Organic Knowledge Network Arable

State-of-the-art research results and best practices

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1. Summary with conclusions and recommendations

In this summary, the findings from peer-review research on the productivity of organic arable crops are reported (see 1.1). Then the conclusions and recommendations for five most important levers which can be used by the farmers are presented (see 1.2 to 1.6). And finally, the most important recommendations of the EIP-AGRI Focus Group on Organic Farming - Optimizing Arable Yields are summarized in order to put innovation on organic farms in its social context.

In the summary, scientific literature is not quoted. They can be found in the main text.

1.1 Productivity and yields

1) The global literature for temperate and Mediterranean climate zones narrows the yield gap between organic and conventional farms down to 9 to 25 percent. The 2 most comprehensive studies (de Ponti and Ponisio) found 20 percent difference which might be the best value to calculate with. As long as the yield difference is not bigger than that, the comparative ecological advantages of organic farming systems remain relevant. Many of the supporting, regulating and cultural ecosystem services resp. the environmental impacts of farming systems make reference to the land area anyway, especially for nitrate losses, biodiversity or soil fertility. However, for some of the environmentally negative impacts such as the nitrous oxide emissions, the per-ton yield is the reference as it is a global problem and directly linked to the amount of food produced and consumed. A meta-analysis shows that in the range of approximately 20 percent less yields in organic farming, N2O emissions are equal in organic and conventional systems. A growing yield gap might question the role of organic farming, especially when the production grows out of the niche. There are namely findings that under best climate and soils conditions, the yields of organic crop rotations shrank to 50 percent only, in comparison to good integrated farm practice. The tendency towards an increasing yield gap between organic and best practice conventional agriculture becomes noticeable. This indicates that both the organic farmers' endeavour for best organic practice and ecological, social and technological innovation driven by the co-operation between scientists and farmers is important. This is basically the objective of the OK-Net Arable.

1.2 Soil fertility management

2) Best soil fertility management is the backbone of productive organic farming, especially in arable crops. Research findings on how to practice best soil fertility management are comprehensively available, see (ii) to (v). Many organic farmers partly ignore elements of best practice because of economic reasons (e.g. high proportion of few cash crops in the rotation, specialisation of the farm business, soils compaction because of untimely tillage). Many other farmers have knowhow deficits and need support. Both groups can be motivated for best organic practice by farmer friendly tools that help in the visual assessment of soil structure which are now becoming widely available. They need to become trained. In addition, the next generation tools which help to understand soil fertility is being researched and might become available for farmers within a couple of years as well. These tools help the farmers to become responsible for the soil fertility on their land.

3) Rotation design and increased diversity through the use of alternative crops and techniques such as intercropping show great promise for both nutrient supply and soil structure management. The importance of pre-crop in determining yield and N supply to following crops by grain legumes is

important. Both annual and perennial legumes are essential for supplying nitrogen. Crop choice and rotation are also well known to influence P availability and green manures could be chosen, specifically to increase P availability for following crops. This knowledge is not yet sufficiently available in a farmer friendly way.

4) There is evidence that organic reduced tillage has a positive effect on soil microorganisms and earthworms in terms of abundance and diversity. In the long run, it increase top soil organic matter and leads to higher yields. It is only used by few farmers because they fear problems with annual and perennial weeds. It is a very promising technique. Further improvements of the synchronisation of nitrogen availability and plant nutrient requirements and of the weeding technology are needed, and more importantly on-farm research with producers.

5) Intercropping offers many benefits as different crop and forage species have varying abilities to extract macro and micro nutrients from soil (variation in root morphology and their interactions with the mineral and biological soil matrix). Farmers are often not yet familiar with these techniques and they need to be convinced with economic advantages as well (e.g. usage as alternative feedstuff, mills that are willing to process and separate crop mixtures).

6) In livestock based arable systems the use of nitrogen fixing perennial legumes and manures help in the provision of nitrogen and improve soil structure. In systems without livestock perennial leys are generally not economically viable and animal manures and slurries may be expensive or difficult to obtain from acceptable sources. Regional co-operations between livestock producers, mixed farms and stockless farmers are then a viable and eco-friendly solution.

7) Inoculating soils with suitable rhizobium, arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria may be important in the future for mobilising nutrients but are not currently technology ready.

8) Bio-effectors which can added to organic fertilizers improve plant biomass production in pot experiments in a considerable way. These bio-effectors can be fungi strains, mycorrhiza and humic acids. These technologies are not yet ready for farmers.

1.3 The availability and the uptake of plant nutrients

9) Nitrogen is the most limiting factor for many crops but nor for all. Grain legumes are equally productive in organic as in conventional farming.

10) Legumes are the number 1 source of nitrogen. Average fixation rates are roughly in the range of 20 to 200 kg N per hectare and year depending on the species and on the wetter conditions. Grain legumes have considerable higher fixation rates than forage legumes on temporary or permanent grassland but grain legumes consume most N for their own growth. Forage legumes in grassland stands are stimulated by the N consumption of the monocotyledons (grass) and have higher fixation rates than in pure stands. Latest research results show that charcoal dramatically stimulates the nodulation of soybean and increases biological N_2-fixation. This is a mechanism with a high potential but not yet ready to be recommended.

11) Livestock manure and slurry are important as mixed farms have sustainably high yields. At low stocking densities (<< 1 livestock unit per ha) the yield gap is much higher than at high stocking densities (>> 1 livestock unit per ha). As the farms have become more specialised in general, the regional cycles of livestock manure (between livestock and crop producers) are important to be organized. The level of

yields of organic arable crops receiving livestock manure is often between 80 and 90 percent of conventional crops.

12) Specialised stockless farms might run into a P deficit. Experience comes from very old organic farms. This can threaten yields. Strategies include composts, regionally available manures, and commercial fertilizers based on rock phosphate. As the latter is almost inert in certain soils, novel treatments through fermentation or composting with organic material are interesting but not yet ready for practice.

13) A lot is already known on the production of composts from different sources of waste and residues from farms, food processing and households. Yet, there is still a need for research on the production of high quality composts with higher nutrient availability and faster effects. The knowledge on the preparation and application of composts is very heterogeneous among European farmers and generally low. Excellent und easy to use information material in national languages is urgently needed.

14) Composts from separately collected household bio wastes deliver in recommended application rates 5 to 10 kg plant available N per hectare in the first year and 25 to 35 kg in the following ones. In order to compensate for P and K exports from the farm, much lower compost applications are needed.

15) Commercial fertilizers from slaughterhouses (N and partly P: feathers, horns, hoofs, meat-bones, wool, hides etc.) are important but often too expensive for arable crops. Vinasse in contrast is an often used source of N und K. P and K fertilizers are most commonly phosphate rock and potassium sulphate. As phosphate rock is not plant available in certain soils (acidic, Fe- and Al-Oxides), scientists try to macerate it with fermentation or compost. Probably with only little effects.

16) The future strategies of increasing productivity on organic farms will be found in the recycling of sewage sludges, although not accepted by the organic standards for the time being because of pollutants (heavy metal, xenobiotics, pathogens). This is a hot spot of research and therefore technological solutions are already available and will become further improved. In the far future, communal sewage systems will be based on an early separation of pollutants, liquid and solid human excretions which will make macro and micro nutrients available for agriculture. A state-of-the art report can be found on the website of the ERAnet CoreOrganic project Improve P.

1.4 The crop-weed competition

17) Cropping systems and especially crop rotations are the pivotal element of weed control. As organic farmers “use” weeds in arable crops to increase biodiversity, an optimum balance between control and tolerance is perfectly feasible by rotations and crops which suppress weeds in a sufficient way. This can be best achieved in livestock-based arable systems. Bi- or multi-annual leys control annual weeds with an appropriate cutting regime.

18) In contrast, in stockless arable systems the control of annual weeds poses greater challenges. Among preventive methods, use of the false seedbed technique is still perceived as important.

19) In both arable systems, economic reasons and unfavourable weather conditions are the most important reasons that preventive measures are neglected.

20) For arable crops in general, the physical weed control techniques are very advanced and machinery is excellent. Information is extensively available with leaflets, websites and films. There is a certain mismatch between countries with many organic farmers and with less. Physical weeds control is a field

of innovation where farmers play a very active role and combine observation with engineering savvy and craftsmanship.

21) Challenges can be found with perennial weeds in livestock arable systems and in stockless ones. Turning the soil, stubble cultivation, competitive cover crops and a ley phase are till know the most effective ways to control them. New techniques are needed though.

22) New productions systems like reduced tillage require modification of the weeding techniques.

23) Precision farming and robots might revolutionise weed control in organic arable cropping systems. As in agricultural engineering mainly techniques for conventional farmers are focused on, organic agriculture will have soon a tremendous backlog. This should become a major focus of organic research as well and it is a field where cooperation with farmers will add to cooperation with technology and engineering companies.

24) Weeds are a challenge which is predestined for researcher-advisor-farmer cooperation and mutual learning.

1.5 The control of diseases

25) The most important preventive strategies of disease control are less susceptible, tolerant or even resistant crop varieties. These varieties are available for a number of crops, but not for all. In addition to variety testing – preferably on organic farms and by using the variability of site conditions – plant breeding will become a focus of future research in organic farming. Both variety testing and breeding are ideal fields of scientist-farmer co-operations.

26) In arable crops, potato and legume breeding has the highest priority.

27) Other preventive strategies include crop rotation design, multi-annual breaks for single crops, soil tillage, soil treatment and cultivation technique (e.g. deep ploughing, avoiding soil compaction, cultivation with dams and wide rows, liming, compost application, planting depth, intercropping etc.). All these preventive measures are important for organic farmers to be applied.

28) A good example is the knowledge which has been gathered in different national and European research projects on the control of late blight of potatoes. A combination of pre-sprouting of seed tubers, early planting date, tolerant varieties, improved soil fertility status, combination of copper with plant strengtheners, spraying technique and decision support systems (DSS) the dosage of copper can be minimised. This example underlines that research has not yet led to innovation in the practice in a sufficient way.

29) The list of fungicidal active compounds is short. This illustrates, how important preventive measures are. So called plant strengtheners and other basic substances partly compensate for the precarious lack of plant protection products (PPP). Novel techniques and products are urgently needed, especially for virulent diseases like light blight in potato. Depending on the weather, yields losses can become big. As the application of copper is a critically negative aspect of organic agriculture, many scientific groups work on alternatives. This research has also bound a relevant part of the EU funding for organic research. Scientists work on physical methods, biocontrol organisms and botanicals. The number of potential solutions is amazing. Therefore, there is a real chance that new techniques and fungicides will come on the market. This might take 5 to 10 years from now.

30) The use of certified seeds is very important for plant health. For cereals, seed dressing is sufficiently solved (several physical, 2 biological and 1 botanical methods). For other crops, further improvements are still needed.

1.6 The control of pests

31) In arable farming, yield limitations are mainly due to diseases, insufficient nitrogen supply or weeds. Severe, unsolved pest problems only occur in oilseed rape (pollen beetle *Meligethes aeneus*; stem weevils *Ceutorhynchus ssp.*, flea beatles *Psylliodes chrysocephalus*) and in potato production (wireworms, mainly *Agriotes spp*. but also others from the family *Elateridae*). A non-specific pest of arable crops – especially during crop emergence – are slugs. All these pests can cause severe yield losses and still need a lot of attention of scientific research. Ready to use solutions for farmers are not yet fully available.

32) In all other arable crops, pest insects rarely lead to severe yield losses. Many of the pests can be directly control with cultural measures (e.g. crop rotation in the case of the Western corn rootworm), biocontrol (e.g. European corn borer or Colorado beetle). Problems also occur with field vegetables, often part of the crop rotation (carrots, Brassica species etc.). Some effective insecticides are available, but also physical methods (e.g. nets). A problem with some of the insecticides is that they can have detrimental side-effects on non-target organisms (e.g. spinosad and pyrethrum). In general, the development of excellent and selective control agents is most advanced in pest control.

33) Preventive measures are very important the keep pests in arable crops under the economic threshold. A lot is known on how to integrate all these measures into the cropping systems. Many of them concern the biodiversity in the fields, around the fields and adjacent landscape elements. The information material is rich and also available for farmers in different languages. In order to improve the effect of prevention, techniques of habitat management have become important. Specially optimised landscape elements, buffer zones like hedgerows and wild flower strips along fields lead to a functional biodiversity. Other element can be companion plants planted into the field (example cornflower in field cabbage).

1.7 The social context of innovation on organic farms

34) Securing yields and high quality of organic crops requires a lot of knowledge and is sometime complicated and time consuming to handle. Therefore, successful innovation on farms requires more than excellent research and good farm advice. There are many activities which support and accelerate innovation among farmers. These are applied research activities on farms and with farmers. In most advanced cases, this includes the entire research process from defining the research question, to conducting the research, analysing the results and disseminating them. There are also other methods of involving the farmers in an active way, such as field courses, farmer-to-farmer exchange, open days for farmers in research facilities and letting farmers evaluate research results. All these activities are typical and especially important for organic agriculture.

2. Introduction

Organic agriculture transforms natural resources with a high efficiency into yields and delivers substantially more non-commodity ecosystem services (ES) than conventional agriculture (Niggli, 2014). Whether it is productive enough to feed the growing human population is a controversial topic, hotly debated in recent literature. A number of studies have sought to answer this question by quantifying yield gaps between organic and conventional agriculture, with recent estimates of reductions in yield for organic systems ranging from 9 to 25 percent. Diverse meta-analytical approaches have been employed to arrive at these values, in some cases presenting global averages and in others dividing the analysis based on crop types and/or geographical regions. Recent meta-analyses are reviewed here in **Section 3**, with a discussion of the individual categories of cereals, legumes, oil crops, and tubers.

Section 4 briefly covers the important debate of the productivity and the sufficiency paradigms in agriculture. It looks at alternative scenarios for securing global food supply and analyses different ways of reducing trade-offs between the four categories of the ecosystem services, i.e. (i) supporting, (ii) provisioning, (iii) regulating and (iv) cultural (MEA 2005). This section was added as many organic stakeholder argue that the productivity narrative is overrated in the context of global food security.

In **Section 5**, we look at the state-of-the-art of the most important levers of securing high yields on organic arable farms: soil fertility management, nutrient availability, crop-weed competition and control of pests and diseases. All these levers can be deployed for crop productivity by the farmer, either in a more preventive way of advanced planning (e.g. crop rotation), or with direct or curative actions (e.g. spraying an approved fungicide). What might be typical for organic farmers' best practice is that preventive, anticipatory actions are favoured against curative, short-term ones. The focus of this section is on arable crops in temperate - and to a certain extent also Mediterranean – zones, as this report is part of the EU and Swiss funded project "OK-Net Arable". We also focus on the most urgent deficits of farm practice threatening crop productivity, both in single crops and in entire crop rotations. We identify the latest research activities addressing these bottlenecks. Solutions in the pipeline ready as potential innovations but not yet being mainstreamed will sum up this section.

Section 7 finally opens up the perspective on the wider context of how innovation can be promoted on organic and agro-ecological farms. This section follows the recommendations of the Focus Group installed by the European Innovation Partnership on Agricultural Productivity and Sustainability (EIP-AGRI) on yield gaps of arable crops in organic agriculture as this group provided a relevant insight into innovation and sustainable agriculture.

It is important to mention that most scientific papers that look at the productivity of organic farming compare yields of single crops or of entire crops rotations to the yields of conventional farms. A different perspective is to look at the yield gap between best and mediocre practices among organic farms. In fact, this information might be even more helpful as it highlights the pathway to be followed to organic producers towards best practice. Unfortunately, systematic data on the latter approach is insufficiently available. In Section 3, the productivity gap between organic and conventional farms is focused on. Yet, the variability of the organic data gives sufficient information on how high organic yields could be if farmers applied only best practice. In Section 5 where the focus is on crop specific problems, the difference between best and mediocre productivity is prominently enough emphasised.

3. Scientific State-of-the-Art of the productivity gap between organic and conventional cropping

3.1 Meta-analysis approaches

Stanhill (1990) was one of the first to approach the yield gap concept from the perspective of a meta-analysis, using 205 comparisons of 26 crop types and 2 animal products to arrive at an average yield gap of 9% of organic compared to conventional production. Data was obtained from three categories: commercial farms, short- and long-term experimental studies, and a 25-year comparison of three agroecosystems. It was clear that the starting conditions of the studies was very diverse even within the first category, where farms ranged from biodynamic systems in Western Europe to corn-dominated systems in the American Midwest, but data were obtained primarily from developed countries with temperate climates. The standard deviation of 0.24 for this dataset reflects the wide variation in yield resulting from these diverse starting conditions. The author acknowledges the difficulty of comparing closed and open systems, although not explicitly linking yield gaps to non-renewable external inputs such as fossil fuel energy.

Subsequent meta-analyses have broadened the geographic region under consideration. In an extensive review of organic agriculture, Lotter et al. (2003) cites an average yield gap of 10-15%, noting that the gap was higher in regions characterized by intensive agriculture, such as parts of Central Europe and Japan, and lower under extensive conditions such as those in the American Midwest. However, the methodology behind the reported value is unclear and the study does not distinguish between crop types.

