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08/25/17

Dear Prof. Charlotte Poschenrieder,

please find enclosed a manuscript with the title „Intensify production, transform biomass to energy and novel goods and protect soils in Europe – a vision how to mobilize marginal lands“ for publication in your journal after review.

It is a review paper summarizing the opinion of a project consortium on options for improved production on marginal lands, a topic of high interest in the EU and worldwide.

Since agriculture will have to nourish 9 billion people on this planet very soon, it will be necessary to increase productivity on all available lands, including those that have been abandoned for certain reasons.

The paper details technologies for precise agriculture, remediation techniques, decision support systems for sustainable production, as well as indicators for sustainability and economical safety. Hence it tries to cover the whole array of problem fields connected with land use and its conflicts.

We are convinced that our paper will be interesting for a large audience and stimulate the discussion on this burning topic.

Therefore we would be glad if you would consider it suitable for your journal and forward it to be reviewed.

Of course, the manuscript is an original and has not been sent to review elsewhere.

Hoping for favorable reviews

Sincerely

Peter Schröder
(for the authors)

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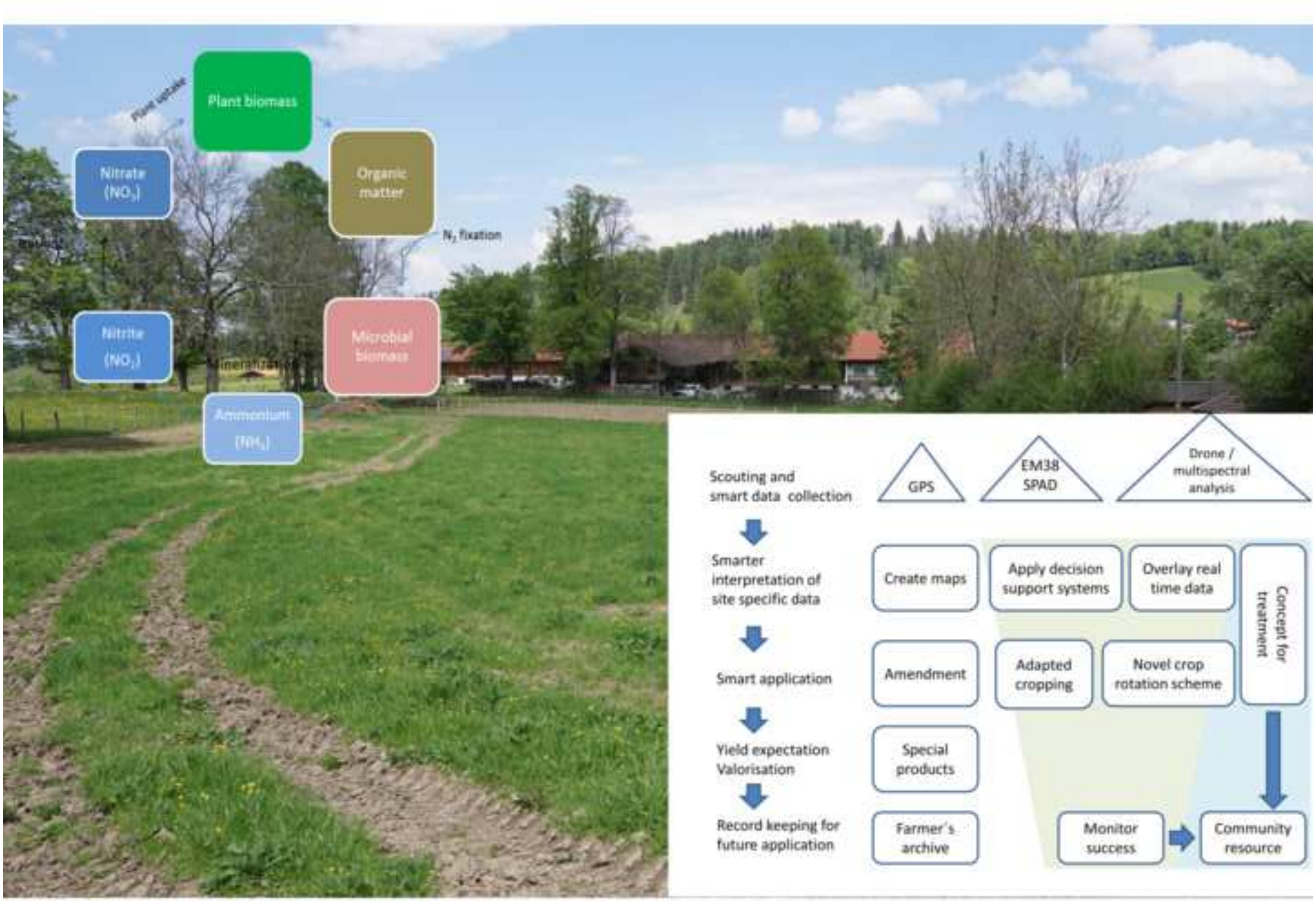
***Graphical Abstract**



Highlights

Challenges for smart intensification of agriculture are manifold

Marginal soils have a high potential for productivity

Tools for precise agriculture will aid to detect pollutant hotspots and poor soils

Crop rotation and adapted crop choice will yield biomass

Amendments will sequester carbon and release fertilizer when needed

Potentials of marginal soils can be unlocked and lead to ecological and economical success

Intensify production, transform biomass to energy and novel goods and protect soils in Europe – a vision how to mobilize marginal lands

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Abstract

The rapid increase of the world population constantly demands more food production from agricultural soils. This causes conflicts, since at the same time strong interest arises on novel bio-based products from agriculture, and new perspectives for rural landscapes with their valuable ecosystem services. Agriculture is in transition to fulfill these demands. In many countries, conventional farming, influenced by post-war food requirements, has largely been transformed into integrated and sustainable farming, but, since it is estimated that agricultural production systems will have to produce food for a global population that might amount to 9.1 billion people in 2050 and over 10 billion by the end of the century, we will require even smarter use of the available land, including fallow and derelict sites. One of the biggest challenges is to reverse non-sustainable management and land degradation. Innovative technologies and principles have to be applied to characterize marginal lands, explore options for remediation and re-establish productivity. With view to the heterogeneity of agricultural lands, it is more than logical to apply specific crop management and production practices according to soil conditions. Cross-fertilizing with conservation agriculture, such a novel approach will provide (1) increased resource use efficiency by producing more with less (ensuring food security), (2) improved product quality, (3) improved nutritional status in food and feed products, improved sustainability, (4) product traceability and (5) minimized negative environmental impacts notably on biodiversity and ecological functions. A sustainable strategy for future agriculture should concentrate on production of food and fodder, before utilizing bulk fractions for emerging bio-based products and convert residual stage products to compost, biochar and bioenergy. The present opinion paper reviews recent developments and indicates ways how to unlock the potentials of marginal land.

Keywords: marginal land, derelict site, polluted soil, precision agriculture, decision support tool, surplus production, soil amendments

1. Introduction

“When soils fail, civilizations fall”. This phrase, coined in 1937 by US president Franklin D. Roosevelt under the shock of the “American Dust Bowl” that had destroyed millions of hectares of arable land in the American Midwest is still of topical relevance today and a threatening reminder to protect our valuable production base for nutrition, drinking water supply and the living and important ecosystem services.

All across the EU and the world, agriculture is in transition. Until now, conventional farming, influenced by the post-war food requirements, has largely been transformed into integrated and sustainable farming, at least in advanced countries (Schröder et al., 2008). In 2011, 12 billion tons (t) dry matter (DM) biomass from agriculture, grazing and forestry have been utilized for feed (58%), bioenergy (heat and electricity, 16%), food (14%), material use (10%) and biofuels (1%) worldwide. Today, the share of biofuels might have reached 2%, and the volume of biomass used for materials and chemicals in 2011 was 1.26 million t DM. But the rapid increase of the world population constantly demands even more food production from agricultural soils, sold to retailers at very low prices. This causes conflicts, since at the same time strong interest arises on novel bio-based products from agriculture, and new perspectives for rural landscapes with their valuable ecosystem services (De Marsily and Abarca-del-Rio, 2016).

