organic farming, processing and retailing sectors; as well as research carried out in universities, research stations and together with advisors and farmers at private farms.

1.2 Impact Assessment

Impact assessment involves a number of complex issues that are difficult to fully address in a single study (Bloch et al., 2014). Furthermore, conducting cost-benefit analysis and productivity analysis for research is costly (Pedersen et al., 2011). Due to this, it was decided to carry out the analysis as a mixed methods approach, including both quantitative and qualitative methods (Bloch et al., 2014).

The purpose of the analysis of the effect of the organic research was to document the role of research in the development and growth of the organic sector and to achieve a deeper understanding of the utilisation and the effect of the research results in practice. The analysis was published in a report in 2012 (Halberg et al., 2012). The analysis has been conducted by consultants from the Knowledge Centre for Agriculture (now SEGES) (Note 1) and from the Institute of Global Food & Farming (Note 2) as well as staff from ICROFS.

2. Methods

The analysis was based on a triangulation approach (Halberg et al., 2012) to collect qualitative as well as quantitative information from three perspectives (Figure 1), each being independently documented:

1. End-users' (representatives) perception of the R&D results – to investigate the views of stakeholders on how their part of the sector has developed and the extent to which this has been supported by R&D

2. Focus and implementation of R&D research – to investigate the correlation bewteen the resarch projects and the results and effects pointed out by the end-users, as well as comparing research projects with needs identified by the sector and included in the action plans

3. Dissemination of R&D results – to document which results (and feedback) have been communicated between research and the users of research

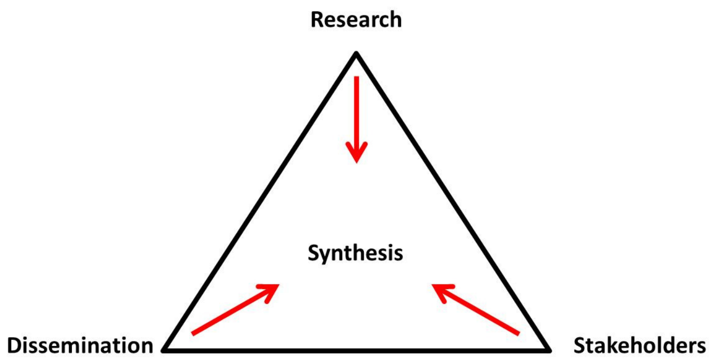

Figure 1. The three perspectives of the triangulation approach used in the organic program evaluation

The purpose of the triangulation method was to create a solid foundation for any conclusions in the areas where R&D could have had an effect. By combining the three perspectives, it was expected that a robust analysis of the effect of the R&D effort in the period in question could be made. The triangulation approach was developed based on an analysis framework of the dynamics of research programing and implementation as illustrated in Figure 2. The illustration includes the traditional interpretation of research, dissemination, and use, but not necessarily as separate and consecutive phases. With the flows of information and interactions between phases and with feedback loops to planning and programming the framework becomes more dynamic and illustrative of how the four organic reseach programs have been implemented.

There has been a continuous influence on research by the stakeholders via a number of processes. These include consumer influence on programs where representatives of the sector influence project focus, and also influence from within the projects, as end-users are deliberately involved with scientists in the design of the experiment. This feedback is not systematically included in the current analysis, although the formal influence on the research themes via DARCOF's user group was addressed. While we in this article focus on the effect of research on users, Figure 2 also illustrates direct research products such as scientific papers, conference presentations and PhD dissertations resulting from these programs.