Table 1: Yield gaps calculated by different meta-analyses (all categories and all crops under consideration)

Study	Category	Crop	Yield gap
Lotter 2003	All	All	-10-15%
Seufert et al. 2012	All	All	-25%
Stanhill 1990	All	All	-9%
Ponisio et al. 2014	All	All (global)	-19%
de Ponti et al. 2012	All	All	-20%
Badgley et al. 2007	All	All (developed countries)	-9%

Badgley et al. (2007) calculated two separate organic/conventional yield ratios for developed and developing countries in order to account for substantial differences in agricultural methods. Where the developed world yield ratio was 0.914 for plant foods (-8.6% in organic), the ratio in developing countries was 1.736 (+73.6% in organic). Nitrogen availability was cited as the predominant yield-limiting factor for organic agriculture under most conditions. Yield gaps were calculated for separate crop categories as well, ranging in developed countries from 1% for oil crops to 18% for legumes. This study was criticized for failing to define organic systems and for applying single-study yield ratios to national agricultural data (Cassman 2007; Connor 2008).

More recent studies have calculated larger yield gaps, ranging from 19-25% (de Ponti et al. 2012; Seufert et al. 2012; Ponisio et al. 2014). In a meta-analysis of 362 conventional-organic comparisons, de Ponti et al. (2012) arrived at a global average of 20% reduction under organic conditions, with a standard deviation of 21%. The authors hypothesized a higher yield gap under conditions where observed yields approach the theoretical maximum due to intensive management and lack of water limitation, such as northern Europe, but found little support for this hypothesis. One multi-annual field study from Schleswig-Holstein where

cereal yields are generally high thanks to prime soil types, optimum rain water supply and low disease pressure as a result of good stand aeration by ocean breeze, showed that conventional crop rotation yields may be twice as high as their organic counterparts at similarly low nitrate leaching rates (Loges et al. 2005).

Seufert et al. (2012) found the largest yield gap (25%) among the meta-analyses, with wide variation depending on crop type and management practices. Legumes had the smallest yield gap (5%) of crop categories reviewed, and best-practice organic management reduced the all-crop-yield gap to 13%. In contrast to Badgley et al. (2007), only certified-organic or non-certified systems in compliance with organic regulations were considered under the organic category, and conventional-organic comparisons were required to have similar temporal and spatial scales. The authors noted that nitrogen availability limited yields in organic, but not conventional systems, as evidenced by increased organic yields when additional nitrogen was provided.

Using a larger dataset of 1071 conventional-organic comparisons and a novel meta-analytical method, Ponisio et al. (2014) calculated a yield gap of 19% and also looked at impact of some management factors. No difference was found between yield gaps in developed and developing countries, in contrast to Badgley et al. (2007).

3.2 Yield gaps of crop categories and single crops

Crop yield is the result of the transformation of i) natural resources, of ii) farmers' knowledge and of iii) inputs. All three transformation processes differ between organic and conventional agriculture, but the most relevant differences are on the input side (Figure 1).

Ad i): Both conventional and organic systems are fundamentally based in site-specific natural resources: light availability, the inherent fertility of the soil, and local climatic conditions. Because these resources are unaffected by agricultural management practices, they are identical between conventional and organic systems at a certain location and thus yields formed from the transformation of these resources are also similar. However, that is not to say that conventional and organic systems respond identically to a given set of starting conditions. For example, the higher soil microbial diversity and activity found under organic conditions may increase the bioavailability of nutrients and organic carbon stored in the soil to crops managed under these conditions, even when the soil is identical (Breland and Eltun 1999; Mäder et al. 2002). Organic management also provides an advantage under dry conditions, as higher levels of soil organic matter increase soil water capacity (Gomiero et al. 2011). In a drought year, Lotter et al. (2003) found that a manure-based organic corn system out-yielded the conventional treatment by 37% and organic soybean yields were 52-96% higher than conventional. Compared with conventional approaches, organic agriculture provides a more attractive alternative under changing climate conditions, as it increases carbon sequestration, has higher energy use efficiency and resiliency to climate change, and reduces global warming potential as compared to conventional (Gomiero et al. 2011; Kremen and Miles 2012).

Ad ii): All farming systems depend largely on farmers' knowledge. Basically, organic and conventional farmers both use the best available and appropriate technology and the knowledge related to it. While conventional farmers have many more quick fixes in their hands, organic farmers rely more on observations of agroecosystems, preventative planning and traditional knowledge. Knowledge about organic agriculture is less widely available and more time consuming to acquire.

Ad iii): Re transformation of inputs into yield, conventional farmers are in a high position and most of the productivity backlog can be explained accordingly.

Applying this model (see Figure 1) to cereals, grain and forage legumes, oilseeds, and tubers helps to explain why yield gaps reported in meta-analytical studies differ for these crop categories. As mentioned above, differences in inputs account for conventional-organic yield gaps, but each crop category is unique in terms of which inputs are most significant. Liebig's concept of the most limiting factor applies here: gaps are determined not by the average of yield losses imposed by individual factors, but by the factor with the greatest influence on yield. For cereals and tubers, this is nutrient availability, whereas weeds and disease play a greater role for legumes and insect pests limit yields of oil crops such as rapeseed.

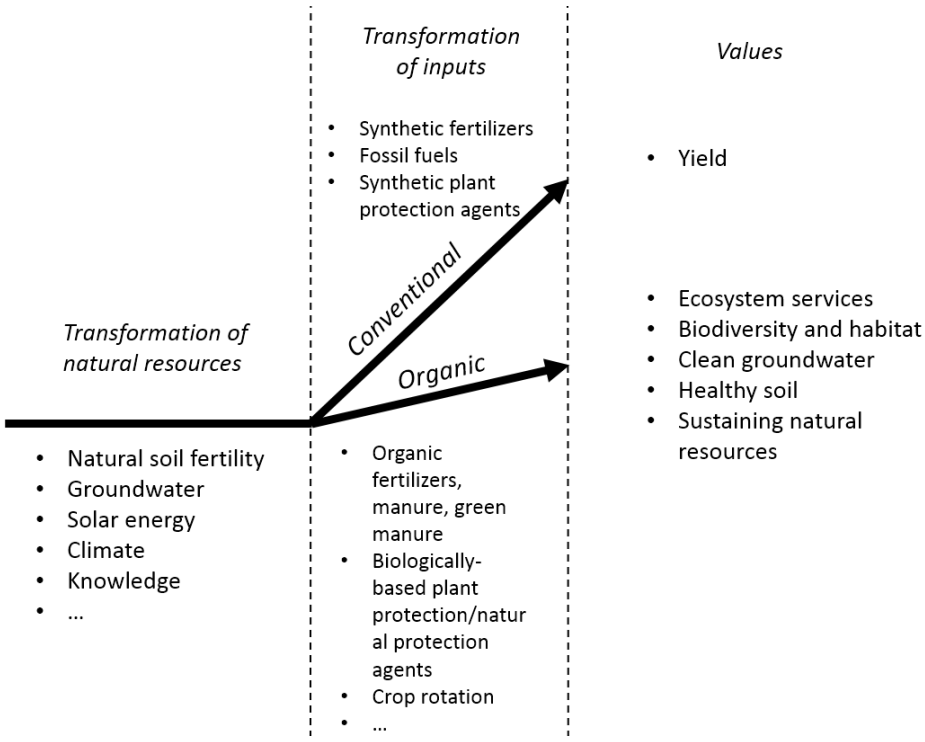

Figure 1: Cropping systems as a process of transformation: a conceptual model (farmer knowledge is mentioned under natural resource for simplicity of the figure only).

3.2.1 Cereals

Yield gaps for cereals calculated in meta-analyses range from 7-26% (see Table 2). Badgley et al. (2007) calculated a yield gap of only 7% for cereals in developed countries, the smallest difference of any of the meta-analyses, whereas Seufert et al. (2012) calculated the highest value with 26%. De Ponti et al. (2012) found that the gap was smallest for maize (11%) and highest for barley (31%). Seufert et al. (2012) likewise found that maize had a smaller yield gap than the mean for all crop types (25%), whereas barley and wheat had larger yield gaps. One could speculate that barley and wheat have been bred to thrive in high input conditions meaning they don't do well under lower input conditions. The productivity of maize in organic systems may be explained by the late planting date when the soil is already warm and mineralisation activity is higher. The yield gap for cereals as a whole is generally lower than for vegetables (figures not shown), but higher than for legumes.

Nitrogen availability is the primary factor limiting cereal productivity (Gunst et al. 2013), and differences in nitrogen inputs account for the majority of the yield gap here. Natural N mineralization processes are poorly

matched with the timing of greatest N uptake in wheat (Pang and Letey 2000), such that N availability from natural sources plays a lesser role than inputs in forming crop yield. Because synthetic N fertilizers, which are often applied in high doses, can be better targeted to crops demand peaks in conventional systems, cereal yields may be higher in these systems. However, nitrogen availability can be increased by organic best practices rather than by relying on synthetic fertilizers. Olesen et al. (2006, 2009) showed that supplementing with 50 kg/ha farmyard manure raised organic cereal yields by 4-13 dt/ha in an N-limited system. Other supplements such as biogas slurry or green manure could likewise contribute, as could management strategies that better match the timing of N availability to crop requirements (again Olesen et al.2006, 2009).

Protein content is often considered an important indicator of quality in cereals, as it contributes to baking properties, and has been the subject of many conventional-organic comparisons. Studies have found 3-23% lower protein content in organic wheat as compared to conventional (Hildermann et al. 2009; Arncken et al. 2012; Bilsborrow et al. 2013); this gap is primarily ascribed to nitrogen limitation (L-Baeckstrom et al. 2004). However, discussions of grain protein content have little to contribute to the debate about feeding the world, and testing the quality of protein rather than the quantity gives a better indication of the baking properties of organic wheat (Linnemann 2010). Furthermore, the late fertilization often employed by conventional farmers to boost grain protein is not taken up, instead leaching into groundwater and contributing to nitrate pollution.

Worthy of note is that the yield gap is generally smaller for maize than other cereals in temperate zones with sufficient water availability. A major limiting factor for maize is weed pressure, accounting for 23% of the yield gap by one estimate (Lotter et al. 2003; Cavigelli et al. 2008; Larsen et al. 2014). However, the yield gap disappears when organic weed management is effective. Posner et al. (2008) showed that in years where mechanical weed cultivation was successful, the yield gap was only 1%, as compared to 26% in years when it was unsuccessful. Crop rotation is significant for maize, as organic maize grown in rotation with multiple cover crop species yields over 100% more than organic maize grown in monocultures, attaining yields not statistically different from the county average for conventional maize (Smith et al. 2007).

Table 2: Yield gaps calculated by different meta-analyses (category 'cereals', different crops under consideration)

Study	Crop	Yield gap
Eltun 1996	Barley, oats, wheat	-30%
Eltun et al. 2002	Barley, oats, wheat	-35%
Gabriel et al. 2013	Cereals	-54%
Poutala et al. 1994	Cereals	-25%
Seufert et al. 2012	Cereals	-26%
Badgley et al. 2007	Cereals (developed countries)	-7%
de Ponti et al. 2012	Cereals (global average)	-21%
Cavigelli et al. 2008	Corn	-24-41%
Larsen et al. 2014	Corn	-50%
Poudel et al. 2002	Corn	NS
Wortman et al. 2012	Corn	-13-33%
Lotter et al. 2003	Corn (legume rotation)	-62%
Lotter et al. 2003	Corn (manure-fertilized)	+37%
Wortman et al. 2012	Sorghum	-16-27%
Cavigelli et al. 2008	Wheat	NS
Ryan et al. 2004	Wheat	-17-84%
Wortman et al. 2012	Wheat	-10-+10%
Arncken et al. 2012	Winter wheat	-42%
Bilsborrow et al. 2013	Winter wheat	-39%
Hildermann et al. 2009	Winter wheat	-38%
Mäder et al. 2002	Winter wheat	-10%
Mäder et al. 2007	Winter wheat	-14%
Mayer et al. 2015	Winter wheat	-36%
Posner et al. 2008	Corn, soybean, wheat	-10%

3.2.2 Legumes

Yield gaps are generally much smaller for legumes than other crop categories, e.g. 5% as calculated by Seufert et al. (2012) (see Table 3). This can be explained partially by the greater reliance of these crops on natural sources of fertility rather than inputs. Legumes obtain nitrogen primarily through the symbiosis with diazotrophic bacteria, and additional synthetic N fertilizer might have even a detrimental effect.

The yield gap for forage legumes, which have a higher frequency in organic than in conventional crop rotations, is extremely small. This can be explained by the fact that these crops require negligible inputs: there is no need for synthetic N fertilizer, other nutrients are not usually limiting except in low-fertility soils low in potassium and phosphorus, and plant protection agents are not often used.

Grain legumes have a slightly higher yield gap than forage legumes, but it is still much smaller than for other crop categories and in some cases yields are higher under organic conditions. Beans were the only crop observed to have significantly higher yields under organic conditions in the meta-analysis by Stanhill (1990). Badgley et al. (2007) found a higher yield gap for legumes (18%) than cereals (7%) in developed countries, but legume yields were 52% higher under organic conditions when considered globally. De Ponti et al. (2012) calculated organic soybean yields in the U.S. to be 92% of conventional. This yield gap was smaller than for any other legume considered. Soybean also had a smaller-than-average yield gap in the meta-analysis by Seufert et al. (2012). In contrast to that analysis, Ponisio et al. (2014) found no yield gap differences between leguminous and non-leguminous crops; legumes were not considered as a separate category from vegetables and oil crops.

Yield gaps can arise, however, when inputs differ significantly. Weed management and disease can limit organic yields if no biologically-based strategies for weed and pest management are used. De Ponti et al. (2012) calculated the largest yield gaps for soybean between intensively managed conventional and organic conditions, ascribing the magnitude of the gap to pests, disease, and phosphorus limitation. Cavigelli et al. (2008) noted that the 19% soybean yield gap in a long-term study was due entirely to weeds. Here, differences in inputs explain the relative magnitude of the yield gap even within the category of legumes.

Table 3: Yield gaps calculated by different meta-analyses (category 'legumes', different crops under consideration)

Study	Crop	Yield gap
Seufert et al. 2012	Legumes	NS
Badgley et al. 2007	Legumes (developed countries)	-18%
de Ponti et al. 2012	Legumes (global average)	-12%
Cavigelli et al. 2008	Soybean	-19%
Wortman et al. 2012	Soybean	-17%
Lotter et al. 2003	Soybean (legume rotation)	+96%
Lotter et al. 2003	Soybean (manure-fertilized)	+52%

3.2.3 Oil crops

Oil crops as a whole often have a small yield gap, but some oil crops, such as oilseed rape, are practically impossible to grow under organic conditions in regions where insect pests are present (see Table 4). Sunflower, for example, is a commonly grown oilseed crop for which organic yields can often equal conventional levels, contributing to the small yield gaps reported for oilseeds. Badgley et al. (2007) found the smallest yield gap for oil crops of any category considered, 1% in developed countries. As crops in this category were not listed, however, it is difficult to determine whether this included oilseed rape. Oilseed crops had the smallest yield gap of any category except fruits in the analyses by Seufert et al. (2012) and Ponisio et al. (2014). In contrast to the minor yield gaps found by the aforementioned meta-analyses, de Ponti et al. (2012) found organic oilseed yields to be 26% lower than conventional. Oilseed rape, however, represents a special case, where almost all production in Central Europe is conventional. Insect herbivory is the limiting factor in this case, and there are no effective organic methods of control for pests, especially the pollen beetle (Meligethes aeneus). Weed pressure at sensitive developmental stages also affects yields

(Valentin-Morison and Meynard 2008), but the yield gap is primarily explained by differences in plant protection agents. Here, it would make no sense to try to increase nutrient availability to make organic oilseed rape cultivation more feasible; research into organic pest control methods must be prioritized.

Table 4: Yield gaps calculated by different meta-analyses (category 'oil crops')

Study	Crop	Yield gap
Seufert et al. 2012	Oil crops	NS
Badgley et al. 2007	Oil crops (developed countries)	-1%
de Ponti et al. 2012	Oil crops (global average)	-26%

3.2.4 Tubers

The yield gap for tubers is often greater than for cereals, but also more variable (Palmer et al. 2013). Starchy roots had the second-highest yield gap of categories considered, 11% in the developed world, as calculated by Badgley et al. (2007). In 21 organic-conventional comparisons, all from Europe, de Ponti et al. (2012) found that organic potato yields were only 70% of conventional. In contrast, organic sugar beet and sweet potato yields were 105% of conventional, raising the tuber average to 74% of conventional. Tubers were considered under the vegetable category by Seufert et al. (2012), where the yield gap amounted to 33%. This is similar to the yield gap of nearly 30% presented by Ponisio et al. (2014). In potato, the primary yield-limiting factor is nutrient availability, followed by pathogens such as *Phytophthora infestans* (Finckh et al. 2006; Palmer et al. 2013). Möller et al. (2007) found that 48% of the yield gap in organic potato could be attributed to N limitation, whereas 25% was explained by disease for which no organic management was possible. Inputs of synthetic fertilizers and plant protection thus primarily account for the higher yields in conventional farming. (see Table 5).