Cascading and recycling of bio-based products (SCAR-report, 2015) characterizes the core elements in a novel visionary circular economy, where the term “waste” may lose its meaning. However, a sustainable strategy for future agriculture should always be to first use agricultural products for food and fodder, before utilizing the rest fractions for emerging bio-based products (bioplastic, chemicals, biomaterials, etc.) and next stage products are converted to compost, biochar and bioenergy. Roughly, the average value of 11.3 EJ of residues is estimated as available in Europe, equal to about 269 MTOE (million tons oil equivalent). The current bio-economy market is estimated at about € 2.4 billion, including agriculture, food and beverage, agroindustrial products, fisheries and aquaculture, forestry, and wood-based industry. In addition, biochemicals, enzymes, biopharmaceuticals, biofuels and bioenergy are produced, using about 2 billion tons of biomass and employing 22 million persons (Scarlat et al., 2015). The development trend of emerging bio-based sectors foresees a total biomass demand for 2050 of about 290-320 MTOE. Finally, it is estimated that agricultural production systems will have to produce food for a global population that might amount to 9.1 billion people in 2050 and over 10 billion by the end of the century (UNFPA, 2011). This will require smarter use of the available land, and high attention to avoid falling back in the mistakes of the past.

In future, land use has to embrace efficient production and utilization of biomass for improved economic, environmental and social outcomes. We will have to focus on integrated, systems-based approaches of land management with sustainable intensification of agricultural production, even on neglected sites: underexploited grassland, abandoned and set aside lands, marginal lands and brown-fields with actual or aged pollution. The potential of such sites has to be unlocked by innovative and sustainable production systems, open for a wide range of novel products and services. At the same time, important ecosystem services have to be conserved or strengthened. Hence, challenges for smart intensification exist on many levels, and have to relate to the actual stakeholders and market developments. End users may be farmers or policy makers, as well as the consumers with their demands.

1.1 Challenges for smart intensification

Having postulated that the best soils should always be used for food production, whilst less productive fields could serve as production sites for biomass or energy, we have to elucidate reasons why some lands are unproductive. One of the most severe impacts of expanded production and non-sustainable management is land degradation, which reverses the gains obtained from converting forest or grassland to agricultural use and will threaten yield increases obtained from nutrient enrichment or other technologies (McLaughlin and Kinzelbach, 2015). Therefore, it is vital to support and improve cropland management without further degrading soil and depleting water resources. In the EU, the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI) aims to steer research to support sustainable agricultural production and economic growth, while maintaining and restoring ecosystem services under future climate change. Such an approach will promote a sustainable agriculture which also has the potential to deliver ecosystem services in the form of reduced GHG emissions and increased carbon sequestration, contributing to climate change mitigation and adaptation (Branca et al., 2011; Paustian et al., 2016).

Innovative technologies and principles aid to identify spatial and temporal variability in crop production. Once having recognized the heterogeneity of agricultural lands, it is more than logical to apply specific crop management and production practices at a given site according to soil conditions. Cross-fertilizing with conservation agriculture, such a novel approach will provide the following benefits: increased resource use efficiency by producing more with less (ensuring food security), reaching targeted product quality, improved nutritional status in food and feed products, improved sustainability, product traceability and minimized negative environmental impacts notably on biodiversity and ecological functions.

With regard to climate change, one of the biggest challenges for agricultural management is the loss of carbon into the atmosphere after changes in soil processes. Hence, there are numerous attempts to decrease the flux of carbon to the atmosphere from cropland, and, on the other hand, to sequester carbon in agricultural soils (Smith and Falloon, 2005). Among those options, management practices like reduced and zero tillage, setting-aside, perennial crops, deep rooting crops, addition of organic amendments (animal manure, sewage sludge, cereal straw, compost, biochar), improved rotations, irrigation, bioenergy crops, organic farming, are most prominent (Smith and Falloon, 2005). The sequestration potential is up to 45 Tg (C) per year.

Insert INFOBOX 1

In this context, a controversial discussion is ongoing whether grassland soils are richer in carbon than soils hosting any other type of crop. While some authors find that forage crops store more carbon than any other crop except for grasslands (Gardi et al., 2016), others conclude that geographic distribution and climatic conditions may be more important. Soils in United Kingdom and Ireland (UKI) seem to contain significantly more carbon than soils e.g. in the Mediterranean region. Baltic and Scandinavian soils have more carbon than Atlantic Europe, Continental Europe, and those in the Mediterranean, but still less than UKI (Gardi et al., 2016). The potential to increase soil organic content (SOC) by land management practices seems to be generally higher in Central Europe compared to Southern or Northern Europe. While there is considerable potential in European croplands to sequester carbon in soils, it must be clear that carbon sequestration has a finite potential and is non-permanent. Furthermore, improved agricultural management often has a range of other environmental and economic benefits in addition to climate mitigation potential, and this may make attempts to improve soil carbon storage attractive as part of integrated sustainability policies. Well-managed agricultural landscapes can also provide protection against extreme natural events like drought, storms and flooding. Clearly, trade-offs and synergies among ecosystem services need to be more fully understood and addressed hierarchically.

Covering major aspects of this complex issue, the present opinion paper sketches soil problems, indicators of degradation and resilience, management strategies, soil amendments, and solutions for certain scenarios of European marginal lands.

2 Status of European soils: a plea for smarter biodiversity and soil management

2.1 Marginal lands

Marginal lands generally refer to areas not only with low production, but also with limitations that might even make them unsuitable for agricultural practices and important ecosystem functions (Heimlich, 1989). Across Europe, marginalization of land caused severe losses of arable and permanent crops as well as permanent meadows and pastures in the past. Overall, all forms of degradation amounted to about 10 million ha per year, which was not counterbalanced by the recovery of set aside land since 2008. The principal causes of soil degradation have been identified to be the following: overgrazing (35%), agricultural activities (28%), deforestation (30%), and over-exploitation of land to produce fuel wood (7%), and industrialization (4%) (IP/B/AGRI/IC/2009_26). Similar results were reported by Longobardi and Co-workers (2016). According to estimates by the European Environment Agency (Bardos et al., 2008), the number of sites where potential polluting activities have been carried out in the EU is approximately three million and, of these, an estimated 250,000 sites may need urgent remediation (Panagos et al., 2013). Costs for remediation projects of polluted sites usually fall in the range €50,000 to €500,000 (40% of the reported cases). Hence, the problem has been recognized, but not solved. In any case, degraded soil is less suited to prevent droughts and flooding and more prone to biodiversity loss (EEA, 2012).

It has been common practice, until 2007, to abandon sites of low productivity, and finally the area under obligatory set-aside amounted to 3.8 million hectares in the EU (Keenleyside et al., 2010). Considering average trends, yields from such areas would likely bring around 10 million t of grains onto the market (IP/07/1402, 2007). However, in many places the potential yields are not realized although improved agricultural practices could probably result in much larger food production. Hence, marginal lands have recently received attention for their potential to improve food security and support bioenergy production. Although this seems a promising perspective, environmental issues, concern about losses of ecosystem services, and reduced sustainability have also been discussed in connection to the use of marginal land (Kang et al., 2013).

Given the large areas of land which can be considered degraded, a huge opportunity in developing and implementing practices aimed at restoring the production potential exists. Such a restoration could be a major contribution to unlock increased production of food, bioenergy and other ecosystem services from land (Kidd et al., 2015). Hence, and following consequently the strategy of the FACCE agenda, a change in the EU´s agricultural policies will be needed taking into account that poor, neglected or polluted sites will have to be considered for agricultural production, at least for raw materials and/or bioenergy, if not for fodder and food.

2.2 Soil degradation by poor land husbandry

Ancient farmers erected their settlements close to their fields and meadows, in the areas of highest soil fertility (Fig. 1). In Europe, this pattern remains largely unchanged, and recent settlements in rural areas still occupy a lot of good agricultural land. It has been long debated that the best soils are frequently sealed by different types of infrastructures, such as roads, industry, settlements instead of utilizing them for sustainable production. Besides, in industrialized countries where agricultural foods are inexpensive and easy to reach for everybody, the production base seems to be neglected more and more. But poor land husbandry will have various effects on different soil types (Scherr, 1999), and possibilities of soil improvement can vary substantially, depending upon soil resilience (the resistance to degradation) and soil vulnerability (the degree to which soils degrade when subjected to degradation processes).