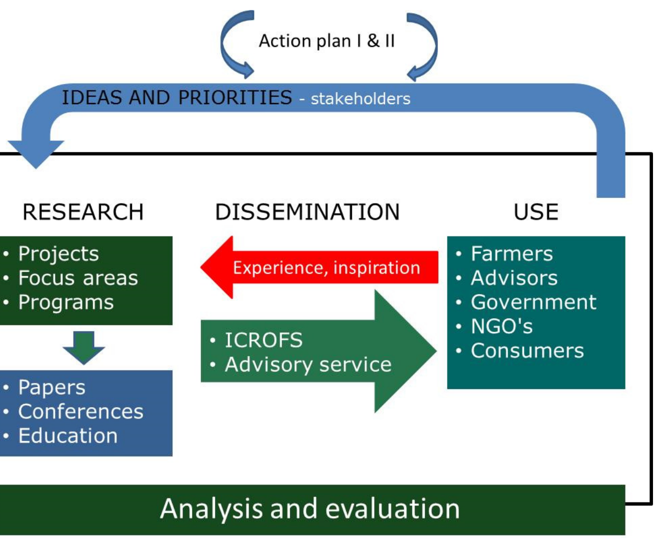

Figure 2. Analysis framework illustrating phases, interactions and communication in the programming and implementation of the four organic research programs

The findings of the investigations of the three perspectives were compared to identify the areas where R&D could be documented to have had an effect and the extent of this effect. The R&D results were judged to have had a positive effect when there was overlap between the end-users' identification of useful results and the dissemination of these results via projects that have focused on these areas – in other words, when there was coincidence between the three perspectives in the triangulation approach (Figure 1). In most cases, these three perspectives were uncovered independently of each other, but in a few cases this has been followed by an in-depth investigation to reveal the link between research and use. This applies to some of the more detailed investigations, where, for example, the results suggested by a scientist as having had a large effect have been verified through targeted interviews with the users.

2.1 End-users Perception of the R&D Results - Approach

This perspective is based on questionnaires and interviews with key persons within the farmer-owned advisory service (in Denmark organised by the farmers' union in local private advisory companies and a central center of expertise as well as the organic movement in Denmark also provides advisory service); with companies in the organic sector; and with a number of other possible end-users in organisations and public authorities.

<u>Primary production advisors</u>: Seven centrally placed advisors within organic crop production, milk, pig, poultry, and fruit/vegetable production, respectively, were interviewed in a systematic process. Fifteen local advisors (dedicated to organic agriculture) in crop production and livestock production were subsequently interviewed using a combination of questionnaires and follow-up interviews. In both types of interviews, the consultants' own understanding of the development in their subsector over the last 10-15 years formed the basis for the discussion. Questions posed included: What were the challenges for the sector, how have they been overcome in practice, how had the production otherwise evolved and to what extent would the consultants attribute this development to the results of R&D? The advisors are in Denmark important for facilitating the linkage between research and farmers and a main channel for communicating and interpretating results to farmers. To ensure that the respondents would have the information needed to determin to what degree the continuing development and improvement in knowledge could be attributed to R&D, the systematic interviews were targeting the advisors as representatives of the end-users. Only in a few cases farmers have been directy involved in the investigations.

<u>Companies</u>: A questionnaire was sent to a total of 15 companies that, partly or exclusively, process and retail organic products. Staff responsible for the organic production was asked to what extent organic R&D has influenced the development of their company and new products and the supply of commodities. For selected cases the questionnaire was followed up by an in-depth interview.

<u>Organisations and authorities</u>: A number of R&D projects have focused on topics relevant for society such as the impact of organic farming on environment, animal welfare, etc., and on consumer motivation for purchasing the products. To analyze the effect of these results, a questionnaire was sent to five persons from four public authorities in charge of legislation in the area of organic agriculture and the environment, and to ten persons from seven relevant, private organisations. Key persons were asked to give their views of the most important challenges that the organic sector had been facing in the period of 1996-2010, and to what extent organic research has contributed to solving these issues.

2.2 Focus and Implementation of R&D Research - Approach

The description of this perspective is based on two main sources of information. First, the range of projects was divided into the thematic areas of cattle/milk, pigs, crops, cultivation systems, etc., based on project descriptions and thematic areas in final reports; the scientists' indications of which results they expect to have had an effect and on whom. Thereafter, the focus of the research projects was compared with the relevant recommendations in the two action plans for the development of the organic sector prepared by the Danish Government's Organic Food Council under the auspices of the Ministry of Food, Agriculture and Fisheries in 1995 and 1999 (Det økologiske Fødevareråd, 1995, 1999).