Table 5: Yield gaps calculated by different meta-analyses (category 'tubers')

Study	Crop	Yield gap
Eltun et al. 2002	Potato	-15%
Mäder et al. 2002	Potato	-36-42%
Badgley et al. 2007	Starchy roots (developed countries)	-11%
de Ponti et al. 2012	Roots/tubers (global average)	-26%

4. Critical concerns about productivity comparisons

The focus on the productivity of farming systems is important as the output of food is the primary purpose of agriculture and all farmers try to optimize yields and quality of crops. Yet, by looking at crop yields exclusively, important other aspects are most likely to get lost or partly ignored:

- The provision of non-commodity ecosystem services and public goods of agriculture (actually it is about maintaining the perpetual production capacity).
- The externalization of environmental and social costs to society, either to tax payers or to future generations.
- The efficiency of the use of both natural and non-renewable resources.
- The finite nature of relevant resources such as phosphorous, land, water or oil based inputs needed a sufficiency approach in food production.

Organic methods are superior when it comes to **providing ecosystem services and preserving the quality of natural resources**. Biodiversity, especially of insects, is higher on organic farms, which increases ecosystem services such as pollination and biological control (Gomiero et al. 2008; Mondelaers et al. 2009; Rahmann 2011; Winqvist et al. 2011; Kremen and Miles 2012; Tuck et al. 2014, Niggli 2014). Soil quality parameters are improved under organic management, including reduced losses through erosion and runoff, increased organic matter, higher microbial biomass and diversity, and more rapid N mineralization (Mäder et al. 2002; Kremen and Miles 2012; Thiele-Bruhn et al. 2012; Wang et al. 2011; Cavigelli et al. 2013; Williams and Hedlund 2013; Larsen et al. 2014). Nitrate leaching and phosphorus runoff are reduced under organic management, both when scaled by yield or production area (Kirchmann and Bergström 2001; Eltun et al. 2002; Mondelaers et al. 2009; Benoit and Garnier 2014).

Pillar 1 (direct payments) and pillar 2 (rural development programmes) of the Common Agricultural Policy of the EU make reference to both the higher provision of ecosystem services and public goods and the higher degree of internalization of deteriorating impacts on the environment in organic farming. The EFTA countries Lichtenstein, Norway and Switzerland also push organic agriculture with their agri-environmental measures. The converse approach of pricing externalities of farmers e.g. by taxes on nitrogen, phosphorous, pesticides, CO_2 emissions or energy consumption has not been popular so far in agri-political debates, although organic associations are sympathetic to the idea of true cost accounting in order to increase the economic competitiveness of organic farms. Whether this will actually help organic farmers is not yet clear. The uncertainties are on the one hand that organic inputs and techniques will also become taxed (e.g. nitrogen and CO_2 emissions from livestock and green manure or fungicides with copper hydroxide) and on the other hand that taxes on conventional inputs will accelerate technology shift towards minimized and precisely targeted applications which will reduce again the relative advantage for organic.

Farmers can only be freed from the pressure to increase productivity if harvest losses and food waste are reduced, less grain is fed to livestock for the production of meat, eggs and dairy products, agricultural land is not used for the production of energy crops, and if people change their dietary habits. Organic agriculture is not in a particularly advantageous position to solve all of these problems at hand.

As at least 30 % of food produced globally on agricultural land is lost or wasted (FAO 2014), reducing food waste would be the most powerful approach to secure global food security with environmentally sound farming methods like the organic and agro-ecological ones. Unfortunately, organic agriculture and consumption alone does not yet reduce food waste (Kreft et al. 2013). The inefficiency of food production is a challenge for the entire society **including the organic sector**.

A potentially successful alternative strategy is to reduce livestock feed components that compete with direct human food crop production (Schader et al. 2015). In the most extreme scenario where animals are fed only from grassland and by-products from food production so sufficient food (equal amounts of human-digestible energy and a similar protein/calorie ratio as in the reference scenario for 2050) could be produced and arable land occupation could be reduced by -26 % in 2050 compared to the reference scenario with no change. In this scenario, all environmental impacts are reduced between -12 to -46 % (Schader et al. 2015). These improvements are accompanied by reductions of animal products in human diets (protein intake per capita from livestock products reduced by -71%). Such a scenario shows the potential way out of the discussion about ecological or sustainable intensification if organic wants to become ready for mainstreaming.

Feeding the world primarily requires raising yields in subsistence agriculture; conversion to organic agriculture in developing regions is therefore predicted to make a substantial contribution to global food security (Halberg et al. 2006; Hines et al. 2008).

And a final concern is that ever since the Earth Summit in Rio (1992), there has been a discussion as to whether ecological sustainability is more likely to be achieved by **sufficiency** (Sachs 1993; von Weizsäcker et al. 1997; Princen 2005) or **efficiency.** Sufficiency in this context is taken to mean a strategy of frugality, voluntary reductions in consumption, or the imposition by law of quotas for resource consumption and environmental pollution. Among the food production systems, organic agriculture is partly an example of a strategy of sufficiency. In ecological accounting, **foreseeable shortages** (e.g. energy, soils, phosphorus fertilizers, water) must be taken into account so as to avoid increases in efficiency being undermined. Sufficiency objectives would prevent, for example, a situation where food produced using less energy and labour leads to more wastage or obesity as a result of the food being less expensive (rebound effect).

The efficiency paradigm predominates the Life Cycle Assessments (LCA) community where assessment results relate to units of output (tons of food) although farming is land-based. However, a range of ecological impacts (positive or negative) cannot be detached from the land area. For example, groundwater pollution with nitrates from agricultural sources cannot be offset by high yields; while perhaps lower amounts of nitrates per ton of yield may leach out, the absolute quantity of nitrates leaching from a field into the groundwater is the relevant parameter for the quality of the drinking water. The same could be stated for biodiversity or humus formation in soils. Most of the ecological impacts are therefore absolute, not relative impacts and are thus area-related. However, nitrous oxide emissions in contrast are different. This climate gas is a global environmental problem that is directly proportional to the total quantity of food produced. A recent meta-analysis of Skinner et al. (2014) comparing organically and conventionally managed fields revealed that yield-scaled nitrous oxide emissions became bigger in organic when the yields gap exceeded 17% (average). This global meta-analysis demonstrates that productivity in organic agriculture must be given greater attention, despite all other arguments as to the system's benefits.

To conclude, this excursion on the complexity of the productivity debate demonstrates that the current average yield deficits do not threaten the advantageous position of organic agriculture. Yet, what should not be dismissed is the concern that in the future, organic and conventional will diverge in terms of productivity increases, and on the other hand, will approach in terms of reduced environmental externalities. The topic of this report – and of OK-Net Arable on the whole - is therefore highly relevant.

5. Key levers of productivity improvements in organic farming systems

In Section 5, the focus is on how the yield gaps described and partly analysed in Section 3 can be addressed in organic farming. In the subsections, we proceed from the complex system approach incrementally down to problems of single crops.

Organic farmers use an array of strategies and tactics to manage both the magnitude and the stability of yields and the quality. An important framework is not to harm the environment and to minimize negative impacts on regulating, supporting and cultural ecosystem services. Firstly, this includes the avoidance of agrochemicals like herbicides and pesticides and by aiming to use appropriate tillage to avoid soil compaction. Secondly, the farmers use many techniques to enhance ecosystem services related to plant growth such as growing hedgerows to fostering beneficial arthropods or highly diverse farm and rotation designs to avoid emergence of pests and diseases. Thirdly, farmers only use and apply inputs and techniques which are approved by the organic standards and selected – with a few exceptions - for lowest risks for the environment and farmer's and consumer's health.

To put oneself in a farmer's position, he or she has to tackle the fertility of the soils, the availability of nutrients for the crops, the competition between crops and weeds and the risks caused by pest and diseases. This is how the next section is structured.

5.1 Soil fertility management

5.1.1 Definition

Soil fertility is generally defined in terms of the ability of a soil to supply nutrients to crops (Patzel et al., 2000; Scheffer and Schachtschabel, 2002; Gisi et al., 1997). However in organic farming it is helpful to use a broader definition of soil fertility as a concept which integrates a number of diverse soil functions which promote plant production. These include nutrient supply, soil structure and water holding capacity. Organic farming systems rely on the management of soil organic matter to enhance the chemical, biological, and physical properties of the soil, in order to optimize crop production (Watson et al 2002). Thus it is critical that farmers take a long-term view of soil fertility management as well as dealing with the needs of the crop in a given growing season. Managing soil fertility has onward consequences for livestock nutrition and ultimately human nutrition. There is also an important link between soil fertility management and the environment in terms of optimising resource use and minimising nutrient losses. In livestock based arable systems the use of nitrogen fixing perennial legumes and manures and slurries help in the provision of nitrogen and improved soil structure. In systems without livestock perennial leys are generally not economically viable and animal manures and slurries may be expensive or difficult to obtain from acceptable sources. This makes soil fertility management more challenging in systems without livestock. The use of off-farm fertilizers and composts is discussed in section 5.2.

5.1.2 Soil organic matter

Maintenance and improvement of soil organic matter is critical as this plays a major role in soil structure, water management, the prevention of erosion and nutrient supply. Organic farming has the capacity to increase soil organic matter in the top-soil (Gattinger et al., 2012). Soil organic matter is also very important in providing both a habitat and an energy source for soil micro and macro fauna. As soil processes are complex in nature soil management impacts on soil biological activity are still not fully understood. There is

evidence that organic reduced tillage has a positive effect on soil microorganisms and earthworms in terms of abundance and diversity (see table 6) but there are still open questions (Peigné et al. 2007; Gadermaier et al. 2009; Kuntz et al. 2013, Säle et al. 2015). A shift in microbial communities towards fungi based associations in reduced tilled systems (Kuntz et al. 2013; Willekens 2014) might e.g. play a role in the stabilisation of organic matter and should be further investigated. In the most recent internal literature review paper yet to be published (Cooper et al., 2016), the additional organic matter building capacities of reduced tillage is quantified.

5.1.3 Legumes and crop rotations

Both annual and perennial legumes are essential for supplying nitrogen but in many parts of Europe only a few legume species are used. This reflects both the availability of suitable varieties but also a lack of understanding of management and the system level benefits of these species. Synchronising supply and demand of both nitrogen and phosphorus is challenging and there are few reliable models available to help with decision making. Rotation design and increased diversity through the use of alternative crops (e.g. buckwheat), and techniques such as intercropping show great promise for both nutrient supply and soil structure management. The importance of pre-crop in determining yield and N supply to following crops by grain legumes has recently been reviewed by Preissel et al. (2015). Crop choice and rotation are also well known to influence P availability and green manures could be chosen specifically to increase P availability for following crops (Cavigelli and Thien 2003). Farmer friendly tools that help in the visual assessment of soil structure are becoming widely available, as the Soil Quality Test Kit (USDA 2001), the Visual Soil Assessment Field Guide for Annual Crops by the FAO (Shepherd et al. 2008), Visual Soil Assessment Field Guide for cropping and pastoral grazing (Shepherd 2000) or the Soil Assessment Manual by Spade Diagnosis (Hasinger 1993). Such assessment tools are now also being developed specifically for subsoil as well as topsoil assessment (Ball et al. 2015).

Table 6: Amount of soil organic carbon (SOC) and microbial biomass carbon (C_{mic}) next to biomass and abundances of earthworms sampled in 2011 in the Frick tillage trial after 8 years.

	SOC	C_{mic}	Total earthworm biomass	Total earthworm density	Adult earthworm density	Juvenile earthworm density	Cocoon density
	%	mg kg-1 dm soil	g m-2	no. m-2	no. m-2	no. m-2	no. m-2
Conventional Tillage CT	2.3	885.0	50.2	157.0	54.0	103.0	21.0
Reduced Tillage RT	2.7	1290.0	77.1	262.0	75.0	187.0	113.0
RT/CT (CT= 100%)	118	146	154	167	139	182	538
p-values (ANOVA)	0.003	0.002	Ns	0.026	ns	0.024	0.004

Source: Extracted from Kuntz et al. 2013

Much research is focused on individual crops or the use of specific products. Research which incorporates pre-crop effects and takes into account rotational design is still lacking in part because of its complexity.

Therefore, a better understanding of the integration of different spatial and temporal approaches within rotations including cover cropping and under sowing and their interactions with tillage is needed. Optimising the use of legumes for the supply of nitrogen is an important component of this. Benefits to soil structure and organic matter may not be visible or measurable over a single season meaning that a combination of experimental and modelling approaches is likely to be very valuable in understanding longer-term effects.

5.1.4 Intercropping

The use of crop mixtures is receiving a lot of attention in academic and farmer based research (e.g. Field Labs) for a variety of benefits both above and below ground. Different crop and forage species have varying abilities to extract macro and micro nutrients from soil (Lindström et al. 2013, see table 7) as a result of both root morphology and their interactions with the mineral and biological soil matrix (Richardson et al. 2009). Deep rooting species also improve soil structure and drainage because different morphological and eco-physiological traits benefit from different niches. Another interesting idea which requires further research is the principle of "ecological precision farming" which very much relies on intercropping to overcome the limitations of soil variation and to reduce adverse environmental impacts (Jensen et al., 2015). In the past, soil research has mainly focused on physics and chemistry. The advent of new tools for understanding soil biology offers the opportunity for truly integrated approaches to understanding soil fertility. The gradual development of indicators for soil biological activity e.g. nematodes (Ugarte et al. 2013) is highly relevant but requires development.

Table 7: Average micronutrient concentrations in flowers, leaves and stems of red clover, perennial ryegrass and timothy at the flowering stage (n=4) (Lindström et al. 2013)

Species	Component	Co	Cu	Fe	Mn	Mo	Ni	Zn
		mg kg^{-1} DM						
Red clover	Flower	0 08^{a}	4 6^{ab}	51^{c}	37^{b}	4 6^{a}	3 6^{a}	14 9^{b}
	Leaf	0 05^{b}	5 6^{a}	83^{ab}	56^{a}	1 5^{cd}	1 2^{b}	7 5^{cd}
	Stem	0 04^{b}	2 9^{c}	18^{e}	11^{d}	2 1^{c}	1 4^{b}	4 4^{e}
Ryegrass	Flower	0 02^{cd}	4 0^{abc}	25^{d}	18^{c}	2 2^{bc}	3 3^{a}	19 7^{ab}
	Leaf	0 04^{b}	3 6^{bc}	95^{a}	16^{cd}	3 6^{ab}	0 8^{b}	9 5^{c}
	Stem	0 01^{cde}	2 0^{de}	13^{f}	15^{cd}	1 1^{d}	0 9^{b}	6 2^{cde}
	Leaf	0 01^{de}	2 8^{cd}	43^{c}	12^{cd}	1 5^{cd}	0 4^{c}	8 0^{cd}
	Stem	0 01^{e}	1 3^{e}	9^{g}	12^{cd}	0 5^{e}	0 5^{c}	5 3^{de}
Component effect		***	***	***	***	***	***	***
Species effect		***	***	***	***	***	***	***
Species x Component		***	**	***	***	***	***	*

*P < 0 05; **P < 0 01; ***P < 0 001. Values in the same column for each micronutrient followed by the same lowercase letter are not different at P < 0 05.

5.1.5 Bio-effectors

Bio-effectors are able to promote crop growth and nutrient acquisition. They comprise microorganisms (plant growth promoting rhizobateria/PGPR, mycorrhizal fungi and endophytes) and bio-active compounds such as seaweed, compost and plant extracts. Research is done in the EU project Biofector ((http://www.biofector.info), the CORE organic project Improve-P (https://improve-p.uni-hohenheim.de/) and in the international project Biofi (ISCB) (http://iscb.epfl.ch).

Under stress conditions (e.g. drought, cold temperatures or low nutrients availability) bio-effectors could offer alternatives to the conventional use of chemical fertilizers by transforming plant-unavailable forms of nutrients into plant-available forms (e.g. N_2 fixation, solubilisation of inorganic P, mineralisation of organic N and P) and by extending the volume of soil explored for nutrients uptake (root growth promotion and/or mycorrhizal associations).

In organic agriculture, soils are primarily amended with organic fertilizers and their combination with bio-effectors could increase their value by improving the bioavailability of their nutrients. Adding organic fertilizer to bio-effectors will increase their population which will have beneficial effects on the plant and the nutrient acquisition (from both the soil and the fertilizers).

Several currently running projects have the objective to study the potential of these bio-effectors when they are combined with alternative sources of fertilizers or when they are integrated into intercropping systems. The results indicate that the efficacy of these bio-effectors differs with soil type with more positive effects in slightly acidic to slightly alkaline soils or in soils with low levels of fertility. The chemical composition of the alternative fertilizers (organic or inorganic) also plays an important role with better results obtained with organic fertilizers containing a large proportion of ammonium (e.g. digestate) (Thonar, not yet published). Crop species and variety choice is also important in modulating crop responsiveness (maize and tomato are e.g. responsive, while wheat is poorly responsive). Figures from different projects show the effects of bio-effectors on plants, as compared to their corresponding controls (see

Table 8).

Table 8: Positive results obtained with bio-effectors on different crops when combined with alternative fertilizers or reduced levels of mineral fertilizers.