Insert Fig. 1

Degradation processes that can be aggravated by agricultural activity include water and wind erosion, physical and chemical weathering, and salt accumulation (Lal et al., 1989). Soil erosion is a land degradation process, often found in cultivated environments due to natural processes (e.g. climate events) and accelerated by human activities (e.g. extensive tillage). It may reduce crop production potential, lower surface water quality and damage drainage systems (Toy et al., 2002). Extensive tillage over extended times may encompass loss in soil nutrients and organic matter which are stability factors, especially for the topsoil.

Topsoil is important for both, agricultural productivity and other soil functions, such as supporting amenity or nature conservation. Its damage will lead to irreparable long-term loss of an irreplaceable resource, since topsoil contains the majority of soil organic matter (carbon) and most of the biological population responsible for nutrient cycling and maintaining soil structure. Loss of organic matter, soil biodiversity and consequently soil fertility are often driven by unsustainable practices such as deep ploughing on fragile soils or cultivation of erosion-facilitating crops such as maize, and continuous use of heavy machinery destroys soil structure through compaction (German Advisory Council Global Change, 1994). Soil aggregation indices can be used as key-indicators for degradation processes in top soils at a fine scale with implications for runoff and sediment generating processes at the hillslope scale. The degradation of soil aggregates is one of the primary processes in the loss of organic matter caused by long-term cultivation and overgrazing, but data on how the formation and stabilization of macro-aggregates control C enrichment when disturbance is reduced are scarce. Inputs of organic matter, e.g. plant debris, might rapidly stimulate the formation of particles or colloids that are associated with minerals, are physically protected, slowed down in decomposition and promote the development of stable micro-aggregates. Although amending organic matter to soils will increase the aggregate formation potential, over-fertilization can lead to an uncoupling of processes that challenge the whole ecosystem and its productivity.

It becomes clear that anthropogenic activities cause soil quality losses over time, which may not be reverted easily. Failure to protect soils after disturbance results inevitably in their degradation, will consequently have environmental impacts and affect other precious ecosystems and even human life. Hence, the primary objective of soil restoration must be to minimize further degradation and unbalanced nutrient losses. Mitigation technologies are urgently needed, effective both in decontaminating and in preserving soil quality and functions, including biodiversity. Emphasis should be on affordable costs and to promotion of the re-establishment of a functional plant-soil system for the long-term. Methods must aim at the natural rehabilitation potential of the soil, integrating existing knowledge on soil resilience functions.

Given the large areas of soils which both according to production, ecological and health criteria can be considered degraded, it is ever so important to develop and implement practices which aim at restoring the production potential and in ecologically sound and sustainably way.

3. Scenarios from an interdisciplinary project

In the Framework of the EU-FACCE JPI, the INTENSE project investigates test sites in France, Germany, Italy, Norway, Poland and Spain (Figure 2, Table 1). These test sites represent problems associated with fertility and the agricultural production on marginal soils.

Some sites have been set aside because of their low productivity, others are prone to pollution by trace elements or organic pollutants. Their situation is complicated by the fact that mixed and multiple pollution occurs.

Insert Fig. 2

Insert Table 1

Insert Fig. 3

4 A toolbox to transform marginal land in productive land

4.1 Detecting the hotspots

Conventional farming of land always involved homogeneous application of seeds, agrochemicals and mechanical methods. With increasing mechanization, larger farms and bigger machines, standard application practices according to the average soil characteristics on regional scale developed. However, farmers and land owners always knew from long term observation and site inspections that their land was not homogeneous at all, and that soil quality and yields differed strongly on certain spots. Indeed, when the first yield monitors were operated in the 1990s such differences in different parts of arable fields could be documented in an exact manner (Schmidhalter et al., 2008). It was in fact a revolutionary step when spatially resolved soil information could be gained by electromagnetic induction, near-infrared spectroscopy, and indirectly by correlating spectral analyses of plant stands to soil properties. Using such an array of novel methods, soil texture, soil carbon, and plant available water in the soil could be characterized much better and faster than ever before. Determining relevant soil properties by contactless sensor techniques became highly effective and provided long-term information for optimized management. Even more, today remote and proximal sensing allows also determining plant biomass, nitrogen content, and nitrogen uptake, by that providing promising techniques for management decisions. With increasing computer quality and speed, data processing became easier and faster, and precision agriculture developed. This technology bundles IT based tools to account for the variability and uncertainty within agricultural production systems.

Computer based sowing, plantlet positioning followed by precise irrigation or agrochemical application completed the picture, however at increasing costs. Nevertheless, farmers express willingness to pay for these services (Vuolo et al., 2015). Of course, this may depend on the size of the farm and the return of investment for the land owner. Instead of investing in precision farming equipment themselves, farmers may rely on extension services providing them with the required information and tools. The EU has recently addressed the application of precision agriculture as an approach to sustainably intensify food production, achieving food safety and security (European Parliamentary Research Service, 2016). This will lead to optimized use of natural resources such as water and nutrients as well as the site- and culture-specific application of agrochemicals and will pave the way for tomorrow´s integrated productivity.

Mobile proximal sensors and drones are emerging technologies designed to overcome many of the limitations associated with current instrumentation of satellite- or aircraft-based sensing systems for mapping crop condition and soil organic matter distribution in agricultural fields. Recent advances in optical designs and electronic circuits have allowed the development of multispectral proximal sensors. The polychromatic bank of light emitting diodes (LEDs) emits light in three wavebands: red, red-edge and near infrared (NIR). The NIR:red ratio is sensitive in detecting water stress of crop canopies, while the red:red-edge ratio is sensitive to chlorophyll content and consequently, to nitrogen deficiencies (SPAD, Olfs et. al. 2005). Similarly, soil humidity sensors based on electric conductivity (EM38) are also in use (Heil & Schmidhalter 2017).

When site management is assisted by such multi-parameter measurements of the status of soils and plants, datasets can be integrated and georeferenced to support decision making. Taking into account that factors affecting crop yield are so complex that even elaborate statistical methods can only give improved, but never accurate results, fuzzy logic approaches are more and more replacing older models in agriculture (Papageorgiou et al., 2011). Utilizing tools of precision agriculture is no longer cost intensive and time consuming. Nevertheless, they may require that the farmer adopts a different way to manage and treat the available land – from map creation to community support (Fig. 4).

Insert Fig. 4

Interestingly, remote sensing is scarcely used for marginal lands (Gibbs and Salmon, 2015), although it would be of significant benefit to apply it (Fig. 5). For plants grown on degraded land hyperspectral instruments can be used to identify plant stress due to leachate percolation from landfills (Ferrier et al., 2009), and pesticide contamination (Morari et al., 2013). Statistical methods such as data fusion could be used to optimize the outputs from the above-mentioned tools. Future scenarios must include an open and unbiased view on existing technologies, and options for practical implementation. It would make a lot of sense to combine practices of integrated farming with ecological and biological approaches, to allow moderate productivity at simultaneous protection of ecosystem services.

Insert Fig. 5

4.2 The role of amendments to increase long term productivity

Adding amendments to soils has been agricultural practice for generations, with the underlying idea that addition of external nutrients or structure building matter would improve soil fertility more or less immediately, and that soils were perfect sinks for (organic and inorganic) waste. This partial misinterpretation has led to countless smaller or bigger soil problems in agriculture and gardening, causing over-fertilization at best, but also salinization or soil destruction, before the faults of the over-simplified concept had been recognized. In itself, addition of compost is a beneficial act, but, as we know today, it has to be properly planned with respect to sources, amounts and timing. In many conditions, especially sandy soils, the most effective methods of improving soil fertility treatments relate to the retention of water in the soil and increasing the capacity of the sorption complex (Table 2).

Insert Table 2

4.3 Compost qualities: reducing pathogens by suppressive composts

The processing of waste organic matter is very popular in Europe. Almost 50% of the whole amount of compost produced in Europe is used in agriculture (Sayen and Eder, 2014). With regards to compost qualities, most important from a practical point of view are nutrient composition and physical, chemical and physico-chemical properties, directly followed by the state of disease suppressiveness (pathogenic organism indicators). Both factor groups will be influenced by the degree of compost maturity and stability. Within EU Member States, standards on the use and quality of compost differ substantially, partly due to differences in soil policies (Tab. 3).