2.3 Dissemination of R&D Results - Approach

To be able to document the extent to which knowledge and results from R&D projects have been accessible to advisors, an overview of the communications directed at farmers and advisors, scientists and other interested parties was prepared. The Knowledge Centre for Agriculture (VFL) regularly updates advisors with the latest knowledge, and some of this information refers directly to R&D projects and their investigations and results. By carrying out a search for results of the DARCOF projects and on the themes that were identified under perspective 1 (end-users) as important for the different segments of the sector, it has been possible to determine whether new knowledge in these areas has been conveyed to the local advisors and to the farmers. Due to the large number of articles, an exhaustive search has not been made, as sufficient documentation was found for dissemination from projects to end-users in the most important areas.

In relation to all the R&D programs, DARCOF has taken the initiative to disseminate knowledge from the projects via their own and external media, also facilitating that scientists provided articles to the agricultural press and by supporting web-based communication, the preparation of newsletters, pamphlets and events where the results were presented. Since the start of DARCOF II the projects have been required to report and archive their articles and other written communication in the open-access online archive, Organic Eprints (Note 3). This has made it possible to make a thorough analysis of the output of the projects without having to go through each final report. In this way, publications which have been produced after the end of the project – which is typical for peer-reviewed papers – could also be included in the analysis.

3. Results

3.1 End-users Perception of the R&D Results – Findings

Overall the results showed that new research knowledge has had a considerable effect both on the advisory services and on farming practices. The interviewed advisors highlighted, for example, that research results have contributed to higher crop yields (including forage) and improved management of weeds and crop rotations, decreased calf mortality, and higher milk yields and income for dairy cows. Moreover, research and innovations in combined feeding and housing/outdoor keeping significantly improved health, welfare and productivity in pigs and poultry. In Table 1 the main challenges during 1996-2010 in the organic production sector, as identified by the respondents, are listed together with mentioned effects or changed practices at the farm level during the same period of time, the degree to which the challenge was solved, and if research had contributed to the solution.

The private sector respondents provided a couple of good examples of research projects contributing to the development of new products and marketing opportunities, but in general it was found that organic research only to a lesser degree has had an effect on product development. Respondents acknowledged, however, the positive effect of research on the development of the organic market, including growth in volume and turn-over, due to a more stable supply of uniform and high quality raw material. This has, e.g., been a precondition for expanding the processing and marketing of eggs and meat. The government institutions and private organisations responded that research results mainly have had an impact on environmental and animal welfare issues – which had been particularly important in the organic sector from 1996 to 2010. Research had contributed to solving challenges to some or a high degree and had an impact on public awareness and the development of legislation in agriculture, particularly in livestock.

Table 1. Summary of challenges, solutions, and contributions from research as identified by the advisory services for more details see (Halberg et al., 2012)

Challenge	**Success rating (Note 4)**	**Effects/change at farm level**	**Did research (Note 5) contribute?**
Crop Production			
Crop rotations	6	Partial break with conventional thinking	Yes
Nutrients	7	Optimization of fertilization (crop dependent, nutrient source)	Yes
Perennial weeds	7	New strategies for perennial weeds; testing of mechanical weeding	Yes
Marketing	7	Professionalization and credibility of businesses	No
Healthy seed	6	-	-
Fruit and vegetables			
Yields	6	Intensification of fruit production, planting system, selection of variety	Yes
Pests	5	Flower strips (balanced predator-pests populations in vegetables)	Yes
Varieties	5	Regular variety testing, development of stable varieties, quality control	Yes
Weeds	6	New technologies (mechanical control, flaming, soil cover, crop rotation)	Yes
Market growth/ sales	7	Rationalization, efficiency improvements, specialization, consumer focus	Yes
Product Development	5	Consumer focus	-
Org.-conv. interactions	7	Open-house events/farm visits, seminars, publications	Yes
Credibility	7	Discussion, openness and information, debate, political responsiveness	-
Integration of livestock	-	Organic project demonstration	Yes
Livestock (cattle)			
Grazing (efficiency, land allocation)	3	Regulation	No
		Persistent plant cover close to stables, efficiency in feed value	Yes
Calf mortality	6	Reduced by improved housing and management, including pasteurization of milk for calves	Yes
Udder health	4	Better economy, animal welfare, milk quality, less use of antibiotics	Yes
Forage quality	5	Improved variety selection, plant breeding, admixing of herbs/less feed supplementation	Yes
Protein supply	4	Supply stability, protein crop cultivation, testing methods for feed value, improved sustainability and less climate impact	Yes
Consumer perception	3	Milk quality (healthy inputs, less antibiotics, taste, diversity)	Yes