Crop	Bio-effector	Alternative fertilizers	Effect	Experimental set-up	Project
Maize	Pseudomonas strain	Composted manure	Early growth promoted	Field experiment	Biofector
Maize	Humic acids from artichoke compost	Composted manure, fresh digestate, rock phosphate	up to + 40 % crop biomass (in alkaline soils)	Pot experiment	Biofector
Tomato	Pseudomonas and Bacillus strains	Composted manure	+ 80% crop biomass	Field experiment	Biofector
Pigeon pea intercropped with finger millet	mycorrhiza and Pseudomonas strains	50% recommended mineral fertilizer	+ 48% crop biomass (in low fertility soils)	Field experiment	Biofi (ISCB)

Source: Thonar C., internal report of FiBL, not yet published).

5.2 The availability and the uptake of plant nutrients

5.2.1 Definition

Organic growing depends first and foremost on the mechanisms in the soils that convert nutrients from non-plant available to plant-available forms in the root zones. This conversion process is based on beneficial microbes -- bacteria, fungi, protozoa, nematodes, and micro-arthropods. Therefore, soil fertility (section 5.1) is the key for plant nutrition. The second important mechanism is the recycling of organic material and nutrient elements, mostly on-farm (e.g. livestock manure, green manure, compost, field residues), between farms and probably in the future to an increasing extent the recirculation from the food chain and households. This is important for both macro and micronutrients (Watson et al. 2012). Crop rotation is also very important for managing the availability and the uptake of plant nutrients.

The most important bottleneck for plant productivity is nitrogen. Mixed farms with sufficient livestock can best cope with nitrogen and can achieve high yields. Therefore, novel concepts for farm co-operations between livestock and crop production have to be encouraged to address this, especially on the level of farm advice, farm management and socio-economic research in order to mimic a traditional mixed farm (See for example Nowak et al. 2013). For stockless farms, mix- and intercropping with legumes is important. Most recent activities on co-breeding of cereal and leguminous crops (e.g. maize, barley, lupines, beans or peas) might lead to ideal partner stands. The unspecific problem of clover fatigue in grass-clover lays might be addressed by breeding for robust clover, by a broader range of legume species or the application of compost in order to strengthen beneficial microorganisms in soils.

Phosphorus deficiencies are a problem of stockless arable crop farms, especially longstanding ones. In order to improve the P supply in such cases, beneficial microorganisms (see chapter 5.1.2) are a relatively new finding of currently on-going research. Improving the bioavailability of poorly soluble mineral sources of P (e.g. rock phosphate) through fermentation or composting with organic materials is also worthy of further investigation (Stockdale et al. 2006). In line with the organic concept, the recycling of different sources of P from households (sewage sludge, urine) and from slaughterhouses (meat and bone meal) must be intensively researched and might become differently regulated in the organic standards one day. For more detailed information on alternative P recycling fertilizers see fact sheets on Improve-P home page (https://improve-p.uni-hohenheim.de/).

5.2.2 Legumes

Leguminous crops are an important source of nitrogen in organic crop production, in both mixed and stockless farms. On mixed farms, the inclusion of leguminous crops in the rotation serves or four reasons: fixing aerial nitrogen, improving soil fertility and soil structure, and finally delivering feedstuff for ruminants. Legumes are also very important in organic permanent grassland. On stockless farms, legumes are mainly important for nitrogen fixation, soil organic matter improvement and soil fertility and are therefore called green manure. Stockless systems commonly use grain legumes as they have a cash value and the usage for feedstuff is economically less important in stockless systems. European agriculture relies on a fairly small number of key legume species but climate change may increase the number of species which can be utilised in different parts of Europe, for example, Lucerne is now grown much further North than previously.

The potential N-fixation for a wide range of legumes is very high, about 200 to 400 kg ha^{-1} yr^{-1}. In reality, it is considerably lower because of different limiting factors like temperature, water scarcity, limited nutrition or pest and diseases (Ledgard 2001). Realistic N-fixation rates are between 17 and 200 kg N $ha^{-1,}$ yr^{-1} for grain legumes and between 63 and 236 kg N ha^{-1}, yr^{-1} for temperate forage legumes (Peoples et al. 1995) which shows how important legumes are for the productivity of organic agriculture. In Europe as a whole, grain

legumes have been calculated to fix about 13 and 20 times more N per hectare than temporary or permanent pastures respectively (Baddeley et al. 2013). Most current work at FiBL has shown that the use of charcoal can dramatically increase the nodulation and biological N_2-fixation of soybean, pointing out that combined biotechnological approaches have an enormous potential to ameliorate N-supply to crops (Scheiffele, not yet published). Furthermore, cold tolerant *Bradirhizobium japonicum* strains and soybean cultivars could substantially increase the soybean dry matter and protein yield.

Unfortunately, "clover fatigue" is increasingly a problem in organic dairy production systems but the exact rational behind it is not yet known (Koopmans et al. 2015; Søegaard and Møller 2006). This phenomenon reduces the input of nitrogen from the grass-clover leys into the arable crops. In a recent research project in Germany (Fuchs et al. 2014) Oomycetes pathogens were identified as the primary reason for limited germination rates, and, in some soils, also for limited growth of established seedlings. In other soils, a multitude rather than a single group of pathogens was involved in limited growth. Plant-pathogenic nematodes were never found to be limiting for crop growth parameters. Harmful effects of pesticides were found in several soils, hinting at an important role of beneficial soil organisms in the suppression of pathogens causing yield depression in legumes (Fuchs et al. 2014). Maintaining levels of available phosphorus, potassium and micronutrients is also important for maintaining fixation rates.

5.2.3 Decision tools

Estimating N delivery from legumes to the following crops is of crucial importance. Several decision tools support the farmers to optimize yields and to minimize nutrient losses of organic arable crops. With the tool "ROTOR", a farmer or extension agent can compare different crop rotations regarding N-fluxes and impacts on the long-term humus balance of the soil (Reckling et al. 2013a). In contrast to ROTOR, the "ERA-nitrogen budget calculator" includes N-fluxes only and is limited to arable forage systems with legume-grass mixtures (Reckling et al. 2013b). By means of the overall N-input (biological N-fixation) and N-output (harvest, gaseous losses for mulching) the final N-budget is given in order to adapt the proportion of legumes in the crop rotation. The tool "HU-MOD" focus on soil organic matter (SOM) and N-pool fluxes (Brock et al. 2012). Therefore, not only N- but also carbon-fluxes are evaluated. Thus, depending on farm management, positive or negative impacts on SOM can be estimated (Koopmans et al. 2013). Another well working tool for predicting the effect of rotation design on N, P, K balances on organic farms is NDiCEA (Smith et al. 2015).

5.2.4 Livestock manure

Actually, the prototype of an organic farm is a mixed farm where livestock manure secures the productivity of the arable crops. Mixed farms are also environmentally advantageous as the run-off of nitrogen and phosphorus can be strongly reduced as demonstrated in the EU project BERAS in the countries around the Baltic Sea (Granstedt et al. 2008) and by the EU project Baltic Manure (http://www.balticmanure.eu/). However, most farms in Europe are specialized.

In a long-term field trial with a seven year crop rotation, Berner et al. (1995) could show that the productivity of mixed livestock-crop farming is very high. The harvested yields of all crops amounted to 84 to 93 % of the treatments with NPK mineral fertilizers (all fertilizers were P equivalent). In contrast, the non-fertilized treatments were at 76 % only. Between the different ways of how livestock manure was processed, the yields differed. For anaerobically rotted manure, yields were 92 % of mineral fertilizers. For liquid manure (slurry), it was 91 %, for composted manure, it was 90 % and for stacked manure, it was 84 % only. Stacked manure (mainly air-sealed) - often the practice of farmers – is hence not the best practice. Livestock density is often low in organic arable farming. Results from the DOK long-term experiment have shown that yield gap between organic and conventional systems is 25 % at a stocking density of 0.7 livestock units per hectare,

but was 18 % at a density of 1.4 livestock units over 28 years on a fertile Loess soil (Jossi et al., 2009; Mäder et al., 2002). Unfertilized plots archived 50% of the yields of the conventional system with full fertilization.

5.2.5 Compost

Composts play a crucial role in securing the productivity of crops in horticultural and in arable systems on organic farms related to their role in maintaining and enhancing the fertility and physical stability of soils.

Bio-degradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants (bio-waste) accounts for 88 million tons of municipal waste each year in the EU and has major potential impacts on the environment. Currently, only 23 % is effectively recycled. By 2030, the EU wants to strongly stimulate Europe's transition towards a circular economy. This means that large amount of compost and digestate will enter the market, creating opportunities for farmers.

Organic waste composts can be returned to soils as fertilisers or soil improvers. Their sustainable use in agriculture reduces the need for mineral-based fertilisers, the production of which has negative environmental impacts, and depends on imports of phosphate rock which is a limited resource.

However, the circulation of fertilisers based on recycled nutrients is currently hampered by the fact that most of waste-based composts are classified as wastes, and have to be marketed and applied according to waste regulations. The expected end-of-waste regulation will offer a tool for simplifying the trade of composts. The backbone of compost trading will be the implementation of national Quality Assurance Schemes and compost certification. Quality and environmental standards, however, differ across Member States. The Commission will propose a revision of the EU regulation on fertilisers. This will involve new measures to facilitate the EU wide recognition of organic fertilisers and waste-based fertilisers. Experts also discuss currently, if the heavy metal content per unit P would not be a more accurate quality measure than the heavy metal content per unit dry matter. This would have considerable implications on the use of compost in the field, because currently heavy metal thresholds are defined per unit dry matter.

The EU Commission aims to broaden the scope on organic fertilisers, soil improvers and growing media for specific secondary raw materials. The revision of the EU Fertiliser Regulation 2003/2003, currently under discussion, will widen the scope of the Regulation to include inorganic, organo-mineral and organic fertilisers, organic soil improvers, liming products, growing media, plant bio-stimulant and agronomic fertiliser additives. This will considerably facilitate the placing on the market both of organic products containing recycled nutrients (e.g. processed biosolids, digestates, composts, biochars) and inorganic recovered phosphate products (e.g. struvite, phosphates recovered from sewage sludge, incineration ash). However, the simplification of trade for recycled wastes does not automatically mean that these can be used in organic agriculture as organic fertilizers or soil conditioners. On the one hand, in-depth research is needed for their use in organic farming systems (see e.g. the project 'Improve-P' in the next chapter) and the fertilizers or soil conditioners have to be approved by the organic regulations.

The two German organic farmer associations Bioland and Naturland approved composts from household waste (separately collected bio waste, 'grüne Tonne') by November 2014. Additional requirements for the composts are the residue thresholds for heavy metal (EU organic regulation), for surfactants (tenside) and for Thiabendazole (from skin treatments of citrus fruits). Maximum application rates are between 9 to 12 t of fresh matter (FM) with a total amount of N of 100 kg. Many research experiments show that 5 to 10 kg N is plant available in the first year and 25 to 35 kg in the following ones. In order to compensate for P and K exports from the farm, much lower compost applications are needed (Gottschall 2015).

Relevant sources of information on compost in the EU:

- Roadmap to circular Economy. http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf
- Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM (2015) 614, and ANNEX. Closing the loop - An EU action plan for the Circular Economy

Information material on the processing and the application of composts is already available but should become published in much more national languages:

- There are national guidelines for compost and digestate (Germany, Austria, Belgium, Netherlands, Switzerland, Italy, Sweden, UK, etc);
- There are professional guidelines and quality assurance scheme (QAS) by European Compost Network (ECN) http://www.compostnetwork.info/;
- For new Member States it can be recommended to follow ECN recommendations, if no national ones exist. Estonia and Bulgaria have adapted ECN QAS;
- There are numerous assisting materials, brochures and leaflets available (FiBL, Bundesgütegemeinschaft Kompost e.V. (BGK). These materials could be translated into national languages and adjusted to other Member States (example of Estonian leaflets: http://www.recycling.ee/toodete-sertifitseerimine/komposti-kasutusjuhised/)
- There are professional guidelines about anerobic treatment of biowastes by The European Biogas Association (EBA): http://european-biogas.eu/
- There was a recent article in Bioland that illustrates well the nutrient impact from two different types of compost, http://www.bioland.de/fileadmin/dateien/HP_Dokumente/Verlag/bioland_12_2015_Naehrstoffe_und_Humus_aus_dem_Kompost.pdf

5.2.6 Sewage sludge

Phosphorus is a key natural resource for agriculture and phosphate sources from mining are finite. Recovered phosphorus from wastewater sludge could theoretically meet about 20 % of Europe's current demand. However, the traditional application of some of these waste products and sludge in agriculture is facing increasing concerns about pollutants (heavy metal, xenobiotics) and protection of soils and environment. Therefore to date, sewage sludge and P recycling from it is not accepted by organic regulations. However, there is a significant effort to propose alternative methods for utilising phosphorus from sludge. Currently alternative methods are not well established jet, only about 2 000 to 3 000 tonnes of struvite, a phosphorus-rich mineral, is produced each year in Europe from municipal sewage.

The state-of-the-art of the discussion about the recovery of P from sewage sludge for organic agriculture is summarized in a fact sheet of the project 'Improve-P' as follows (Wollmann and Möller 2015):

"There are many technological alternatives to recycle and clean the phosphorus already available, affecting P bio-availability and pollutants content. The use of precipitation processes is a promising option to recycle a substantial part of P using a relatively simple procedure. In this regard, struvite and Ca-P products recovered from sewage sludge, urine or waste water could meet basic organic principles. However, a more detailed assessment of the chemicals consumed to produce struvite and Ca-P from these waste products needs to be

conducted before a conclusive recommendation can be made. The potential contamination with pathogens has to be a matter of further research. The precipitation processes are limited to recovering the dissolved ortho-P (and in processes with acidification, the re-dissolved phosphates) and not the total P. One option for a more efficient P recovery could be to combine these procedures with an incineration step where insoluble P as well as toxic elements can be separated and recovered."

Numerous scientific groups investigate the possibilities of recycling of sewage sludge:

- Improve P, https://improve-p.uni-hohenheim.de, project funded by the ERAnet CoreOrganic
- LIFE ANADRY – https://www.facebook.com/Life-Anadry-720556708048321/
- RecoPhos, http://www.recophos.org/
- ROUTES –http://www.eu-routes.org/.
- END-O-SLUDG –http://cordis.europa.eu/result/rcn/54875_en.html
- P-Rex http://p-rex.eu/.

5.2.7 Commercial mineral and organic fertilizers in organic arable farming

Under the regulation of organic farming, the supply of mineral N fertilisers is restricted. There are commercial organic fertilisers available to farmers. However high costs limit the use considerably as the costs of these fertilizers calculated for N content are about 5 to 7 times higher than the most popular conventional mineral N-fertilisers and about 23 to 29 higher for liquid fertilisers compared to urea (see different lists of organic certifiers and fertilizer companies all over Europe. The average figures given here have been calculated by Niggli, unpublished). The sources of commercial N fertilizers are animal feathers, horns, hoofs, meat-bones, wool, hides and others. An exception is vinasse, a by-product of the sugar industry[1]. In most European countries it is a low cost source of N and K. Purchased mineral and organic fertilizers should be seen as an addition to the nutrient elements acquired in the crop rotations and the efficient use of on-farm organic materials (crops residues, manures etc). For other macro elements like P and K, the most important sources are phosphate rock and potassium sulphate. The application of phosphate rock is approved in organic agriculture, in contrast to water-soluble phosphate salts obtained with the treatment of phosphate rocks with sulfuric or phosphoric acids. As the availability of phosphate rock is insufficient in many soils (e.g. soils with high levels of Fe- and Al-Oxides; acidic soil) research is undertaken with fermentation or composting with organic material. The effect is little as much stronger acids would be needed.

[1] 1] Sugar beet is processed to produce crystalline sugar, pulp and molasses. The latter are further processed by fermentation to ethanol, ascorbic acid or other products. The remaining material is called vinasse.

5.3 Crop - weed competition

5.3.1 Introduction

The problem of weed management in organic arable cropping systems can be approached by considering two issues: the typology of (i) prevailing weeds and (ii) cropping system. As to (i) it is important to distinguish between annual and perennial weeds because the currently available solutions, including recent innovations, and the improvements needed basically differ between them. The same can be said for the typology of arable cropping system, where it is useful to distinguish between livestock-based and stockless systems.

5.3.2 Cropping systems and rotation

Crop rotation design strongly influences the diversity and abundance of the weed flora (Bond and Grundy, 2001). Depending on the sequence of crops cultivated, soil remains uncovered for a longer or shorter period which has a significant role for weed establishment. Mostly, weed growth cycles are adapted to the cultivated crop and the associated agricultural disturbances. Therefore, changes between crops which are more or less competitive with different germination and growing periods (spring or autumn sown) helps to reduce weed pressure (Dierauer and Stöppler-Zimmer, 1994). Generally weed pressure increases with a higher share of grains and a lower share of grass-clover leys in the crop rotation. Lundkvist et al. (2011) showed that a bi- or multiannual crop in the rotation could effectively suppress even perennial weeds by 71-98%, compared to a rotation with annual crops only.