Insert Table 3

Sanitary properties play an important role in evaluating the quality of composts. Across the EU the most common evaluation criteria are the contents of *Salmonella* and *E. coli*. Untreated composts prepared from waste organic matter may transfer microbiological risks, depending on the initial composition of the substrate. Application of immature composts may even increase the population of pathogenic organisms. The addition of e.g. sewage sludge probably increases the content of pathogenic organisms and the risk of crop failure or health effects (Matei et al. 2016). In many EU countries, basic procedures are implemented to achieve hygienization, e.g. by raising the temperature during the composting process (Supplementary Tab. 1). According to US Environmental Protection Agency regulations (EPA, 2002), maintaining a minimum temperature of the composting mass of 55° C for 3 days (aerated static pile or in-vessel) or 15 days with 5 turns is recommended to meet the regulatory requirements of class A fertilizers, and a minimum of 40° C for 5 days - during which temperature should exceed 55° C for at least 4 h - to meet class B fertilizer requirements.

In summary, fermentation processes should reach at least 55°C for 24 hours, and the duration of the fermentation process should not be less than 12 days (Supplement, Tab. 1).

Besides, the quality of the compost and speed the composting process is influenced by many factors. Among them, the more important are (a) the **C/N ratio -** this relationship depends on the dynamics of microbial processes. The optimal ratio is 25-30. High C/N ratios make this process very slow as there is an excess of degradable substrate for the microorganisms. In the low C/N ratios microbiological processes stop, which may lead to leaching nitrogen from composting mass; (b) **pH**: optimum values are between 5.5 and 8.0. Usually pH is not an important factor for composting. However it becomes relevant in controlling N-losses by ammonia volatilization, especially when the pH is very high, e.g. more than >7.5; (c) **aeration**: Aeration is an important factor for composting. The optimum O_2 concentration is between 15% and 20%. Turning the compost pile provides air circulation, temperature maintenance and proper development of aerobic microorganisms which determine the speed of the composting process; and (d) **moisture**: The optimum water content for composting varies between 50–60%. Moisture contents higher than 60% inhibit the composting process due to low oxygen concentration, on the other hand, if moisture is too low, the composting process will be hampered.

4.4 Municipal slurries

Municipal slurries may differ a lot in quality according to cleaning methodology and to which units connect to the system. The treatment of slurry may imply methodology affecting availability of certain nutrients, for example precipitation of phosphorus through use of $FeSO_4$ which may decrease availability of P to plants (Krogstad et al., 2005). The hygienization of slurry through use of large quantities of lime may increase the pH to very high levels and thus limit the availability of nutrients in the soil. If enterprises on the slurry net have production that comprises use and leaching of heavy metals, then metals will follow the stream to the cleaning unit and will be carried to the final slurry. Another worry may be organic pollutants from both enterprises and from use and (inappropriate) disposal of medicines from private households. Finally, the content of microorganisms should be monitored in municipal slurry. Prior to agriculture use of municipal slurry, specific quality parameters on the content of metals and organic and inorganic pollutants should be checked, and guidelines on amounts to be used in a safe way to different soils should be followed. The aim for agricultural production should always be to secure that potentially dangerous waste fractions will never be applied to soils. The responsibility for the slurry quality lies in the enterprises producing it, but the receiver should also have liabilities that the quality is according to what is to be expected. Lack of analysis methodology for all problematic compounds may be a problem related to municipal slurry. For many types of municipal slurry, the same quality criteria as for compost apply.

4.5 Utilize manure/digestate from biogas production

Besides adding plant residues, recycling of animal manure is a well-established method to provide nutrients to agricultural crops. For centuries, the combination of crop and animal production has been a vital part to maintain soil fertility and uphold plant production. However, the introduction of synthetically produced plant fertilizers meant that supply of farm manure was not anymore a prerequisite for successful crop production (Schröder, 2005). Under the pressure of animal husbandry for meat production, immense amounts of manure are produced that have to be managed, e.g. by spreading it on fields for intensive crop production. In the best case, the produced crop biomass will be fed to the animals, by this approaching a closed system. Again, over-fertilization will negatively affect soil sustainability, and lead to damage. Nevertheless, manure is still a useful resource, which can increase soil organic matter, water holding capacity and improve other soil physical properties such as infiltration capacity and hydraulic conductivity (Haynes and Naidu, 1998). Efficient recycling of manure could help to reduce the need of mineral nitrogen fertilizers whose industrial production requires large amounts of energy frequently supplied from fossil sources (Fischedick et al., 2014) and mineral phosphorous fertilizers which is a limited resource, even though estimated world phosphorous reserves have increased during the last years (Scholz et al., 2013).

Since our current understanding of soil processes has greatly moved forward, there has been a clear focus on improving the efficiency in recycling of manure as plant fertilizer during the last decades. Several studies show the benefits of manure application on soil microbial activity and functionality under a wide range of conditions. (See chapter 4 for a review of links between soil microbial activity, functionality and soil productivity.) Field experiments with agricultural crops showed a greater soil microbial biomass after application of organic manure than after application of non-organic fertilizers or no fertilizer application (Peacock et al., 2001; Chu et al., 2007; Liu et al., 2010). In addition, field experiments have proven that manure has an effect on microbial community composition (Peacock et al., 2001) soil enzyme activity (Liu et al., 2010) and catabolic substrate utilization profile (Sradnick et al., 2013) than ammonium nitrate or no fertilizer application. However, despite beneficial effects of manure on resource use efficiency and soil productivity, manure application can at the same time impose stress to the environment. Application of plant nutrients through manure or other organic substrates means that the nutrients are largely bound in compounds that cannot be taken up easily by plants. Thus, efficient use of manure requires that nutrient availability is synchronized with plant nutrient demand and climatic conditions that favors nutrient uptake in roots. If manure applications are not synchronized with plant nutrient demand and uptake, risk of losses of nutrients to the environment is large, notably for nitrogen through ammonia volatilization, denitrification and nitrate leaching through surface runoff and drainage water processes. Besides resulting in an inefficient resource use, such losses can contribute to climate change, depletion of the ozone layer, eutrophication and acidification (Cameron et al., 2013). Other risks to the environment associated with manure are the spread of antibiotic resistant bacteria (Heuer et al., 2011) and heavy metals (Dach and Starmans, 2005). In addition, manure application to agricultural crop is often done with heavy machinery which can easily cause soil compacting and entail negative effects on soil physics, biological properties and plant growth (Nawaz et al., 2013).

The production of bioenergy may decrease this dilemma of overloads. Anaerobic digestion (AD) of manure and other organic feedstocks including food waste and plant residues may be used to generate methane replacing fossil energy. Energy production through AD has increased rapidly during the last years, especially in farm scale facilities (Mao et al., 2015). The rest product from AD, digestate, is still suitable as a plant fertilizer due to its high content of nutrients (Möller and Müller, 2012). Although digestate composition is related to the feedstock that is digested, the AD process changes its physical and chemical properties. Typically for manure, the major changes in the chemical composition through the AD process include increased pH, increased ammonium nitrogen as the share of the total N, lower organic matter and C/N ratio, and lower biological oxygen demand (Möller and Müller, 2012). The AD process also leads to easier penetration of the biorest into the soil as compared to untreated manure. Similar to manure, digestate has a positive influence on soil microbial activity and biomass (Chen et al., 2012; García-Sánchez et al., 2015*b*), indicated by beneficial effects on soil functionality. While differences in soil microbial community and activity between manure and digestate were not such that they justified the recommendation of either substrate before the other (Abubaker et al., 2013), Insam and co-workers (2015) concluded that digestate could enhance soil microbial activity and biomass compared to manure.