Livestock (pigs)			
Welfare generally	8	Focus on early treatment, culling, control of worms, behavioral changes	Yes
Product (meat) differentiation	4	Finishers on grass/Jerusalem artichokes; breeding	Yes
Mortality	4	More systematic management, vaccination, attention	Yes
Environment	3	Crop rotation in enclosures, willow and poplar in enclosures	Yes
Balanced fodder	2	-	Yes
Marketing	-	-	No
Stability of feed supply	-	-	No
Poultry			
Diseases (Erypsipelas, Pastorella, *E. Coli*)	8	Vaccination, reduced infection pressure, better indoor climate, less stress	Yes
Predators	5	-	?
Behaviour (e.g. feather pecking, cannibalism)	6	Optimal nutrition, stimulating environment, stable indoor climate	Yes
Economy	9	-	?
Ammonia emission (housing)	8	Regular removal of manure, manure stored as slurry	?
Nutrient leaching (yard)	6	Chicken yard as paddock grazing; combinations with perennial crops	Yes

3.2 Focus and Implementation of R&D Research - Findings

The projects in the four programs were divided into nine thematic areas for the purpose of this analysis. Livestock production was divided into the different types of livestock (cattle/milk, pigs, poultry/eggs and aquaculture). Crop production was divided into crops and cultivation systems. Finally, thematic areas also include consumption, society and environment, and bioenergy. The government’s action plans I and II (Det økologiske Fødevareråd, 1995, 1999) include recommendations for the implementation of research initiatives for solving certain challenges in the sector. Table 2 shows the areas covered by the recommendations and the expected effects of the projects within each of the areas. The DARCOF I projects have primarily had the expected effect on primary production. About 100 scientists from 15 institutions took part in the projects. Moreover, the projects in DARCOF II (200 researchers), DARCOF III (200 researchers) and CORE Organic have had an expected effect on the industry (processing) and on society, including environment and health, and at the consumer level, including integrity. The organic research has thus followed the general growth and development in the sector, embracing new issues along the entire supply chain.

Table 2. Total number of research projects per thematic area and research program. Many of the research projects addressed more than one research theme, but have been categorized according to main research focus

Thematic area	**Research programs, number of projects and relevant action-plan (AP) recommendations**					
	DARCOF I	**AP I Rec.**	**DARCOF II**	**AP II Rec.**	**DARCOF III/ CORE Organic**	**Total**
Cattle/milk	1		7	2	4	12
Pigs	5	1	4	1 *	2	11
Poultry/eggs	1	1	1	*	0	2
Fish					1	1
Crops	7	1	13	7 *	5	25
Cultivation systems	14	*	10	2 *	3	27
Bioenergy					1	1
Consumption			1	2	2	3
Society and environment	2	2	7	9	4	13
Total	**30**	**5**	**43**	**23**	**22**	**95**

* Recommendations apply to several thematic areas.