In livestock-based arable systems, annual weeds are relatively easy to control by appropriate mowing regimes of the ley. Cutting grass-clover or similar leys usually break the life cycle of annual weeds before they are able to form seeds, determining their decline over the whole crop rotation. On top of this, use of flex tine harrows like the Treffler one would result in improved annual weed control in both the ley and annual crop phases of the rotation (Huiting et al., 2014).

Figure 2: Precision flex tine harrow (Treffler)

In livestock-based arable systems improved control of annual weeds may come from more targeted mowing times which, at the moment, is mainly dictated by the ley growth stage. Anticipating mowing times may result in control of a higher amount of weed species before they are allowed to set seeds – with important long-term effects – without necessarily reducing forage quantity and quality to a large extent.

In contrast, in stockless arable systems the control of annual weeds poses greater challenges. Among preventive methods, use of the false seedbed technique is still perceived as important, but increased climate unpredictability may jeopardize its adoption due to the higher risk of delaying crop sowing because of adverse weather conditions. With the growing importance of reduced tillage in organic farming, the use of mulches and cover crops is increasing, but they have to be well-managed in order to non-inversion tillage to impede proliferation of weed populations (Anderson, 2015). Under these conditions, improved equipment to terminate cover crops while impeding regrowth is needed. In this respect, the roller crimper is gaining pace as one reference tool for no-till cover crop-based organic systems (Davis, 2010). Among cultural methods, the use of intercrops is yet to be fully valued, although some classic solutions for narrowly-spaced crops (e.g. barley-pea mixture) are still used. Use of competitive cultivars could be another option, especially in small grain cereals (Andrew et al., 2015), but they are not always easily available everywhere. Among direct methods, the finger weeder has reached some popularity as intra-row mechanical weed control method, also due to its limited cost. Adoption of high tech solutions like camera-guided (semi)automated systems for mechanical weeding is expected to increase (Bakker et al., 2010, Shah and Lee 2015), but it may increase the gap among European farmers due to the different attitude to innovation and budget availability in different countries. The latter may be addressed by co-ownership of machinery or contract farming.

Figure 3: Finger weeder in action[2]

In stockless arable systems improved control of annual weeds may come from more targeted use of species and/or varieties in either single stands (Drews et al. 2002), cover crops or intercrops. Varietal or species mixtures may increase weed suppression and simultaneously enhance the array of genotypes with the right traits available for the different environments. More fine-tuned tools for mechanical termination of cover

[2] www.kress-landtechnik.de

crops under reduced or no-till organic arable systems are needed. Incentives to make high-tech solutions (e.g. precision farming with sensors and weed recognition) available to a larger number of farmers are also needed.

Docks (*Rumex spp.*) are major perennial weeds in most organic livestock-based systems. It is likely that improvements would arise from strategic use of tillage which, however, may not be in agreement with other important management goals, e.g. the need to keep soil cover over the winter season. Recently, localised hot water injection has been proposed as an effective method of direct weed control for docks (Latsch and Sauter, 2014)[3.]

Thistles (mainly *Cirsium arvense*) are also major perennial weeds in most European organic stockless arable systems. Their control is presently targeted either through stubble cultivation, the use of competitive cover crops and/or the introduction of a ley phase (Lukashyk et al., 2008) but effects are not always outstanding.

Improved management of perennial weeds may require prescribed tillage – including ploughing – to gradually reduce the load of vegetatively reproductive propagules ('bud bank'). More targeted combinations between this and e.g. the use of smother crops is needed, as well as improved tools for direct non chemical weed control of creeping perennials.

5.3.3 Effectiveness of weed control in organic arable crops

The efficacy of the various direct control methods depends on the composition of the weed flora, the timing and frequency of the applied technique and environmental conditions. However, the correct handling and adjustment of the machines turns out to be crucial. When mechanical control is compared to herbicide treatments, both strategies can be equally efficient in terms of crop yields (Armengot et al. 2012). However, mechanical weed control does not negatively influence weed diversity and species richness like herbicides do (Armengot et al. 2012).

The timing of mechanical weed control is important (pre-crop emergence, early or late post-crop emergence). For a single pre-crop emergence and early post-crop emergence harrowing, weed reduction was found to be around 40% (Mangerud et al. 2007) whereas variance can range from 5% to 90% depending on weed species (Davis and Welsh 2002). As small weeds are more vulnerable to soil cover, an early harrowing (weeds < 3-leaf stage) lead to higher weed reduction (60-63%) compared to late harrowing (weeds > 3-leaf stage), where weed reduction was 33-63% (Böhrnsen 1993). At the same time, early harrowing can slightly reduce yield due to harming of crop seedlings (Mangerud et al. 2007).

In several studies it was found that a second, late mechanical weed control pass increased weed reduction significantly compared to one single early pass (Lukashyk et al. 2005, Lundkvist 2009). Although weeds can be significantly reduced by different direct control strategies, a negative impact of weeds on crop yield is not always found (Popay et al. 1992, Samuel and Guest 1990, Peruzzi et al. 1993). In a recent meta-analyses of Cooper et al. (accepted but not yet published), it was found that weed incidence under organic reduced tillage schemes may be increased by 50% compared to plough systems, without necessarily jeopardizing yields. A recent Master Thesis in the Frick tillage experiment at FiBL has shown that wheat yields under reduced tillage and the plough system were on pair. However, after clearing the weeds, yields were distinctly greater in reduced tillage plots, most likely due to increased mineral N contents in the latter, and the improved soil structure (also not yet published).

[3] https://www.youtube.com/watch?v=iB4eI0nAaIw

5.3.4 Outlook

In general, holistic (system-based) weed management (Bàrberi, 2002) is yet to be fully implemented in organic arable systems. In recent years, some interesting research has been done on ecological weed management, meaning by this those methods that eventually reduce the weed seedbank by making use of ecological interactions (Bastiaans et al., 2008). These include increased weed seed decay due to e.g. appropriate use of green manures and mulches (Gómez et al., 2014) and increased weed seed predation from insects and rodents due to appropriate management of field and field margins (Davis et al., 2013). This branch of weed research is still in its infancy but it is expected that it will become progressively more important, especially for application in organic systems.

In terms of innovation on direct weed control methods, despite a rising interest of research for robotic[4] and site-specific weeding (López-Granados, 2011), there is little novelty in terms of low tech solutions that would be more likely to be adopted by a much larger number of farmers across different European countries.

Although basic and applied knowledge on aspects like weed community dynamics, crop/weed interactions and weed management tools is progressing, there is still a gap to be filled in before saying that new scientific evidence would straightforwardly turn into potential innovation for organic arable farmers. Despite its growing interest, participatory research is still sparsely used, determining a potential mismatch between farmers' requirements and scientists' preferences. Novel methodological approaches based on multi-actors' engagement like 'mental models' have been recently applied to weed management issues under organic conditions (Jabbour et al., 2013) and may pave the road towards enhanced tuning between farmers and researchers objectives. These ¨mental models' compare the knowledge on and attitude towards weeds of farmers and scientists. They diverged in many crucial points such as the seed persistence in soils, the role of diversity of weeds, the economic consequences of weeds (e.g. causing more labour against causing yield losses) and the question whether weeds are indicators for soil nutrient status or not. The knowledge gained from such 'mental models' might lead to more appropriate extension work and might be worth to implement in different countries.

[4] See video on:
http://www.utilajeagricolelopez.ro/verProducto.php?codproducto=998&codcatalogo=14&codsubcatalogo=38&codmenu=26&sid=de16c191a280752a5cc717383769eccb

5.4 Control of diseases

5.4.1 Introduction

In organic agriculture, all preventive measures to support plant health and productivity should be exploited first. Since the occurrence of diseases depends on many factors, e.g. the susceptibility of the cultivar, pedo-climatic or general weather conditions, the risks and virulence of diseases may vary in different countries and cropping systems. However, the use of plant protection products (PPPs) against plant pathogens is often a necessary tool. With the PPPs, decision support systems (DSS) have become introduced and used in organic farming.

Against that background, tables 9 to 14 summarize the general points associated with diseases in arable crops. In the tables, up-to-date preventive and curative measures and references are listed and added by aspects related to possible impacts of suggested solutions e.g. on soil conservation etc.

5.4.2 Variety choice and plant health

For several crops and diseases, the risk of infections by plant pathogens can be lowered by the use of less pathogen susceptible or tolerant and resistant varieties. These varieties are available for a number of crops (Annex, Tables 9 to 14). In these tables, links are given to different websites and literature. One website with description of organic varieties for different countries in the EU is www.organicxseeds.com. However, resistant varieties are not available for all diseases.

Nevertheless, further activities with respect to breeding of varieties especially suitable for organic farming should be intensified (Lammerts van Bueren et al. 2011), especially in the light of diseases. Among the arable crops, potatoes should be more intensively targeted. As the quality aspects of potatoes are dominant and late blight *(Phytophthora infestans)* resistance is not stable, local participative breeding programs for speciality cultivars for niche markets are especially interesting (Lammerts van Bueren et al., 2015). The adoption of radical changes in production systems may be difficult to achieve due to high initial costs to farmers (e.g. change of cultivation practices or replanting with resistant cultivars) and a general reluctance of other stakeholders and consumers to embrace slight changes in product quality (e.g. potatoes with different skin or flesh colour, or wheat with different baking properties etc.). However, Lammerts von Bueren and others have shown ways to overcome this obstacle and to increase consumer and retailer acceptance of new varieties (workshop at Biofach 2015[5]).

Different legumes will become a crucial element of very productive organic crop rotations. Many of the legumes have been neglected in breeding for decades. The major foliar necrotic pathogens on lupines are brown spot *(Pleiochaeta setosa Hughes)* and anthracnose (*Colletotrichum lupine).* Breeding programs are urgently needed.

5.4.3 Resilience of cropping systems

Increasing the resilience of a cropping system is a major goal for organic farming in order to maintain productivity. It may be further supported by diversification strategies, as shown e.g. for potato and late blight (*Phytophthora infestans*) in the EU-funded project BlightMOP (Leifert and Wilcockson 2005). Intercropping in general is a measure proposed for support of productivity in many crops but not for all as denser canopies can also have the contrary effect. A topical question is, whether co-breeding of crops (e.g. maize or other cereals with beans or peas) would increase the agronomic and economic attractiveness of intercropping

[5] http://www.co-free.eu/index.php/co-free-events

systems. Agroforestry takes diversification even further. „Agroforestry is a concept of integrated land use that combines elements of agriculture and forestry in a sustainable production system. There are both ecological and economic interactions between the trees and crops and/or livestock elements on an agroforestry system. These interactions can lead to higher productivity compared to conventional systems, and provide a wide range of services“[6]. The potential of agroforestry in reducing the risk of plant pathogen development or spread is under investigation[7] and should be exploited further.

Overall, in order to re-design organic production systems with the aim to be more resilient to disease attack, it is essential to provide a range of component strategies and to combine different approaches, including novel PPPs, DSS and cropping systems adapted to specific crops and pedo-climatic conditions. This should also take into account regional and cultural differences as well as the economic realities and the local legal framework.

5.4.4 Crop rotations

The implementation of optimal crop rotations is another important measure to reduce the risk of disease build-up. In cases of pathogens that can survive for several years in the soil, rotation breaks of several years for the same crop are necessary. For example, to avoid infection with *Sclerotinia sclerotiorum* in soybean or other legumes, cultivation breaks of at least 4 years should be met, both, for these crops and other host plants of the pathogen, such as sunflower and rape seed (Table 10). Diversification of a system by intercropping of different arable crops may help to raise productivity in general or help against lodging (Table 10 and Table 13).

5.4.5 Soil tillage

Tillage, such as deep ploughing after harvest is a general measure to reduce inoculum for the next season, e.g. for infection structures of *S. sclerotiorum* (Table 10 and 13) or for pathogens causing seedling diseases in sugar beet (Table 11). However, tillage choice will be influenced by soil type and trade-offs with soil organic matter storage, greenhouse gas emissions and weed management. Deep ploughing, however, is contradictory to soil conservation and such aspects need to be considered as well.

5.4.6 Seed quality

Seeds infested with pathogens are one major source of disease outbreaks in many arable crops (Tables 9 to 14). This can be avoided by the use of certified seeds. When seeds are produced on-farm, they should be inspected and when infested, need to be treated by appropriate methods such as heat or PPPs suitable for organic farming (Annex, Tables 9 to 14).

5.4.7 Plant protection products (PPP)

However, not every farm can implement the entire know-how of disease prevention. Sometimes, lowering one risk may enhance the risk for another disease. Finally, certain weather conditions, development of resistant pathogen races etc. may lead to disease outbreaks even when all possible preventive measures have been taken into account. Thus, the use of PPPs allowed for organic farming is often the only way to restrict the spread of causal agents of diseases and thus help to maintain productivity. The number of PPPs allowed in organic farming is small compared to the overall number of PPPs on the market. In the case of

[6] http://www.organicresearchcentre.com/?go=Research%20and%20development&page=Eco-agroforestry
[7] www.co-free.eu

fungicides registered for arable crops, in the EU, only copper hydroxide, sulfur, Pseudomonas chlororaphis and Coniothyrium minitans are listed as active ingredients.

All PPPs sold and used in the European Union have to be registered (Regulation (EC) 1107/2009). Products registered for organic farming need additional approval (Regulation (EC) 834/2007).

In most European countries, the certifiers publish the lists of approved and commercially available plant protection products. In Germany, Austria and Switzerland, independent lists of products are available[8,9,10,11].

In addition to registered PPPs, plant strengthening agents or basic compounds may be used in organic farming. In Germany, plant strengtheners are regulated in the German law on plant protection whereas in most countries, they can be used without regulation. They are defined as "compounds and mixtures, exclusively determined to serve the well-being of a plant, given that they are not PPPs as defined in Art. 2(1) of Regulation (EC) 1107/2009." Basic substances on the other hand are defined under Regulation (EC) 1107/2009 and can be prepared on farm. Among other points addressed in the regulation, they need to be e.g. (i) no substance of concern, (ii) not predominantly used for plant protection purposes but nevertheless are useful in plant protection and (iii) must not be placed on the market as PPPs. An example is the watery extract of common horsetail (*equisetum arvense*). Active ingredients that fulfil the criteria of foodstuff as defined in this regulation shall be considered as basic substance.

With regard to direct measures against plant diseases the list for organic farming is rather short (see foot note above). For many diseases, direct measures are not available. Thus, there is a strong need for the development of new alternative compounds. This even more, when compounds used in organic farming raise critical concerns (see cooper, next chapter).

Here, it needs to be considered that the time span for development of a compound, registration and final market introduction is generally much longer than 10 years. Thus, the time between first reports on successful disease control and the availability of a PPP for the farmers is rather long. This needs to be considered by farmers, when planning strategies for disease and pest control and by politics when discussing future policies.

5.4.8 The case study copper replacement

A special case is copper. Agents based on copper are one of the longest traditionally used PPPs for control of downy mildews and for many other diseases. To date, copper based fungicides or bactericides are still of high importance in organic (and integrated) production systems. Since EU policies aim at the promotion of sustainable, quality-based agricultural production and at limiting environmental risks especially regarding soil contamination and, since copper can accumulate in soils (AGES, 2011) and can have adverse effects on the environment (Kula et al., 2002), there is an urgent need to reduce the dependency of organic (and low input) farming systems on copper use. Currently, copper based PPPs are registered in the EC until the year 2018.

The maximum amount of copper allowed by the EC for use in arable crops (e.g. potatoes) is 6 kg/ha and year. On a national basis, countries and organic farmer´s associations have restricted themselves to lower amounts of copper, such as e.g. a maximum of 4 kg/ha and year in Switzerland or 3 kg/ha and year in Germany. Some countries, e.g. The Netherlands or organic associations like Demeter do not allow the use of copper based

[8] www.bvl.bund.de/infoppp (total list)

[9] www.betriebsmittelliste.de/

[10] www.bvl.bund.de/infopsm

[11] http://www.betriebsmittelliste.ch/de/hifu.html

PPPs at all. Copper-reduced or copper-free production systems may be achieved by (i) reducing the dependency of agricultural systems on PPP use by increasing the intrinsic tolerance of the production system by e.g. use of disease-resistant/tolerant cultivars and/or reduction of disease pressure, (ii) providing decision support systems (DSS), such as Öko-SIMPHYT (Tschöpe et al., 2010) or Bio-PhytoPRE (Musa-Steenblock and Forrer, 2005) that facilitate optimal application of PPPs and (iii) providing alternative compounds with a similar range of activity as copper.

With respect to research on copper reduction/replacement, several international (Blight-MOP[12]; Repco[13]; CO-FREE[14]), and national research projects have taken place or are in progress. In organic arable crops, copper based PPPs play a major role in the control of *P. infestans* on potato.

Speiser et al. (2015) published a survey, which showed that Swiss organic farmers apply on average only 2.5 kg copper per hectare and year in potatoes, although the maximum permitted quantities are 4 kg. These farmers pursue a combined strategy for minimising copper applications involving resistant cultivars, adaptations in crop management, optimized copper applications and the use of alternative products. Kühne (2014) mentioned as most important measures to prevent yield losses due to late blight, i) pre-sprouting of seed potatoes, ii) choosing of a resistant variety, and ii) insuring a good supply of nutrients.