Similar to manure, nutrients applied to a crop field through digestate are largely in organic form, which cannot be taken up by plants easily. Hence, the importance of scheduling applications so that the release of nutrients happens in plant available form, synchronized with plant nutrient demands applies to digestate as well. However, the higher share of ammonium nitrogen in digestate means that a larger share of the nitrogen is directly available to plants (Cavalli et al., 2016). Accordingly, digestate has also a higher ammonium emission potential than undigested manure (Nkoa, 2014). Moreover, experimental studies show that the concentration of nitrate in upper soil layers is higher after application of digestate than after applications of manure (Goberna et al., 2011).

It might be critical that digestate, especially when processed from pig or chicken manure, contains higher amounts of heavy metals than manure (Demirel et al., 2013; Zhu et al., 2014), which suggests that its application could be a concern, particularly on soils which are already contaminated with heavy metals. However, other studies found smaller amounts of heavy metals in digestate from poultry manure than in digestate from energy crops (Lehtomäki and Björnsson, 2006) or food and garden waste (Govasmark et al., 2011). In any case, application of digestate may help immobilize mercury and other heavy metals in soils where they occur in high concentrations (Garcia-Sánchez et al., 2015*a*).

There are techniques to separate manure and digestate into liquid and solid phase to facilitate its recycling and adapt its nutrient content to the specific demands of different plats. The solid phase contains most of the phosphorous that is recycled and can be dried further and/or pelleted to decrease transportation costs. The liquid phase has high nitrogen and potassium content and can be applied using traditional or sophisticated techniques. AD, especially when the digestate is separated into liquid and solid phases, thus enhances the possibility to tailor the application of nutrients with respect to soil status and plant demand, compared to the application of green manure or plant residues (Möller and Müller, 2012). Exploration of such tailoring could provide useful knowledge about the effects of digestate and manure application on soil microbes to set efficient application regimes and techniques.

4.6 Adding biochar to soils

Biochar is a recent addition to the list of agricultural amendments but the use of charcoal in soils in truth dates back thousands of years (Qambrani et al., 2017). Biochar is the solid product derived from waste biomass pyrolysis, under mid to low oxygen supply and high temperatures (Lehmann et al., 2011; Ahmad et al., 2014). Still, research on it is in its infancy. Currently, char or biochar is produced from the pyrolysis of different materials, plant biomass but also other kinds of waste of plant or animal origin: applications of biochar residuating from energy production contributes to closure of the production cycles, and its proposed efficacy as adsorbent and amendment may increase environmental sustainability and cost effectiveness. Hence, the properties and applications of biochar must take properties of the feeding material into account. The main role of biochar is in carbon sequestration, with carbon representing up to 90% of the mass, thereby contributing to mitigation of greenhouse gas emission and climate change. Even though carbon in char is considered stable and not bioavailable, its application to soils can increase soil fertility mainly through positive effects on soil structure and functionality. Containing pores and internal surfaces, depending on the structure of the starting material, biochar confers interesting features for amendments, modifying the Cation Exchange Capacity (CEC) and conductivity: use of biochar was shown to increase soil water retention and availability of some nutrients to plants. While larger amounts of biochar could exert negative effects on plant growth, the co-application with manure fertilizers seems to decrease those negative effects (Ippolito et al., 2015). Biochar can limit translocation of non-essential elements to plants (Beesley and Marmiroli, 2011; Beesley et al., 2013; Oustriere et al., 2017), effectively contributing to canopy tolerance towards organic and inorganic contaminants. It may also stimulate microbial communities able to degrade xenobiotics (Rizwan et al.,

2016) and it can reduce leaching and phytoavailability of trace elements (TE) in contaminated soils (Park et al., 2011). However, all these potential gains depend on its quality (Oustriere et al., 2016). At the same time, it can boost plant defense against biotic stresses, and pathogen attacks. Having a microstructure with pores of different dimensions and functional groups exposed on the surfaces, biochar can be favourable to microbial colonization, and this in turn has beneficial effects on soil fertility (Lehmann et al., 2011). Hence, innovative applications foresee functionalization of biochar with beneficial microorganisms to decrease the use of chemical fertilizers. Biochar made from the solid fractions of manure and municipal wastes, after separating out the N-rich liquid fraction, may be most valuable as fertilizer and soil amendment. The phosphorus supply was improved when Jin et al. (2016) tested P-effect of manure char in clay and silt soils. The better use of nutrients in circulation will decrease the climate footprint of chemical fertilizer production and contribute to closing gaps in the circular bioeconomy, also, since it starts from waste material and it produces energy and biofuels.

A main issue with biochar is the need for standardization of requirements for distribution and harmonization of analytical procedures. Efforts in this direction have been performed by the European Biochar Certificate; it is now considered by the "Voluntary Carbon Standard Program" in the framework of agricultural practices contributing to carbon sequestration. Italian legislation allows its use as amendment in agriculture.

4.7 Lower fertilizer inputs, sustainable and economically feasible methods

To date, increased production of fertilizers and soil fertilization contrasts with a relatively low nutrient assimilation by crops. On average, the uptake of fertilizer nitrogen by plants is about 50% of the available N on site, and it is estimated that assimilation of phosphorous is about 10–25% and potassium reaches 50–60% of the applied amounts. This discrepancy leads to an environmental dispersion of excess mineral nutrients that will not be completely used up during plant production (Lubkowski, 2016).

During the industrial production of mineral fertilizers, also climate gasses and waste are emitted, with negative impact on the environment. One method of limiting the adverse effects of fertilization on the environment would be to better adjust fertilizer inputs in crop production.

Reducing the amount of mineral fertilizer can be achieved by either increasing the fertilizer nutrient use efficiency or by replacing mineral fertilization by different kinds of organic amendments (Fig. 6). Fertilizer use efficiency can be optimized by fertilizer best management practices that apply nutrients at the correct rate, time, and place - accompanied by adequate agronomic practices (Johnston and Bruulsemab, 2014).

Insert Fig. 6

Selecting the right source – it is very important to select the right source of fertilizer for achieving your individual goals that will meet specific economic, environmental, and social objectives.

Setting the right rate: The fertilizer requirements vary depending on the type of soil and plants. Therefore, the amount should be determined on the basis of soil testing once every four years. Over- or under-application will result in reduced nutrient use efficiency or losses in yield and crop quality.

Choosing the right time: Fertilizer should be applied during the growing season so that the plants can take up the required amount of nutrients. Fertilizer should never be applied to frozen soil or substrate above field capacity.

Determining the right place: Biogenic components (nitrogen and phosphorus) should be used in accordance with the principles of good agricultural practice especially in sensitive areas (Johnston and Bruulsemab, 2014).

Reducing the consumption of mineral fertilizers can also be achieved by using waste organic substances (Tab. 4). About 32% of the produced compost originates from biowaste and 9% from mixed waste, whereas the remaining part comes from sewage sludge and green waste (Sayen and Eder, 2014).

Insert Table 4

Organic amendments, in particular compost, can represent a valuable tool to improve soil fertility sustainably, since they contain all nutrients required for crop growth. Applying these amendments in marginal soils will positively influence a number of soil properties like soil organic carbon, available forms of phosphorus and potassium, microbial activity, water storage, soil pH and and soil pH. Of course, application of organic amendments will also improve soil structure. The use of such amendments is particularly important in sandy soils, which are characterized by poor water retention and physico-chemical properties.

Table 5 summarizes the main properties of amendments, highlighting the respective advantages and drawbacks. Sustainable agriculture of the future, as Conservative Agriculture, or as Climate Smart Agriculture, will have to exploit all possibilities offered by the specific territory in order to obtain the maximum benefits from the soil amendments available, in order to recycle and reuse all kinds of agrofood residues and close the circular economy. At the same time, Table 6 highlights gaps in knowledge that must be filled with basic and applied research.