3.3 Dissemination of R&D Results – Findings

A total of 3,173 publications consituted the direct ourputs from the projects (Organic Eprints, counted in 2012). About 20% (632) of these were peer-reviewed papers; another 1,311 were other publications in English, while 1,230 were publications or other forms of dissemination in Danish. Based on a search of the archives of Knowledge Centre for Agriculture, it was found that there had been dissemination based on R&D in the projects within all the thematic areas. One example is the Danish Crop Rotation Experiment, from which there were 215 publications in Organic Eprints, and at least 50 dissemination articles based on the R&D in the archives of Knowledge Centre for Agriculture. In the interviews, there were many statements about contributions from research [see, for example Chapter 4 in Halberg et al. (2012)]. In each case, it was determined that there was research results disseminated, so that the statements were justified.

4. Discussion

The projects resulted in a high number of peer reviewed journal articles, in spite the fact that the research under the four programs has mainly been ‘applied research’. As this paper is focused on the effects of the research programs we will, however, mainly discuss how the close association between scientists and end-users in the DARCOF programs has had a large bearing on the effects achieved. The below discussion is based on the results provided in section 3. For certain details reference may be given to the analysis report by Halberg et al. (2012).

A certain degree of uncertainty is attached to the qualitative information of the analysis as it builds on personal observation as well as the fact that respondents may have had different interests in the research. The triangulation approach has been used to remedy this uncertainty thereby verifying that research related to the specific challenge has taken place and that research-based solutions have been disseminated. It should, however, also be noted that this analysis is expected to be conservative in its results, as the user survey was based on a limited number of interviews and the persons interviewed may not have been aware of the practical implications of specific results from R&D, although these results have, in reality, been of benefit for other users.

4.1 Direct Effects on Sector, Growth and Production Forms

There has been a large and significant effect of the research under the four programs on the development of the organic sector. Both crop production and animal husbandry research projects have contributed with significant new knowledge and methods in response to the considerable challenges in primary production, from the handling of manure and weeds to animal health and feeding. The results have been widely applied, partly because many of the projects have been designed and selected as a response to challenges formulated by the sector. The advisors believe that organic production would have been much lower today if the research results had not been utilized. This is because the production itself is more profitable (higher yields per cow, pigs of higher quality resulting in a higher kilo price, etc.) and because some important problems have been solved, which has reduced the incidence of reconversion to conventional farming (for example, improved perennial weed control and recycling of nutrients with the use of cover crops and good crop rotations).

The increasing production and the ability to ensure a good and consistent quality and stability has also been a precondition for the establishment of a professional and profitable processing sector. The companies interviewed found that these conditions have had an important effect on their development opportunities.

Overall, this shows that the research in the DARCOF programmes and CORE Organic had a strong focus on the barriers in the sector and on improving the general market and growth conditions in the sector. Accordingly, the research has laid the basis for a stronger commercial exploitation of the opportunities and the research focus has been consistent with the challenges in the commercial sector and also the political ambitions for market-driven growth in the organic sector.

4.2 Indirect Effects, Greater Integrity and Policy Developments

In addition to the direct effects, there are other – more indirect – effects on processing and marketing, such as a better understanding of consumer motives for purchasing organic produce and a higher degree of integrity as a result of research. Integrity – here understood as consumer trust that the organic sector lives up to its declared ideals and added values – has been improved in two ways. First, the organic production itself has been improved in areas that are important to the consumer, and second, studies have evaluated organic farming in relation to its principles, consumer expectations and/or interests of society. In the first instance, research projects have – according to interviews with consultants and representatives of public authorities and organizations – enhanced animal health and welfare on organic farms through the development and description of better farm management, housing, feeding, etc. In the second instance, a series of projects have probed whether organic farming actually confers advantages compared with conventional systems or products.

In this connection, the projects are both actual research projects and a large number of scientific reviews – the so-called knowledge syntheses - prepared under DARCOF programs and prepared with participation of scientists from the DARCOF projects. Some of these projects have documented positive effects of organic farming on, for example, nutrient balances in livestock farming, conservation of biodiversity in hedgerows, as well as a higher nutritional content of organic produce. However, some results have also been critical regarding specific aspects of organic farming, e.g., when measured either on climate impact per kilo of produce, on flavor or on general healthiness.