Effects of minimum tillage, cover crops, fresh green mulch and compost applications on the development of *P. infestans* in potatoes were investigated by Hohls et al. (2014) in the EU project OSCAR. Reduced tillage combined with about 10 cm of fresh mulch of a mixture of green peas and rye was compared to a system with conventional plough tillage. Within tillage treatments, different pre-crops and compost applications were used. The AUDCP[15] which indicates the disease pressure over time was in the minimum tillage and mulched plots on average with 881 significantly lower than in ploughed plots with 1336. Yield data were not yet reported.

General copper minimisation measures are summarized by Palm et al. (2010). Short-term measures comprise pre-sprouting of seed tubers and early planting date (Leifert and Wilcockson 2005) and further aspects such as use of pesticides with low-copper formulations. Breeding of tolerant varieties is a long-term approach. As medium-term measures, further investigations on the influence of crop rotation, basic research on epidemics and knowledge transfer are proposed. Under medium- to long-term measures the development of new PPPs and plant strengtheners is mentioned.

Krebs et al. (2007) showed the potential of buckthorn (*Frangula alnus*) bark applied as a suspension of finely ground plant material for control of *P. infestans* in the field. Krebs et al. (2013) revealed that limited use of phosphonates may reduce copper amounts applied. However, timing of application needed further investigation in order to avoid residue build-up of phosphonates in tubers. This was reported in potatoes, grapevine and celery by Speiser and Tamm (2007).

A research project funded by the Federal Institute for Agriculture in Germany, investigates the efficacy of the product „aqua.protect“, which is generated by electrochemical activation of water[16]. This is a method used

[12] http://research.ncl.ac.uk/nefg/blightmop/page.php?page=1

[13] http://cordis.europa.eu/project/rcn/73843_en.html

[14] www.co-free.eu

[15] The area under the disease progress curve (AUDPC) is a useful quantitative summary of disease intensity over time, for comparison across years, locations, or management tactics. The most commonly used method for estimating the AUDPC, the trapezoidal method, is to discretize the time variable (hours, days, weeks, months, or years) and calculate the average disease intensity between each pair of adjacent time points.

[16] For more information: http://www.nades.info/produkt/eca/, http://www.aquaagrar.com/produkte/pflanzenschutz/

for the disinfection and hygienisation of drinking water and is residue free. One of the plant pathogens under investigation is *P. infestans*. Authors highlight that aqua.protect has an interesting potential for organic agriculture because it leaves no harmful residues. The research consortium tests the effects of aqua.protect against a broad range of pathogenic fungi *in vitro* and in the field (Delventhal et al., 2014).

Zellner and Nechwatal (2015) investigated alternative agents for control of *P. infestans* as seed potato dressing and on leaves. Extracts from liquorice (*Glycyrrhiza glabra*) and horsetail (*Equisetum arvense*), as well as chitosan, and a foliar fertilizer with low copper content showed some activity against leaf infections in the field. The combination of reduced amounts of copper with an alternative product in some cases reached efficacies almost equal to that of copper alone. Seed tuber dressing did not show clear effects in field trials on primary infection. However, in 2012 plots with treated tubers showed lower late blight infection rates, and in 2014 lower rates of failing tubers. The authors propose that together with other agronomic and technical measures such as mechanical or thermal leaf reduction, foliar and seed treatments with certain alternative preparations in exchange for or in addition to copper could be part of a late blight management strategy for organic potato production. Currently new formulations on the basis of micro capsules of licorice extract for use in the field are investigated by Trifolio-M GmbH[17].

Chitosan is known to have direct effects and to induce resistance in plants against plant pathogens (El Hadrami et al., 2010). The use of chitosan complexed with copper in nanogels is part of an Indo-German research project CuChi-BCA[18] funded by the Federal Ministry of Education and Research (Brunel et al., 2013). In their approach, chitosan/copper nanoparticles are combined with biopesticides. As reported in an oral presentation at the International Workshop on PR Proteins[19] and Induced Resistance against Pathogens and Insects, 2015 in Aachen[20], the combination of copper-loaded chitosan particles with a *Trichoderma* spp. isolate tested in the field, reduced copper amounts of 6kg/ha and year by 70%. Application of the combination was carried out twice prophylactically resulting in very good control of *P. infestans* on leaves of potatoes (Schmitt, personal communication).

The EU-funded project CO-FREE aims at copper replacement in different crops, including potato. The approach is to build strategies based on (i) alternative compounds (CO-FREE test products (CTPs)), (ii) smart application tools and (iii) by integrating these tools into traditional and novel copper-free crop production systems. In first field trials in 2012, application of stand-alone CTPs delayed the time until *P. infestans* destroyed 60% of the leaves by 2 days, while copper (2.25 kg/ha and year) resulted in a delay of 6 days. Yield increase over untreated controls were 4 t/ha (not statistically significant) for the CTPs and 6 t/ha (statistically significant) for copper (Kühne, 2014). Trials in Poland in 2014 showed high potential for control of late blight by the application of two other CTPs from the project. In the cultivar `Ditta' (high susceptibility to *P. infestans*), yield after treatment with the CTP 03E was intermediate between yields after copper applied at 3.5 or 6 kg/ha and year. When CTPs 03E and 6715B were applied in the cultivar `Sante´ (tolerant to *P. infestans)*, yield increase over the untreated control (22.1 t/ha) was 5 to 7 t/ha. In comparison: yields in the susceptible cultivar `Ditta´ treated with copper (3.5 kg/ha and year), reached only 25.1 t/ha (Schmitt, 2014).

With respect to smart application tools, in CO-FREE the DSS Öko-SIMPHYT is further developed to integrate a plant growth model, which helps to cease copper applications at a time point where infection with late blight does not have further impact on yield (Tebbe et al., 2014).

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[17] http://www.fisaonline.de/index.php?lang=dt&act=projects&p_id=6823

[18] http://www.uni-muenster.de/CuChi-BCA/

[19] Pathogenesis related (PR) proteins are proteins produced in the event of a pathogenic attack.

[20] https://prir2015.rwth-aachen.de/program

Kowalska and Bubniewicz (2014) published on positive influence of the use of baker´s yeast (*Sacharomyces cerevisiae)* and strips with plant mixtures of sunflower (*Helianthus annuus*), climbing bean (*Phaseolus vulgaris*) and marigold (*Tagetes*) sown on the margins of organic potato fields on disease reduction of *P. infestans*. Reduction of *P. infestans* by yeast treatments was statistically similar to reduction after copper treatment (3.5 kg/ha and year) in fields surrounded by the plant mixture strips. The effect of *Trichoderma asperellum* on disease control of late blight on potato is reported by Kowalska and Remlein-Starosta (2012). One application to the soil and four foliar treatments resulted in an efficacy comparable with two copper treatments. The yield from microbial treated fields revealed a higher number of small tubers, while total yield was significantly higher.

Overall, there are further publications indicating the potential of alternative compounds against oomycetes in general or specifically against *P. infestans*. However, in many cases, results are obtained on potted plants or under greenhouse conditions, while trials in the field have not yet been undertaken. A plant extract for instant of *Macleaya cordata* showed good efficacy under controlled conditions against oomycetes, but trials in the field still need to be conducted (Schuster and Schmitt, 2015). The ongoing screening and development plant based truly innovative products in EU projects CO-FREE ForestSpeCs and Prolarix, as well as a joint project of FiBL and the University of Basel have so far delivered four highly promising candidate substances including Larixyne®, an extract derived from larch (Thürig et al, 2015). At present, four patent applications have been submitted, providing the basis for the substantial investments necessary for further development and preparation of the registration dossiers (Speiser et al., 2008).

Costs for organic PPPs often are higher than those of conventional fungicides or agents such as copper preparations. On that background, and furthermore with respect to the goal of copper reduction or substitution, financial subsidies may be an important tool to support implementation of alternative PPPs.

Overall it can be concluded, that the development of a stand-alone substitute for copper with similar broad range efficacy remains a difficult task. However, there exist many promising approaches and alternative compounds that can help to further minimise the use of copper.

5.4.9 Annex: Tables of most important disease problems of organic arable crops

Table 9: Cereals and corn

Crop	Disease	Solution	Aspect
All	seed-borne diseases: • smut, bunt (Tilletia spp., Ustilago spp.) • tan spot/yellow leaf spot, net blotch (Drechslera spp.) • snow mould (Microdochium nivale) Fusarium head blight, scab (*Fusarium spp.*)	testing of own seed and if needed: • treatment with warm or hot water or dressing with Tillecur®, Cedomon® and Cerall® (Pseudomonas chlororaphis MA342) [1, 2, 3, 8, 9] • certified seed [4, 5] • resistant varieties [4, 5, 8]	
Wheat, Spelt, Triticale, Barley Oat, Rye	blotch (*Septoria spp.*) take-all (*Gaeumannomyces graminis*) powdery mildew (*Erisyphe/Blumeria f. spp.*) rust (*Puccinia spp.*) ergot (*Claviceps purpurea*)	crop rotation [6, 7] resistant varieties [4, 5, 10, 11] deep under ploughing of residues [10, 11] crop mixtures	Fusarium head blight: cultivation of wheat never after corn deep ploughing contrasts with preservation of soil structure
Maize	Fusarium stalk rot, ear rot (*Fusarium spp.*) common maize rust (*Puccinia sorghi*) Pests: • Oulema spp. • Apids • Oscinella frit • Ostrinia nubilalis • Slugs	resistant varieties [4] crop rotation [12, 13] deep underploughing of residues [12, 13] early harvesting [12, 13] Pests: • insulation space • cutting of pest residues • early spring cereals with fast development	deep ploughing contrasts with preservation of soil structure

Table 10: Oil seed crops

Crop	Disease	Solution	Aspect
Rape -seed	white mould, stem rot (*Sclerotinia sclerotiorum*) Phoma stem canker, black leg (*Leptosphaeria maculans/Phoma lingam*)	general measures: • seeding in wide rows (>30cm) [14] • early N-fertilisation [14] • elaborate seed bed preparation [14, 15] • crop rotation [14, 15, 16] • plant strengthener: *Trichoderma* spp., algae preparations [1] • resistant varieties [4, 20] • intercropping with cereal or legume [18] Sclerotinia: Contans® WG (*Coniothyrium minitans* CON/M/91-08) [1, 17]	
Sun -flower	downy mildew (Plasmopora helianthi) white mould; stalk and head rot (*Sclerotinia sclerotiorum*)	general measures: • crop rotation [19] • certified seed [4, 20] • resistant varieties [4, 20] Sclerotinia: • Contans® WG (*Coniothyrium minitans* CON/M/91-08) [1, 17]	

Table 11: Root and Tuber crops

Crop	Disease	Solution	Aspect
Potato	late blight (Phytophthora infestans) early blight (Alternaria solani) black scurf, Rhizoctonia canker (*Rhizoctonia solani*)	general measures: • general use of agricultural techniques proposed in the Blight-MOP-Project (chapter 10) [21] • crop rotation [22, 23, 24] • resistant varieties [4, 25] • plant strengthener: *Bacillus subtilis*, *Pseudomonas* spp., algae preparations, rock flor [1] late blight: • testing of seed tubers and if needed dressing with Cu-preparation [26] • pre-sprouting [22, 23] • early N-fertilising [22, 23] • use of forecasting models like Ökö-SIMPHYT and Bio-PhytoPRE [26, 27] • fungicide: Cu-preparations [1, 28]	acceptance of new varieties by consumers/retailers Cu-entry has to be limited
Sugar- beet	seedling diseases (*Aphanomyces* cochlioides, Pythium spp., *Rhizoctonia solani, Phoma betae*) Cercospora leaf spot (Cercospora beticola)	general measures: • certified seed [4, 29] • resistant varieties [4, 29] • avoidance of soil compaction [30, 31] • elaborate seed bed preparation [30, 31] • adapted crop rotation [24, 30, 31] • deep underploughing of plant residues [30, 31] • plant strengthener: *Bacillus subtilis*, *Trichoderma* spp., rock flour [1]	deep ploughing stands in contrast to the preservation of soil structure

Table 12: Vegetable crops

Crop	Disease	Solution	Aspect
Carrots	carrot leaf blight (*Alternaria dauci*) low competitive capacity (weed)	crop rotation [24, 32, 36] resistant varieties [4, 32, 34, 36] certified seed [4, 34] seed-treatment with hot water [33] cultivation with dams and wide rows [32, 36] fungicide: Cu-preparations, Serenade (*Bacillus subtilis* QST713) [1, 27] plant strengthener: *Trichoderma* spp., algae rock flour [1, 35, 36]	Cu-entry has to be limited
Cabbage	black rot (Xanthomonas campestris) clubroot (Plasmodiophora brassicae)	general measures: • crop rotation • resistant varieties [4, 34, 35, 37] • certified seed [4, 34, 35, 37] • seed treatment with hot water [33, 35, 37] • beneficial plants in crop rotation (e.g. clubroot: cultivation of perennial aromatic herbs) [24] • underplowing of residues [37] • plant strengthener: *Trichoderma* spp., rock flour [1, 35] blackrot: • avoidance of other cruciferaes nearby[37] • plant density <4 plants/m [24, 37] clubroot: • increase pH above 7 with lime • in case of occurrence, cultivation break of all cruciferae for at least 7 years [24, 37]	

Table 13: Grain legume crops

Crop	Disease	Solution	Aspect
All	seed-borne diseases: foot diseases and Anthracnose by the Ascochyta-complex (mainly Ascochyta pisi, Mycosphaerella pinodes and Phoma medicaginis) Fusarium spp. Anthracnose (Colletotrichum lupini)	certified seed [4, 38, 39, 40, 42, 43] resistant varieties [4, 38, 39, 42, 43] testing of own seed and if needed: seed treatment by heat or dressing (Tillecur®, thyme oil) [40, 41]	
All	soil-borne diseases: • in legumes one aspect of soil fatigue, possible pathogens: • Verticillium spp. • Sclerotinia spp. • Fusarium spp. Rhizoctonia spp.	crop rotation [39, 59, 62] fertilization with compost [46] cultivation of beneficial plants, biofumigation, e.g. mustard (*Brassica juncae*) [24, 60, 61]	mustard-cultivation potentially contrasts with crop rotation (*Cruciferae*) careful application: possible phytotoxic effects
Pea	Ascochyta diseases, root rot (Ascochyta-complex) lodging low competitive capacity (weed)	Ascochyta: • cultivation break no less than 6 years[38, 39, 45, 47, 59] • resistant varieties [38, 39, 40, 42, 43, 49] • avoidance of soil compaction [40, 45] • seed bed preparation with compost [46] • sufficient planting depth:- 4-6 cm [46, 47] • lodging and weed suppression: • intercropping (mainly barley, oat)[44, 46, 47, 63]	intercropping: further processing in the mills may cause problems
Lupine	Anthracnose (*Colletotrichum acutatum/lupini*) brown leaf spots (*Pleiochaeta setosa*) Fusarium-wilt (Fusarium oxysporum)	general measures: • cultivation break no less than 4 years and no susceptible plants in previous seasons [40, 44, 48, 49] • resistant varieties [4, 38, 40, 42, 43, 49, 50] • avoidance of soil compaction [40, 50] • avoidance of contagion by field inspections [48]	

Crop	Disease	Solution	Aspect
Soy bean	Sclerotinia stem rot (*Sclerotinia sclerotiorum*) Diaporthe/Phomopsis by the Diaporthe-Phomopsis-complex, seed decay, pod and stem blight, stem canker (Diaporthe ssp., Phomopsis longicolla)	general measures: • cultivation break for 4 years and no susceptible plants in previous seasons[40, 50] • seeding in wide rows [50] • deep underploughing of residues [57] • avoidance of soil compaction [40, 50] • resistant varieties [50, 51] Sclerotinia: • Contans® WG (*Coniothyrium minitans* CON/M/91-08) [1, 17]	deep ploughing contrasts with preservation of soil structure
Faba bean	Ascochyta blight/leaf spot (*Didymella fabae*) lodging/weed supression	general measures: • cultivation break for 5 years and no susceptible plants in previous seasons[40, 46, 50, 59, 64] • resistant varieties [53, 54, 64] • seeding in wide rows [54, 64] • sufficient planting depth: 6-8cm [54, 64] • lodging/weed suppression/yield security: • intercropping (oat, triticale, barley)[54, 55, 56]	deep ploughing contrasts with preservation of soil structure
Alfalfa	alfalfa wilt (Verticillium spp., Ascochyta spp.) Sclerotinia crown, root rot, clover cancer (*Sclerotinia spp*.) Anthracnose (Colletotrichum trifolii)	general measures: • cultivation break no less than 6 years and no susceptible plants in previous seasons [40, 50, 58] • avoidance of soil compaction [40, 50] • deep underploughing of plant residues[57] • resistant varieties [4, 38, 40, 42, 43, 50, 58] Sclerotinia: • Contans® WG (*Coniothyrium minitans* CON/M/91-08) [1, 17]	deep ploughing contrasts with preservation of soil structure

Table 14: Grass clover

Crop	Disease	Solution	Aspect
Grass	rust (Puccinia spp.) Drechslera leaf spot (*Drechslera spp.*)	resistant varieties [43, 45, 64, 65]	
Clover	Sclerotinia crown, root rot, clover cancer (*Sclerotinia spp.*) Anthracnose (*Colletotrichum trifolii*) for clover soil fatigue see soil fatigue (grain legume crops)	general measures: • cultivation break no less than 5 years and no susceptible plants in previous seasons [58, 60, 66] • deep underploughing of residues [58, 60] • certified seed [58, 60, 66] • resistant varieties [43, 45, 67] • clover stock not too dense [58] Sclerotinia: • Contans® WG (*Coniothyrium minitans* CON/M/91-08) [1]	deep ploughing contrasts with preservation of soil structure

[1] http://pub.jki.bund.de/index.php/BerichteJKI/article/view/3056/3228
[2] http://www.intrachem-bio.de/produkte/pflanzenschutzmittel/cerallr-und-cedomonr/
[3] http://www.biofa-profi.de/de/tillecur-staerkung-fuer-steinbrandanfaelliges-getreide.html
[4] http://www.organicxseeds.com
[5] http://www.bioaktuell.ch/de/pflanzenbau/ackerbau/getreide/getreide-sorten/sorten-aussaat.html
[6] https://shop.fibl.org/fileadmin/documents/shop/1432-bodenschutz.pdf
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[17] http://shop.biocontrol.ch/media/downloads/261/contans_faltblatt.pdf
[18] https://www.oekolandbau.de/erzeuger/pflanzenbau/spezieller-pflanzenbau/oelfruechte/anbau-von-mischkulturen-mit-oelpflanzen
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[66] http://www.oekolandbau.nrw.de/fachinfo/pflanzenbau/futterbau/kleegras/kleemuedigkeit.php
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5.5 Regulation of pests

5.5.1 Introduction

In arable farming, yield limitations are mainly due to diseases, insufficient nitrogen supply or weeds. Severe, unsolved pest problems only occur in oilseed rape (pollen beetle *Meligethes aeneus*; stem weevils *Ceutorhynchus* ssp., flea beatles *Psylliodes chrysocephalus*) and in potato production (wireworms, mainly *Agriotes* spp. but also others from the family *Elateridae*). In all other arable crops, pest insects rarely lead to severe yield losses.