Insert Table 5

4.8 A special case: biological methods for soil remediation

When land is polluted by historical or recent industrial activities or spills, action has to be taken. Soil contamination due to metal(loid)s in excess, other inorganic contaminants and persistent organic chemicals are of particular concern (Mench et al., 2009, 2010). Contamination can seriously affect a soil's ability to perform its key functions in the ecosystem. Remediation is considered as the management of the contaminant at a site so as to prevent, minimize or mitigate damage to human health, property or the environment. A scheme depicting different methodologies for remediation is presented in Supplementary Fig. 1. Using site-specific precision technologies in plant nutrition can support both soil conservation and soil fertility maintenance (Németh et al., 2006). In any case, the aim of remediation is to reduce existing or potential environmental risks, to analyze and assess of health and environmental risks to related pollution in the area, and to reduce the risk to a level that guarantees the use of contaminated sites as planned (Table 6). Phytoremediation using living plants (or plant-microbe associations) may be the suitable method for in situ and ex situ remediation of contaminated soils, sludges, sediments and ground waters through contaminant removal, degradation or stabilization. It can be used to remove various contaminants including trace elements, pesticides, solvents, explosives, petroleum hydrocarbons, polycyclic aromatic hydrocarbons and landfill leachates (Vanek and Schwitzguébel, 2003; Mench et al., 2003, 2006; Cunningham and Berti, 1993; Reeves and Baker, 2000; Schwitzguébel et al., 2002; Van der Lelie et al., 2001). Phytoremediation has been used for point and non-point source hazardous waste control. It receives a great deal of attention from regulators, consultants, responsible parties, and stakeholders as it has become an attractive alternative to other clean up technologies due to its relatively low cost potential effectiveness and the inherently aesthetic nature of using plants to clean up contaminated sites. The accumulation of contaminants/waste in the plants may present a problem with contaminants entering the food chain (e.g. herbivores) or cause the plants to become a waste disposal issue. Consequently, the relative concentrations of contaminants in the plant tissue must be determined, and proper harvest and disposal methods must be developed and approved by regulatory agencies. One option is to valorize the plant biomass to face energy and global change problems. Biomass supercritical gasification, liquefaction and pyrolysis are potential routes to valorize plant biomass. The first process results in the formation of syngas to produce e.g. heat or electricity. The others produce biofuel, biochar or more valuable chemicals. However, the feasibility of such options is still in its infancy. When digestate contains too high trace element concentration for commercial fertilizers, pyrolysis may be an alternative. During pyrolysis mineral elements are concentrated in the solid fraction (sand and char). This may open possibilities for metal recovery from this fraction, or when metal recovery seems not feasible, metals are at least concentrated in only a very small mass fraction (needing to be disposed) compared to the initial biomass amount. Recent studies have demonstrated that smart use of plant-microbe combinations can be applied to metabolize even highly recalcitrant organic chemicals with hazard potential (Sauvêtre and Schröder, 2015, Sauvêtre et al., 2017).

Insert Table 6

5. The role of crops on marginal soils

Crop rotation has been practiced since the middle ages as a result of population growth, land shortage and economic pressure and to counteract decrease in soil fertility. After World War II it was replaced by more intensive farming practices where mineral fertilizers, pesticides and new technologies resulted in enhanced yield (Tilmann et al., 2002). Especially in Northern Europe cereal-based, intensive cropping was used instead of the more balanced cereal-legume-tuber crop rotations that had formerly been applied. Only in the last decades a change in farming management occurred with focus on ecology and sustainability: it has been rediscovered that abandoning crop rotation results in soil fertility decline (FAO, 1993) and increases soil erosion (Wight et al., 1778). With the cultivation of legumes, crop rotation reverts land degradation, increases soil fertility and enhances nitrogen availability. Another beneficial aspect is the regulation of weeds and disease suppression. However, crop rotation is location-based and therefore ecological and economical aspects for regional stakeholders must be considered. Decision support systems with regard to cultivation order, demands for life stock farming or non-food crops for special purposes are required (Castell et al., 2015). In the context of increasing soil resilience, the C/N ratio is pivotal for crop rotation life cycle assessment on the farm level.

5.1 Crop rotation schemes for derelict soils

Especially on marginal lands crop rotation can increase sustainability and lead to productivity. Typical crop rotation schemes in temperate regions could contain legumes (mulch or cut) – tuber crops – winter cereal – spring cereal. Undersowing of leguminous species has been proven to be beneficial (Schröder et al., 2008*a*). On richer soils with higher potential of soil erosion the direct sowing of grass or other lay crops after maize harvest could avoid erosion effects. Since enhanced grass silage amount in mulch lead to extended biomass decomposition, a higher C/N ratio can be observed and therefore N immobilization is higher (Sainju et al., 2006). Some options for crop rotations on problematic soils are summarized in table 7.

Insert Table 7

Eco-efficiency could be improved by exchanging cultivars which are dependent on higher fertilization rates with cultivars less dependent to enhance output from the same rate of natural resources. Solutions that create higher yield and in parallel do not enhance environmental impacts per se have to be selected (Kulak et al., 2013). The aim is to maintain good ecosystem-services under unchanged yield demand and to preserve the quality of plant products regarding the needs of food ration and even their biofortication (Jablonowski et al., 2017). Therefore crop rotation could enhance yield in low-input cropping systems without increasing environmental burdens, while at the same time reducing crop–specific pathogens and taking advantage of symbiotic and biological nitrogen fixation (Kulak et al., 2013).

5.2 Plants for the removal of pollutants from contaminated soils

The selection of plant species and optimization of growth in the presence of contaminants are key players in successful phytomanagement of degraded and contaminated soils under different pedo-climatic conditions. Plants must tolerate numerous abiotic and biotic factors, e.g. water stress, soil acidity or salinity, nutrient deficiency, frost, soil erosion or compaction, herbivory, pests, etc. In addition, for the gentle remediation options (GRO), they must at the same time tolerate any soil contaminant(s) present (Supplement Table1). Of course, the first choice of plant genotypes is pioneer vegetation colonizing natural serpentine soils, present in surrounding areas, or established on metal-enriched substrates, such as ultramafic or calamine soils (Kidd et al., 2015). Regarding plant community development at TE-contaminated sites, abiotic factors can be more limiting than competitive interactions between species (Che-Castaldo and Inouye, 2015). Within the same plant species various ecotypes, cultivars, varieties or clones can differ greatly in their response to the presence of contaminants (Vyslouzilova et al., 2003; Marmiroli et al., 2011; Ruttens et al., 2011; Kidd et al., 2015). To prevent spreading of the TE pollution, it will be important to stimulate microbial processes that could contribute to the phytostabilization of TE in the rhizosphere (Lebeau et al., 2008). The selection of endophytic bacteria and rhizobacteria for enhancing biomass production and quality on TE- and mixed contaminated soils is a current challenge with several field experiments (Janssen et al., 2015; Mesa et al., 2017). Intercropping can be an option to facilitate the phytomanagement of TE-contaminated soils, and plant densities as well (Deng et al., 2016; Bani et al., 2015), notably to phytoextract TE without affecting the productivity and quality of undersown legumes. Additionally, phytomanagement of contaminated soils can promote the structural and functional biodiversity, notably for soil microbial communities (Cavani et al., 2016; Foulon et al., 2016; Touceda-Gonzales et al., 2017*a,b*), mesofauna (De Vaufleury et al., 2013), butterflies (Mulder and Breure, 2006) and animals.

Organic pollutants pose a number of different challenges, however spill sites are manifold and pollutant uptake may be significant through root and foliar exposure pathways. Based on phytoremediation studies, cultivation of edible crops should be avoided. One aim is also to prevent a pollutant plume from moving into groundwater or from spreading into so far unaffected regions of the soil. Using plants with high transpiration rates may be advantageous in this case. A second aim would be the accumulation of organics in the plant rhizosphere, for stimulating microbial activity and xenobiotic rhizodegredation (Taghavi et al., 2005; Barac et al., 2004; Weyens et al., 2009*b*). A bioremediation strategy for soils co-contaminated with Cd, dichlorodiphenyltrichloroethane (DDT), and its metabolites 1, 1-dichloro-2, 2-bis (4-chlorophenyl) ethylene (DDE) and 1, 1-dichloro-2, 2-bis (4-chlorophenyl) ethane (ODD) was developed using the Cd-hyperaccumulator *Sedum alfredii* and DDT-degrading microbes (Zhu et al., 2012). Macroporous trees and shrubs can prevent pollutant spread, and mixed plantations of species with different rooting depths might be capable to control the movement of pollutants in the soil (Schröder and Collins, 2002). Few species can take up lipophilic pollutants deliberately from the soil. In most cases, penetration is limited to the rhizodermis, i.e. the outer parts of the roots, which can be reached by diffusion. Transfer of PAH to shoots and leaves seems possible in *Cucurbitaceae*, i.e. cucumbers, zucchini and melons, whereas in plants like carrots, the compounds remain in the roots.