In several instances, such results have been used by organizations in the sector to launch campaigns to improve practical aspects of the systems (Note 6). In other instances the sector has focused on improving animal health and welfare on organic farms based on the background of research projects and reviews. It can be assumed that the willingness to admit to weaknesses in the organic systems and the readiness to seek solutions to these has helped maintain integrity in the eyes of the public and ensured the continued political backing, although there is no documentation for this. The assumption is, however, supported by interviews with representatives from organiszations and government (Halberg et al. 2012).

4.3 Consumers and Markets and Effects on Conventional Farming

Some of the research projects have documented that large consumer segments favor organic produce for a variety of personal (health, quality, pesticide-free) and altruistic (animal welfare, environment) reasons. These preferences may also affect conventional food production. In addition to the described effects on the organic sector the DARCOF projects have also produced results that are relevant for conventional farming and can aid a general green conversion. This is true, for example, for methods to replace seed treatments, non-chemical weed control, and a reduction in the consumption of antibiotics and the need for supplementation of synthetic vitamins in animal husbandry. This could give large cash savings in the conventional sector if the methods were widely implemented and would further improve the reputation of Danish agriculture as an eco-friendly system supplying high-quality products.

5. Conclusions

At the international level there is an awareness of the need to improve the relationship between research, extension and agricultural production. In the “International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD” (McIntyre et al., 2009), the conclusions stress the fact that it is necessary for a strict departure from the traditional model of research and dissemination as separate actions. Instead, there is a need for the farmers’ situation to have a stronger voice when prioritizing and designing research projects and to integrate their local knowledge and experience into research schemes (Aagaard-Hansen et al., 2007).

The very applied nature and relevance of the projects under the DARCOF programs has been strengthened via the close and continuous contact with consumer representatives, first and foremost, in formal fora such as the user group in DARCOF. There has also been contact with the sector via the organic food council and a number of other actors involved in the preparation of the action plans and later in the knowledge synthesis in 2008 (Alrøe et al., 2008) on the potential for a market-based development of the organic sector. This influence at program level has been – and continues to be – important for maintaining the relevance of the projects offered and funds granted in relation to the requirements of the sector.

At the same time, many of the projects have had contact with advisors and farmers where the acquired knowledge has been continually communicated and discussed. This has had two effects. Firstly, a rapid application of results, because the users have discussed the results of the research with the scientists and thus achieved a better understanding of how results and knowledge can be adapted to specific practical situations; and secondly, there has in many projects been an adaptation of research design and methodology as a result of practical experience. The scientists have been persuaded by the dialogue with the users to ensure that treatments are as relevant and practical as possible, without compromising scientific standards.

This shows that there is a more complex connection between research, development and the application of knowledge in agriculture than the traditional route of one-way communication of scientific results via advisors to producers. Because the project structure and organization of the organic research programs have supported this complexity in knowledge generation and exchange, clear indications suggest that there has been a good effect of the research projects measured in terms of the utilisation of the results and overcoming main barriers in the sector. An additional but important factor is that regardless of the 3-5-year duration of the research programmes, there has been continuity in many central research activities in terms of long-term experiments at the same localities over many years and in many research programmes.

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Notes:

Note 1. http://www.seges.dk/English/NyEnglishsite.htm

Note 2. http://www.igff.dk/

Note 3. Organic Eprints: http://orgprints.org/

Note 4. Success rating: 1 = no progress since 1996, 10 = the challenge has been solved

Note 5. Research in this context refers to the DARCOF I, II and III programs and CORE Organic

Note 6. http://www.dyrenesbeskyttelse.dk/kalved%C3%B8delighed#hw1mQEi1GAplvfFy.97; https://www.okologi.dk/media/474384/kalveskoler%20er%20en%20succes%20440-okt%2009.pdf

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