5.5.2 Resilient systems, their main components and practical measures of farmers

Organic farmers face the same potentially severe pest problems as their colleagues in integrated pest management (IPM) and conventional crop farming. However, approaches to manage the pest insects are different. Organic cropping systems are supposed to put prevention of damaging levels of pests first, thus minimizing the need for direct and curative pest control. This involves increased ecosystem diversity through the establishment of non-crop habitats and biotope networks. Secondly, farmers reduce pest damages by crop rotations, increasing crop diversity, timely planting and harvesting, transplanting, weed management, choice of resistant varieties, and avoidance of farm areas with high pest pressure. These practices go hand in hand with the third step, namely active habitat management at field level, i.e. with companion plants, tailored wildflower strips or push-pull strategies which interlink crop and non-crop habitats. The combination of all these measures creates a broad and solid basis for healthy plant development. Direct control measures, which can be applied in case of threatening pest outbreaks, are available for many pests and crops. Direct control measures include the use biocontrol organisms (micro- or macroorganisms), bio-insecticides (natural and botanical substances), physical control (crop netting), and mating disruption by pheromones. Interactions between cultural practices, biotic and abiotic factors have a huge impact on plant health (scheme): the use of direct control methods can have side effects on beneficial arthropods and thus adversely affect ecosystem services needed for pest prevention. The use of non-selective bio-pesticides should therefore be limited to a minimum.

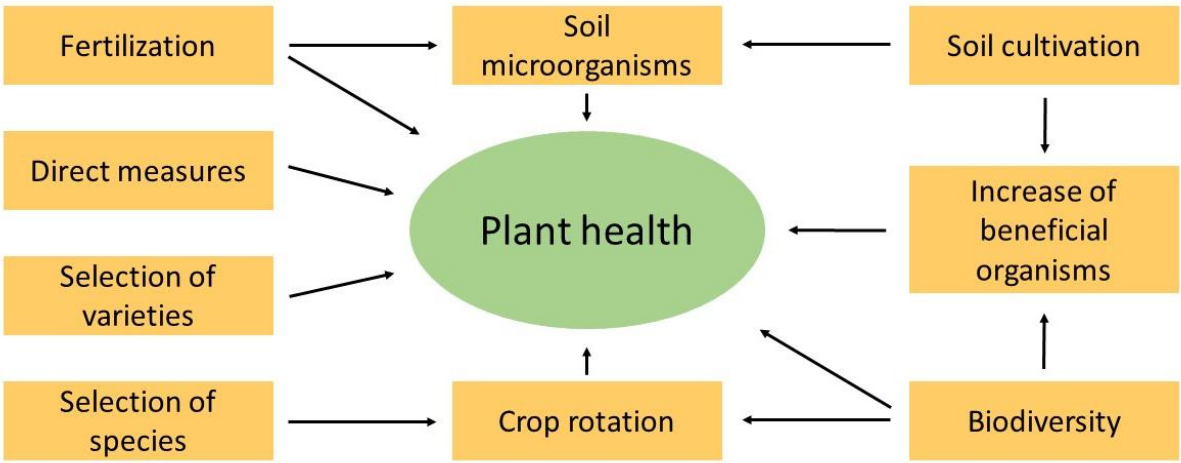

Figure 4: The concept of plant health in organic agriculture

Ecosystem services and functional agro-biodiversity: The use of functional agro-biodiversity (Costanzo and Bàrberi 2014) is a key element of pest control and plant health. In many European countries, agri-environment schemes directly aim at shaping and influencing biodiversity within the productive area ("land sharing concept") with the purpose to provide ecological functions which positively influence agricultural production (functional agro-biodiversity) (Balmer *et al.*, 2014; Balmer *et al.*, 2013; Ratnadass *et al.*, 2012). Interlinking biotope networks with crop and non-crop habitats has a positive effect on abundance and diversity of epigeic predators, such as carabids beetles or spiders, or birds (Östman et al. 2001; Pfiffner and Luka 2000; Weibull et al. 2003). The positive effect of a complex landscape is reinforced by organic farming practices (Östman et al. 2001, Pfiffner and Luka 2003, Winqvist et al. 2012, Winqvist et al. 2011). Differences in farm structure (e.g. number of crops), pesticide and fertilization regimes, rotations, historical removal of particular landscape elements and differing management strategies (MacFadyen et al. 2009; Puech et al. 2014) result in an increase in conservation biological control on organic farms and a subsequently reduced pest incidence (Birkhofer et al. 2008, Crowder et al. 2010, Meyling et al. 2013, Östman et al. 2001). Especially, the ban of herbicides in organic farms leads to a higher weed biodiversity compared to conventional farms, which also alters species richness and food-web structure (MacFadyen et al. 2009, Pfiffner and Luka 2003). Organic farming fosters biodiversity of birds, mammals, invertebrates, arable flora (Hole et al., 2005), microbial and faunal decomposers (Birkhofer et al., 2008), and especially beneficial insects (Gomiero et al. 2011, Krauss et al. 2011, MacFadyen et al. 2009, Puech et al. 2014), such as spiders and carabid beetles (Pfiffner and Luka 2003) or parasitoid wasps (MacFadyen et al. 2009).

A vast variety of measures and strategies are used for habitat management at field level (Malézieux et al. 2009, Parolin et al. 2012): **Intercropping** and **mixed cropping** stands for the simultaneously growing of different harvested crop species in one field. **Under-sowing crops**, often clover, are sown with or after the main crop and are not harvested; their most intensive growth occurs before covering of main crop or after harvest of the main crop. **Companion plants** are non-crop plants grown within the fields for different purposes: (1) attraction and support? of natural enemies by providing pollen and nectar (**insectary plants**), (2) repellence and/or interception pest insects (**repellent plants**), and (3) influence on nutrition and/or chemical defence of the crop plants (Parolin et al. 2012). **Banker plants**, mainly used in greenhouse production, are a mini-rearing system for natural enemies (Huang et al. 2011): The banker plants supply a non-pest prey (e.g. aphids which infest the banker plant but not the crop plant) and thus sustain the natural enemies within the greenhouse. **Beetle banks** – grass covered earth banks in the middle of the field – are shelter habitats which provide suitable over wintering sites for predatory carabid and staphylinid beetles or spiders (Jonsson et al. 2008). **Cover crops** are sown after harvest of the main crop before sowing of the new crop mainly to prevent nitrogen leaching and soil erosion. **Flowering strips** usually consist of plants attractive for insects sown at field margins and aim at attracting natural enemies by providing food and shelter. **Barrier plants** are also sown at field margins and aim at intercepting immigrating pest insects (Parolin et al. 2012). **Trap crops or trap plants** are of preferred growth stage, cultivar or species and attract, divert, intercept, and/or retain targeted insects because they are more attractive than the main crop (Parolin et al., 2012).

In cabbage production, inter- and cover-cropping is implemented as an efficient strategy for *Delia radicum* prevention: oviposition of *D. radicum* is significantly reduced in cabbage fields intercropped with clover, because non-host plants interfere with host plant location of this specialist cabbage pest (Finch and Collier 2000, Meyling et al. 2013). The higher remaining weed number and diversity observed in organic farming can have a similar effect: plants in bare soil are heavier attacked by specialist insect pests than plants growing in diverse backgrounds (Finch and Collier, 2000). Flower strips and companion plants are also used in cabbage production to attract and sustain naturally occurring parasitoids of lepidopteran pests. Resources that selectively benefit key natural enemies are needed. Most important features of flower species are the attractiveness to parasitoids, nectar accessibility, and food quality (Wyss and Pfiffner 2008). Belz et al. (2013)

showed that *Centaurea cyanus*, *Fagopyrum esculentum* und *Iberis amara* were particularly attractive for *Microplitis mediator* - a parasitoid of cabbage pests. Géneau *et al.* (2012) showed that nectar from *F. esculentum, C. cyanus,* and *Vicia sativa* significantly increased fecundity (parasitation rate) and longevity of *M. mediator.* Based on these experiences, *F. esculentum* and *C. cyanus* have been selected for the composition of a tailored wildflower strip (Balmer et al. 2014; Balmer et al. 2013). In addition to the tailored wildflower strips, cornflowers (*C. cyanus*) were established as companion plants within the cabbage fields in order to provide nectar in closest vicinity to the crop (Balmer et al. 2014; Balmer et al. 2013). Legutowska et al. (2014) identified plant species which are most attractive for different groups of insects. The most attractive plants for honeybees were phacelia, chrysanthemum, sunflower and marigold; for bumblebees phacelia, sunflower and cornflower; for Syrphidae chrysanthemum and buckwheat: for wild bees chrysanthemum (Legutowska et al. 2014, in Sesja IOR-PIB abstracts).

Cultural pest control: Cultural control practices aim at prevention, avoidance or suppression of pests by creating conditions that are detrimental to the pest or favourable to natural enemies (Hill 2014). Optimal and expedient implementation of cultural practices requires in-depth knowledge of pest biology and careful long-term planning. Bajawa and Kogan (2004) give a very comprehensive overview on cultural practices for pest control which include crop rotation, sanitation, the use of healthy seed and planting material, the choice of adapted/resistant/tolerant cultivars, agronomic measures aiming at soil quality and functioning (minimum tillage, animal and green manure, compost) as well as agronomic measures favouring healthy plant development (irrigation, optimal nutrition, weed management, row spacing) and adapted timing for planting or harvest in order to disrupt the crop-pest phenological synchrony.

Many factors, processes and mechanisms contribute to the yield stabilizing effect of **crop rotations**: Crop rotation drastically changes the above and belowground environment and thus increases temporal diversity in an agricultural landscape which again promotes biodiversity. Crop rotation for pest control is useful against pests which have a narrow host range and a limited dispersal ability (Karlen et al. 1994): For instance, maize rootworm (*Diabrotica* spp.) is efficiently controlled by a three-year rotation (Francis and Porter 2011). Crop rotation and isolation is also an important control method for the cabbage pest *Contarinia nasturtii*, which overwinters in the soil of the previous crop and migrates less than 100 m. In addition, there are indirect effects of crop rotation on pest incidence: legumes in a crop rotation are an important source of nitrogen and nitrogen availability influences and often increases susceptibility of plants to pest damages.

Level and source of **nitrogen fertilization** also have an effect on pest abundance and can promote crop-plant resistance to insect pests (Culliney and Pimentel 1986) as well as tri-trophic interactions (Banfield-Zanin et al. 2012). In cabbage production, lower densities of flea beetles, aphids, and caterpillars were observed on organically manured plants compared to chemically fertilized and unfertilized plants (Arancon et al. 2005, Culliney and Pimentel 1986). Positive effects of organic fertilization were also observed in other crops. In potato production, Colorado potato beetle densities were lower in organically manured fields due to altered mineral content of potato leaves (Alyokhin *et al.*, 2005). Phelan et al. (1995) showed that females of European corn borer (*Ostrinia nubilalis*) preferred plants in conventional soil for oviposition. Thus, **soil management** practices can significantly affect the susceptibility of crops to pests (Lenardis et al. 2014). While minimum tillage seems preferable based on soil quality and pest susceptibility, tillage is often necessary for weed control as well as to accelerate decomposition of crop residues (Dorais 2007). The destruction of cabbage roots and harvest residues immediately after harvest is a key method to prevent pupation of cabbage root fly larvae (*D. radicum*) or lepidopteran pests (*Mamestra brassicae, Plutella xylostella, Pieris* sp.). However, there is clearly a conflict of strategies: no-tillage is recommended to avoid the spread of clubroot, another major oilseed rape and cabbage disease, as well as to protect parasitoids of pollen beetles which overwinter as pupae in the soil of previous oilseed rape fields and which are destroyed by ploughing (Nilsson, 2010).

Mechanical weed control in organic farming doesn't perturb the flora like herbicide using farming systems which generally leads to a higher weed density and diversity on organic farms. The increased weed density was shown to have a positive effect on carabids beetles in organic wheat fields (Diehl et al. 2012). In addition, a higher weed density interferes with host plant location of specialized pest insects such as *D. radicum*: plants in bare soil are heavier attacked than plants growing in diverse backgrounds (Finch and Collier 2000). Thus, possible positive and negative effects of tillage and soil cultivation require a balanced decision based on the observed situation and pest pressure in the field.

Host plant resistance/cultivar choice: Cultivar choice has a huge impact on the outbreak of insect pests, but pest insect resistance or tolerance usually only play a subordinate role for cultivar choice and is rarely addressed in breeding programs. In many cases, complex defence mechanisms and chemical cues are mediating insect-plant interactions (Bottrell et al. 1998): Semiochemicals emitted by plants after damage with herbivores can directly affect the herbivores due to toxic or repellent properties as well as indirectly by attracting natural enemies (Simpson et al. 2013). However, the active contribution of plants for the efficacy of natural enemies has rarely been addressed in breeding programs. Degenhardt et al. (2009) showed that modern Northern American maize varieties have lost the ability to emit (*E*)-β-caryophyllene which attracts entomopathogenic nematodes that infect and kill the western corn rootworm. Thus, these varieties receive little protection from the nematodes. Currently, organic farming still largely depends on varieties bred by conventional breeders (Lammerts Van Bueren et al. 2002). Varieties that fit in the system perspective of organic farming are still lacking. This is a very vulnerable point of the whole system approach.

Different **other agronomic measures** are used in order to reduce or avoid pest damage. Certified seed and planting material are a prerequisite for healthy plant development. Adapted timing for planting or harvest can disrupt the crop-pest phenological synchrony: In areas with high pressure of Swede midge (*C. nasturtii*), Broccoli is produced mainly in spring and autumn instead of summer. During summer, cauliflower which is less susceptible to Swede midge is produced as substitute. Damage by autumn oilseed rape pests, such as flea beetles (*Psylloides chrysocephala*) or *Athalia rosae* is diminished by early sowing and by creating conditions favourable for rapid plant development. Measures to create favourable growing conditions and healthy plant development include adjusted irrigation, drainage, optimum nutrition, weed management, or adapted row spacing. Overhead irrigation during evening hours instead of drip irrigation was shown to reduce infestation with *P. xylostella* by more than 85% (McHugh and Foster 1995), but this strategy is only possible in areas with low pressure of fungal diseases. An increased irrigation – overhead or by drip irrigation – can also mitigate damages of flea beetles whereas a reduction in irrigation can reduce damage of cabbage fly *D. radicum*, because its eggs are highly sensitive to drought. Thus, an overall pest and disease risk assessment is necessary to select suitable agronomic measurements for pest prevention. As cultural practices can have opposing effects on different pests and diseases, they need to be adapted according to local pest and disease pressure. This requires a lot of attention and knowledge of the farmers. Adapted cultural practices can also stimulate compensatory plant growth after pest infestation: in cabbage production, seedlings are planted deeper and are earthed up after transplanting in order to stimulate secondary root growth to compensate for damages of *D. radicum*. In oilseed rape, favourable growing conditions can stimulate compensatory growth of side shoots after bud damage by pollen beetle (*Meligethes aeneus*) on the main shoot. This can even result in an overcompensation leading to higher yields in fields with moderate pollen beetle incidence compared to fields with low or no pollen beetle incidence (Wahmhoff 2000). Mechanical weed control can also reduce pest incidence: in oilseed rape hoeing in autumn reduces not only the weeds but also removes the oldest oilseed rape leaves with the highest infestation of flea beetle larvae from the plants (Wahmhoff 2000).