If, however, xenobiotics are metabolized, e.g. by hydroxylating or peroxidizing enzymes, in the root and the rhizosphere, the situation changes, and xenobiotics may well be able to enter the plant. Transfer through the plant has been demonstrated for many compounds (Cui et al., 2015). In this case the question remains how effective the pollutant can be further degraded by the species of interest. From a practical point of view it would always be better to digest the plant material for bioenergy purposes, and safely dispose of rest fraction.

I any case, be it organic pollution or excess availability of trace elements, harvested biomass should not be utilized as sources for food or fodder.

6. Going underground: Exploiting microbe-plant interaction to strengthen plant health and production

As has been pointed out above, agricultural management strategies utilizing soil amendments such as compost and biochar mainly seek to improve soil fertility as well as ecosystem services by adjusting soil pH and increasing soil nutrient content and retention capacity (Diacono and Montemurro, 2010).

However, soil amendments may also change microbial community composition and abundance, which in turn may influence nutrient cycles and soil structure, consequently affecting plant growth. In most soils amended with compost and other raw organic materials, microbiological activity and growth is stimulated as measured by increased microbial biomass C, basal respiration measurements and the activity of specific enzymes such as ureases and alkaline phosphatases (Diacono and Montemurro, 2010). Compared to mineral fertilizers, slow and continuous release of nutrients from compost degradation will support microbial biomass for longer periods of time (Murphy et al., 2007). Similarly, in case of biochar, bacterial and mycorrhizal fungi (arbuscular and ectomycorrhizal) are positively stimulated by increased nutrient and carbon availability, decreased susceptibility to leaching through adhesion to the biochar (bacteria), protection against competitors and predators, sorption of toxins to the biochar and increased resistance against desiccation (Lehmann et al., 2011). Therefore, both biochar and compost amendments appear a good approach to stimulate the activity of beneficial plant-associated microorganisms.

6.1. General mechanisms of beneficial plant-associated microorganisms in plant growth

Nutrient cycling and soil nutrient bioavailability

The most prominent impact of microorganisms on soil fertility is their effect on the mineral cycle by facilitating transformation, mobilization and solubilization of nutrients from the gross soil nutrient pool. Through their ability to solubilize mineral nutrients unavailable for the plant, plant-associated microorganisms can act as biofertilizers (Hayat et al., 2010; Bulgarelli et al., 2013). Well-known mechanisms to promote soil nutrient content and availability include (a) biological nitrogen fixation whereby atmospheric N_2 is converted by bacterial nitrogenase activity into ammonia (NH_3) by symbiotic N_2-fixing bacteria and free-living heterotrophic bacteria (Dixon and Kahn, 2004); (b) nitrogen mineralization by fungi. Ericoid and ectomycorrhizal fungi are especially beneficial for plants due to their ability to convert soil organic N into ammonium, which is partly shared with the plant host. To do so, they rely on proteases and chitinases specifically targeting major soil N sources: peptides and chitin (Chalot and Brun, 1998). Together with oxidative mechanisms this process improves the access to organic N from a polysaccharide-polyphenol matrix (Shah et al., 2015). (c) Phosphorus solubilization, whereby insoluble organic and inorganic phosphates (approximately 95% of the soil phosphorus) are transformed to plant-accessible HPO_4^{-2} and $H_2PO_4^{-1}$ forms through microbial production of organic acids (e.g. acetate) and enzymatic mineralization (e.g. phosphatases) (Rodríguez and Fraga, 1999). And finally (d) iron solubilization, whereby inaccessible ferric ions (Fe^{3+}), which are dominant in the soil nutrient pool, can be mobilized through the production of low-molecular-weight iron-chelating siderophores by both plants and microorganisms, thus improving iron bioavailability and uptake by roots and microbes (Wandersman and Delepelaire, 2004; Jeong and Guerinot, 2009). So far, broad-scale field inoculation with specific microbes has been limited to nitrogen fixation and mineralization in greenhouse and field studies with sugarcane, rice and wheat (Hayat et al., 2010). Biological nitrogen fixation approximately accounts for 65% of the nitrogen currently utilized in agriculture (Weyens et al., 2009).

Biosynthesis of phytohormones

Apart from their influence on the mineral cycle, plant-associated microbes can also directly trigger plant health and growth through the biosynthesis of various signals, including homoserine-lactones (Sieper et al., 2013, Götz-Rösch et al., 2015) and phytohormones. Phytohormonal production is frequently observed in plant-associated bacteria (Costacurta and Van der Leyden, 1995). It ranges from the production of auxins (Spaepen et al., 2007), cytokinins (Arkhipova et al., 2007), gibberelins (Bottini et al., 2004), abscisic acid (Karadeniz et al., 2006), 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity (Glick et al., 2007) to the synthesis of volatile hydrocarbons (acetoin and 2,3-butanediol) with hormonal activity (Ping and Boland, 2004; Ryu et al., 2003; Kai et al., 2009). Together these compounds function as signaling molecules (Fig. 5) and elicitors of tolerance to abiotic stressors (drought, salinity or nutrient imbalance) in a process termed induced systemic tolerance (IST) (Yang et al., 2009) as well as serving a role in triggering the host plant immune system in a process termed induced systemic resistance (ISR) (Ryu et al., 2004). The two most documented examples of these compounds are auxins and ethylene. Microbial production of auxins (indole-3-acetic acid (IAA)) stimulates plant cell proliferation and elongation, resulting in higher total root surface and thus enabling the plant for more efficient water and nutrient uptake (Glick et al., 1998; Patten and Glick, 2002; Spaepen et al., 2008). And (b) ACC-deaminase activity which lowers the levels of stress ethylene improving plant growth in stress conditions (Glick et al., 1998; Contesto et al., 2008; Tsuchisaka et al., 2009; Bulgarelli et al., 2013).

Biological control and modulation of the host plant immune system

Besides direct plant growth promoting effects, plant-associated microorganisms can have a major impact on the biological control of pathogens and the modulation of the host plant immune system (Fig. 7).

Insert Fig. 7

Beneficial microorganisms may prevent pathogen growth and activity via competition for (micro)-nutrients. For example, the production of siderophores may deprive pathogenic bacteria and fungi from iron thereby limiting their pathogenicity (Sharma and Johri, 2003; Compant et al., 2005). Alternatively microorganisms can produce a wide array of compounds with antimicrobial activity (e.g. phenazines) (Berg et al. 2001, Berg, 2009) and hydrolytic enzymes catalyzing cell wall lysis, which will control growth and activity of pathogenic fungi (Krechel et al., 2002). Furthermore, soil-borne microorganisms can also prime or boost the plant's innate immune system in the above-ground plant parts in the process of induced systemic resistance (ISR). Induction of ISR and subsequent signaling cascades results in accelerated responses to pathogen intrusion (Ryu et al., 2004; Van der Ent et al., 2009).

Drought, osmotic stress and freezing resistance

Microorganisms also play crucial roles in the resistance of plants to drought and osmotic stress and the tolerance against episodes of freezing and thawing. Established mechanisms include (a) the mycorrhizal mycelium, which has a smaller diameter than root hairs and therefore better access to bound water (Lehto and Zwiazek, 2011); (b) intracellular accumulation of osmolytes in mycorrhiza (mannitol, trehalose); (c) mycelium hydrophobicity and (d) bacterial secretion of exopolysaccharides (Evelin et al., 2009; Dimkpa et al., 2009).

Impact on soil structure and organic matter content

Plant-associated microbes also have a significant influence on soil structure. The best known examples are arbuscular mycorrhizal fungi improving soil aggregation through two mechanisms. The first one is the production of extraradical mycelium, enmeshing soil particles, physically protecting them from erosion, while the second is the production of amphiphilic molecules, such as glomalin, which promotes the binding of soil particles. Since one gram of grassland can contain as much as 100 m of AMF hyphae (Johnson and Gehring, 2007) these two mechanisms are very relevant at the ecosystem scale. Soil bacteria also produce exopolysaccharides contributing to improved soil structure by stabilizing small aggregates, lining of biopores and mechanical stability (Oades, 1993).