Physical methods of pest control include nets, fences, particle films, or inert dusts (Vincent et al. 2003). Crop netting is used in cabbage production against *C. nasturtii, D. radicum*, Lepidoptera or flea beetles *Phyllotreta* sp.. Although this method is highly efficient, it has the disadvantage of excluding natural enemies from the crop. The use of inert dusts is also considered to be a physical control method. In oilseed rape production, the good efficacy of inert dusts (i.e. clinoptilolithe) against pollen beetles was shown to increase yield by 23% (Daniel et al. 2013). Kaolin particle film technology has been developed for fruit production (Daniel et al. 2005) but was recently registered for pollen beetle control in Switzerland (Dorn et al. 2014).

Insecticides for organic farming are of natural origin. Neem can be used against *Aleyrodes. proletella*, but the efficacy is only sufficient if drop-leg technology for under–leaf application is used. Spinosad is used against different Lepidoptera larvae, thrips, *C. nasturtii*, and *D. radicum.* The advantage of most natural products (pyrethrum, neem oil rapeseed oil) lies in their lack of persistence and bioaccumulation in the environment, because they generally degrade faster in sunlight, air and moisture than synthetic products (Grdiša and Gršić 2013). However, some insecticides used in organic farming (such as spinosad and pyrethrum) can have detrimental side effects on non-target organisms (Jansen et al. 2010). After application of Spinosad against *C. nasturtii* or Lepidoptera, side effects on aphid parasitoids often lead to an increase in aphid infestation (Hommes and Herbst 2014). Parasitoids of Lepidoptera are also negatively influenced. Thus, all efforts to establish conservation biological control can be annihilated. In order to avoid negative impact of direct control measures on ecosystem functionality, selective methods for pest control should be preferred and the necessity of applications should be carefully assessed.

5.5.3 The role of varieties, regional cooperation and unavailability of PPPs

In order to fully exploit the benefits of functional agro-biodiversity, the use of non-selective insecticides that are also used in organic agriculture has to be reduced. This can only be achieved if tolerant and resistant cultivars are planted. Currently, organic farming still largely depends on varieties bred by conventional breeders (Lammerts Van Bueren et al. 2002). Pest tolerance or resistance is still a minor breeding goal in general and weakens the system approach practiced in organic farming considerably.

As pest problems do not end at farm gates, a closer collaboration between neighbouring farmers could tackle pest problems at a region wide scale and might increase the impact of conservation biological control and cultural measures. Region wide control approaches, especially for highly mobile pests, will play a bigger role in future pest control.

An immediate problem is that the active substances listed in Annex Commission Regulation (EC) No 889/2008 of 5th of September 2008 are not registered in all countries of the EU are allowed for use in organic farming or on specific plants due to their lack of state registration as an active ingredient in plant protection product available on the national market.

5.5.4 Specific problems in cereals and maize

Cereals and maize are attacked by different pests, but these pests rarely cause complete crop loss. In cereals, Oscinella frit, aphids and Oulema sp. frequently occur but usually damage remains below the economic threshold.

In the prevention and control of O. frit, soil tillage, especially plowing and skimming are important measures. Spring crops that are earlier sown are less attacked, similar like winter crops sown later. Early sowing leads to faster growth and better protection against O. frit. In addition, this insect pest prefers laying the eggs on young plants and therefore it is important to foster fast development of early spring cereals. At the time when pest insects are beginning flight, the plants should be less attractive for them.

The most important procedures limiting the number of aphids on cereals should include insulation space, which hinders the migration between crops. Early sowing dates are also important as they result in sufficient plant growth even when other pests cause damage (Kruczek 2011).

Another important pest of cereals crops is the beetle Oulema spp.. In tests with biological insecticides to control cereal leaf beetle larvae, formulations containing azadirachtin (NeemAzal-T/S) and spinosad (Biospin SC 120, SC 240 SpinTor) were effective (31.6 to 77.2% reduction) (Kaniuczak et al. 2011).

In maize production, European corn borer (O. nubilalis), Western corn rootworm (Diabrotica virgifera), wireworms (Elateridae) and birds are the most important pests. The egg parasitoid Trichogramma brassicae is successfully applied for the control of O. nubilalis. Efficacy and application costs are superior compared to other methods – this strategy is even standard for O. nubilalis control in conventional farming. Recently, application technique was further improved by using drone flights over the fields to drop capsules containing T. brassicae. Alternatively, Bacillus thuringiensis var. Kurstaki (trade product Dipel) has been tested and reduced the number of plants damaged by the European corn borer by 35,4-45,9% (single application) and 23,2-38,1% (two applications) (Bereś 2013). However, spray application in high maize fields are challenging and most farmers lack the necessary application technique. Preventive techniques against O. nubilalis are that the plant residues after harvest should be chopped and deeply ploughed (25–30 cm) (Bereś and Pruszyński 2008).

D. virgifera can be efficiently controlled using an appropriate crop rotation. A two year break between maize is already very effective. This strategy is also recommended in the programs of integrated pest management (IPM).

Wireworms attacking seedlings can be a problem in some years and in some locations. Efficient strategies for wireworm management are missing.

5.5.5 Specific problems in legumes

Soy beans are attacked by birds, slugs and different lepidopteran larvae which can be controlled by Bt application. Faba beans and peas can be infested by aphids and thrips, both usually remain below the economic threshold. Aphids can be controlled by neem applications. Severe damage to Faba beans and peas can be caused by pea weevil *Sitona* sp., especially in spring and early-summer during hot dry weather (most common are *Sitona lineatus* and *Sitona crinite)*. In order to limit the damages caused by them, intercropping peas with mustard or phacelia is effective. Larvae of *Sitona* sp. feed on the roots of many cultivated and wild leguminous plant species which leads to a delayed growth. Damages can be reduced by an appropriate crop rotation, early sowing, additional chopping, application of silicate rock dusts or the use of exclusion nets.

The colonization of legumes by the pea aphid can be reduced by mixed cropping with triticale, barley and oats (Olbrycht and Wiech 2003).

5.5.6 Specific problems of Brassica vegetables

Brassica vegetables are damaged by a plethora of pests: aphids and thrips are usually sufficiently controlled by naturally occurring antagonists. Different lepidopteran pest species can be controlled using Bt-products. Adapted application techniques, such as dropleg technology for spraying the lower surfaces of the foliage of vegetable and field crops, improve the efficacy of Bt-products, but are not available on most farms.

The control of the cabbage fly (D. radicum) and the swede midge (C. nasturtii), however, is a challenge in organic farming. The control of D. radicum is mainly based on preventive measures, such as crop rotation, destruction of infested roots immediately after harvest, and distance to other and previous cabbage fields. Young plants are particularly affected; therefore crop netting is used after transplanting in regions with

known occurrence of D. radicum. Delaying planting until the soils are warmer reduces the risk of damages. More damage is observed in soils with high organic matter content; especially decomposing organic matter (harvest residues of previous crops and manure) is attractive to flies. Therefore, previous crop needs to be thoroughly ploughed and a waiting period of 2-3 weeks before cabbage planting is advisable. Seedlings should be planted deeper and earthed up after transplanting in order to stimulate growth of secondary roots. Minor damage can be compensated for by strong root growth. Eggs are sensitive to drought; therefore reduced irrigation has a certain effect on infestation. Machines for mechanical weed control also have an effect on D. radicum. A drench application of Spinosad on seedlings directly before transplanting was recently registered in many European countries and allows D. radicum to be controlled directly.

C. nasturtii can cause major damage in broccoli, although there are the susceptibility differs among the varieties. In areas with high pest pressure, farmers tend to grow cauliflower instead of broccoli during the summer months. The tiny, short-lived adult midges are very weak flyers and are easily translocated by wind. Infestation is usually higher in moist fields close to wind breaking hedges. Therefore, site selection and crop rotation are the most important control strategies: a distance to previous brassica vegetable and oilseed rape fields (>100m) and the production in windy, dry locations can prevent damage. Harvest residues and plant residues of infested fields should be ploughed or disked immediately after harvest in order to prevent emergence of the new generation. Direct control is possible using anti-insect netting with a mesh-size of 0.9mm (especially in seedling production). Insect fences of a 1.2m height with an outside overhang can prevent immigration of midges into the crops. Spray applications of Spinosad have a good efficacy. Good wetting of all plant parts is essential.

Flea beetles (Phyllotreta sp.) damage is observed especially under dry weather conditions and can be mitigated by additional irrigation. Direct control of flea beetles is possible using exclusion nets with a maximum mesh size of 0.8 mm. Dust or spray applications of silicate rock dusts or kaolin can protect young plants during susceptible development stages by repelling the flea beetles. In addition, applications of Neem, Pyrethrine and Spinosad can be used to control the beetles.

Further ideas to improve the control of Diptera insects are a better understanding of "companion plants" in Brassica fields, better forecast models and more precise timing of the applications. Furthermore, more selective products like biological agents such as entomopathogenic nematodes (Steinernema feltiae) might improve the control strategy (Beck et al. 2014).

5.5.7 Specific problems of oilseed rape

Pest insects of oilseed rape are more challenging than diseases: damage by autumn pests such as flea beetles or *Athalia rosae* is diminished by early sowing and by creating conditions favourable for rapid plant development. To avoid feeding damage of adult flea beetle, *Psylliodes crysocephala*, silicate rock dusts are applied if necessary. Efficacy of dust applications seems to be higher than the efficacy of spray applications of silicate rock dusts. However, spray applications pose less risk to workers because the risk of inhaling dust is strongly reduced. In addition, most fertilizer spreaders are not suitable for the application of dusts and completely calm weather conditions are necessary during application.

As with flea beetles, slugs mainly cause damage in the autumn before plants reach the 3-leaf-stage. Damage is reduced by avoidance of sowing under moist conditions, higher sowing densities at the borders of the fields, as well as by consolidation of the seedbed after sowing. Organic growers are allowed to use slug pellets based on ferric phosphate which are nearly as efficient, but more expensive than, products based on metaldehyde (forbidden).

The rape stem weevil *(Ceutorhynchus napi* and *Ceutorhynchus pallidactylus*) are not perceived as a problem by farmers, because monitoring is difficult. Damage is lower in stronger and better developed plants. However, these pests might be responsible for a considerable yield loss in organic farming. Research is needed to estimate yield loss due to these pests.

The pollen beetle (*M. aeneus*) is assumed to be the main pest insect in organic oilseed rape. Fertilization level (especially sufficient N supply) and plant density within the field increase the ability of the plants to compensate for damage. Damage is reduced by choosing early flowering cultivars and by applications of silicate rock dusts. On-farm experiments showed that applications of sprayable silicate rock dust products increased oilseed rape yield by 23% (Daniel et al. 2013). Spinosad has a good efficacy against pollen beetles, but its use is restricted by many organic growers associations. Because spinosad has detrimental side effects on bees and other Hymenoptera, applications shortly before flowering are no option for organic farming. Alternatives are therefore needed.

A mixture of oilseed rape with turnip as a trap crops has been tested over the last thirty years. However, this strategy does not provide sufficient control of pollen beetles and might attract higher numbers of stem weevils (Ludwig et al. 2011). These kind of control strategies are therefore no longer recommended (Kühn et al. 2013). New strategies to control pollen beetles are currently investigated in Switzerland, especially the use of entomopathogenic fungi and the use of repellent odours.

5.5.8 Specific problems of potatoes

Colorado potato beetles and wireworms are the most damaging pests in potato production.

The Colorado potato beetle (*Leptinotarsa decemlineata*) is one of the most important pests on potatoes. Early-maturing varieties and a quick emergence helps to pre-empt the infestation by the beetle. Other preventive steps to be taken are avoiding both volunteer seeds to emerge and adjacent fields with potatoes in the last year, as the pest always spreads from there (Kühne et al. 2006). In addition, insecticides may be used to prevent economic losses in organic farming. The combination of Neem (NeemAzal-T/S) + *B.t.t.* (Novodor FC) achieved good control of young larvae. The two insecticides should ideally be applied staggered. Neem should be applied first, followed by *B.t.t.*. At the same time, this dual strategy minimises the risk of the development of resistance to the insecticides (Kühne et al. 2008). An improved system of decision support for control of Colorado potato beetle could be helpful for farmers especially on when to start with the first application with insecticides.

Wireworms, the larvae stage of click beetles *(Elateridae)* are serious soil dwelling pests. Pheromones of click beetles were identified for the dominant species in Europe and are used for monitoring (Reddy and Tangtrakulwanich 2014). Ryegrass-clover mixtures in crop rotations increase the populations of wireworms which is a trade-off to the organic practice (fodder production, N_2-fixation and humification). Different agronomic practices or the use of pheromone traps can reduce the damage of wireworms (Böhm et al. 2008). Pheromone traps should be placed at high risk areas, thresholds for Agriotes populations should be given and risky site should be avoided (Barsics et al. 2014). Germinating cereal seed baits is the most efficient sampling for determining wireworm populations in grass fields intended for arable production (Barsics et al. 2014). Biological agents were tested against wireworms. Between entomopathogenic fungi and the insecticide Spinosad, synergistic effects were observed. The use of microbial products to stimulate growth and the natural resistance of potato plants should be developed and results should be implemented to practice. Intensification of the dissemination of experiments' results among farmers is desirable.

6. Important additional recommendations of the EIP-AGRI Focus Group on Organic Farming - Optimizing Arable Yields of the EIP

The EIP-AGRI Focus Group made recommendations on how to optimize arable yields in organic farming[21]. In addition to the state-of-the-art of agronomic and scientific research, we summarize the most important points that go beyond agronomy and focus on socio-economic framework conditions.

The joint goal of researchers, advisors and farmers is to make organic arable cropping systems more productive, profitable and sustainable. Organic cropping systems should be complex and resilience, long-term productivity, agro-ecosystem's stability and homeostasis should be an equally important topic as high yields of cash crops.

There are many specific challenges for organic producers to be considered:

- The production and consequently the knowledge is highly site specific and regional.
- The management is very dynamic and therefore, the knowledge has to be applied flexibly and case-specific.
- The knowledge of farmers has to be combined with observations, interactions with peers and is permanently accumulating due to success and failure.
- Interactions with applied scientists in the format of field experiments, field days, courses etc. are efficient ways towards innovation.
- In addition to traditional knowledge which is especially important for local adoption and to new techniques coming from public and private research, craftsmanship is an important gift of organic farmers as many improvement and inventions are made on farms.
- Many management options for organic farmers have no short return on investment or are difficult to monetarize.

Having this specific framework conditions in mind, the requirements can be summarized as follows:

i) **New approaches in farm extension services.** Many public advisory services have been cut in the last two decades and are nowadays not prepared for taking up the huge knowledge gap which exist in organic agriculture throughout Europe. In countries with most advanced organic production and markets which are mainly in Northern and Middle Europe, the knowledge is quite advanced and well applied whereas in the new Member States, the backlog is considerable. The documentation of the existing knowledge in the local languages, attractive ways of dissemination such as video films (also non-professional ones produced by farmers), interactive Apps, information services via Facebook and Twitter and annual gatherings in the format of national field days are important. In addition, farmer-to farmer knowledge exchange will become important and have to become initiated, facilitated (with trainings, material and tools) and organized. In order to secure the funding, the information gap along the value chain also has to be closed. Many food and processing businesses are not aware of problems of the farmers and take certified raw material for granted as they can import when the domestic supply is not

[21] https://ec.europa.eu/eip/agriculture/en/content/focus-group-organic-farming-optimising-arable-yields-recommendations-and-outputs

sufficient. To let them participate in the knowledge creation and sharing is an important source of funding, in addition the public money.

ii) **New approaches in applied research.** Co-generation of knowledge between farmers, farm advisors and scientists is crucial for organic farming. It helps to generate the complex knowledge needed to successfully deal with productivity, quality and sustainability gaps in organic agriculture. It guarantees a circular knowledge flow and accelerates the innovation on organic farms as the gap between science and practice is dissolved. The kind of participatory research needed to address these challenges goes beyond on-farm-trials and surveys. It involves the farmers actively in defining research questions and hypotheses, in field work, result assessment and data collection and the supervision of the work. This requires training (which is interesting for many farmers). Again, like with extension work, the involvement of the value chain is important. Productivity and quality improvements due to on-farm activities are a benefit for the actors beyond farm gate and a transparent information motivates these to fund more research. The EIP-AGRI is an interesting scheme to fund European networks of pilot farms committed to applied research and joint creation of knowledge.

iii) **Improved information and tools for decision making needed.** The complex knowledge on organic cropping systems in order to stabilize and increase productivity, profitability and sustainability requires more information on economic benefits or potential risks and disadvantages. Organic farmers are often reluctant to go for new solutions without having access to such data that allow them to assess the potential impact on their farm. This is especially true for reduced or minimum tillage, for functional diversity, for soil fertility building techniques and complex crop rotations. For the calculation of economic benefits and potentially increased trade-off, pilot farm network and long-term system comparison trials are both important. This knowledge and data should be generated throughout Europe and a co-operation of scientists especially on the methodology is important.

7. Literature

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