Soil remediation

Finally, plant-associated microorganisms can also play vital roles in the bio-and phytoremediation of contaminated soils and groundwater (Weyens et al., 2009*a*). Exploring and exploiting the vast metabolic potential of microorganisms (oxidative and peroxidative enzymes in fungi and bacteria, surfactants and alkane dehydrogenases in bacteria) enables more efficient degradation of several complex organic compounds (Taghavi et al., 2005; Barac et al., 2004). For the remediation of soils contaminated with toxic metals, the use of plant-associated microorganisms could increase availability, uptake and translocation and decrease phytotoxicity (phytoextraction) and or contribute to the stabilization of the toxic metals (phytostabilization) (Lebeau et al., 2008).

6.2 diversity versus function: what do we have to know about soil microbes

With the knowledge of both, the documented general mechanisms of beneficial plant-associated microorganisms as listed above, as well as the positive impact of amendments on microbial activity, we can speculate that besides directly increasing nutrient content, these soil amendments also stimulate healthy microbial activity and consequently foster plant growth. Indeed, stimulating microbial life in the soil would potentially enhance nutrient uptake, boost plant disease resistance (induced systemic resistance), increase drought resistance (induced systemic tolerance) and all other aspects associated with beneficial plant-associated microorganisms. Within this context, it is also important to address the way we define the ‘quality’ of healthy soil microbial activity. Microbial communities can be defined by their taxonomic diversity, which describes the species present and their abundance within the entire community (Estendorfer et al., 2017) and by their functional diversity, describing the functional processes the microbial community contributes to (Heemsbergen, 2004). To measure the contribution of microbial communities in soil processes, both taxonomic and functional diversity need to be taken into account. For example, high taxonomic diversity could lead to higher stability and resilience of soil processes only if functional redundancy in the community is high. Reversely, some soil processes are dominated by single or a few individual species and therefore the rate of these processes will depend on species identity rather than high functional diversity (Gamfeldt et al., 2008). Hence, a functional trait (such as mineralization, nitrogen fixation) can be a better ecological indicator of soil microbiological quality than the abundance of specific taxa.

7. Indicators and Models – indispensable for land use planning

Actions to improve the quality and production potential of degraded or low productive soils in Europe should be based on well-defined and justifiable indicators of good soils and soil management, to explain how things are changing over time. The advantage of indicators is that they simplify the quantification of complex phenomena so that the core information can be communicated in a more readily understandable form, even or especially to the public (Bell and Morse 2008). Nevertheless, no indicator perfectly reflects reality; each has its own limitations. However, when evaluated at regular intervals, indicators will point out the direction of change of current conditions across different units and through time. Environmental indicators to be used at the international level were first introduced by the OECD in 1974, as a “Core Set of Indicators” (OECD, 1974**)** recommended for use by EU Member States. To date, many indicator-based reports are produced by the European Environment Agency, and a set of indicators contributing to the so-called Environmental Sustainability Index (ESI) has been published (World Economic Forum, 2002). His ESI indexes the overall progress towards environmental sustainability in 142 countries (Moldan et al., 2004). In fact, well assigned indicators may become a potent policy instrument to exert peer pressure among regions to perform better.

In addition to taking into account the state and changes in important components of marginal soils, indicators of land use change must particularly reflect human impacts and counter-measures. The DPSIR model - originally developed by the OECD (1993) for environmental indicators, later developed by the EEA (1999) – takes these processes into account and allows comprehensive causal analysis of key factors influencing land use.

Adapted from the original EEA scheme on biodiversity, such a model may include the following levels:

D = Driving Forces: Drivers to show which human activities are causing the relevant burdens to land use.

P = Pressure: Load indicators to express the concrete impact on biological processes involved.

S = State: State indicators describe the state of selected components of the agroecosystem.

I = Impact: Impact indicators highlight changes in biology/chemistry attributed to certain influencing factors.

R = Response: Action indicators measure the extent to which policies and society react to changes in the defined fields of action.

Some of these indicators are purely descriptive, while others focus on performance or efficiency of a process, and finally, in the response section, some may give a judgement on the benefits for the environment or society.

7.1. Using Indicators and models

The first step of indicator building (Cabell and Oelofse, 2012) is to well define the system to be evaluated. In the present case it is intended to assess how well an agricultural ecosystem is meeting the needs and expectations of its present and future users, followed by elaboration of methods to sustainably improve soils within marginal and/or degraded lands with low productivity potential across Europe. In Suppl. Table 2 we have summarized a number of indicators and categorized them according to their environmental, physicochemical and social background.

If the agricultural production system is considered as one compartment in a larger cultured landscape, indicators will have to provide information not only on imbalances, e.g. releases and deficits of the agricultural production system itself, but also on the external deposition and off-site effects of emissions resulting from agricultural production, e.g. toxic effects in natural aquatic ecosystems due to pesticide residues (Hayat et al., 2010).

The amelioration and intensification of productivity on marginal land across Europe encompasses a wide range of biogeophysical and climatic conditions. Naturally, it is relevant to select indicators based on the specific conditions within smaller regions. For this purpose we selected typical soil and farming for contrasting regions across Europe, which are described below, and tailored indicators, measurements and assessment protocols to these situations. A system which is sustainable under given situations may not be resilient to changed boundary conditions or, vice versa, a system that is not resilient today might become resilient if the boundary conditions change. Decision tree analyses may then be used to decide which scenarios are relevant to investigate.

Both, process-driven dynamic models and conceptual models are useful tools to investigate the sensitivity of a system with respect to defined indicators. Here, we present an example how process-based crop growth models can be applied for this purpose. Such models have previously been used to evaluate the growth, development and yield of annual and perennial crop under a wide range of conditions (Jones et al., 2003; Keating et al., 2003; Stöckle et al., 2003), including climate change projection across the globe (White et al., 2011; Asseng et al., 2013).

The focus of the conceptual model development is carried out on small selected test site areas described above. An initial step of the conceptual model is based on a decision tree model (Fig. 8) were soil conditions of degraded and marginal soils are identified and evaluated and the corresponding mitigation practice is carried out according to experience that has been obtained from different research studies (Kang et al., 2013; Lasanta, 2001; Smith, 2012)

Insert Fig. 8

The above decision tree portrays conditions that are often encountered for soils on marginal lands. These soils are poorly developed and have therefore been abandoned due to their low productivity. For each condition there is a suggested mitigation practice, which can also be influenced by other related practices as indicated. For example, it is recommended to vegetate fallow fields. If this does not apply, then erosion is targeted where tillage along slopes and residue retention in the soil would be the recommended mitigation practice. Marginal lands often have nutrient deficiency and are poor in organic material and structure. In this case crop rotation, N-fixing species and amendments are implemented, correspondingly. In case of contamination, it is common to use phytoremediation practices.

7.2. The economic valuation of biodiversity and selected management practices for marginal land

The economic valuation of environmental aspects of land use is a special case of indicator use. It is an essential tool to valuate ecosystem services and productivity of a given site. Confronted with budget constraints farmers need supporting evidence of the benefits of sustainable intensification at the farm level. Without economic valuation of the environment, policy decisions contradicting economic rationality could be supported. In spite of the need for objectively comparable monetary standards, empirical literature investigating the relationship between species diversity and its valuation from a farmer’s perspective is still scarce (Finger and Buchmann, 2015). However, it is necessary to understand what intrinsic values like *biodiversity* mean to the general public (Bräuer, 2003; Christie et al., 2006, Feest et al. 2010). Furthermore, the willingness-to-pay (WTP) for species or measures that are unfamiliar or undesired by the general public could yield extremely low values despite the fact that these species could perform indispensable ecological services and thereby contribute indirectly to the farmers’ income. Boerema et al. (2016) propose a cascade analysis for the adequate quantification of ecosystem services. The cascade analysis recommends taking into account both the ecological and the socio-economic side for ecosystem service valuation.

Daniels et al. (2017) have proposed an innovative framework effectively integrating ecological and socio-economic aspects into the valuation of biodiversity. Within this wider framework of valuation, functional role-based valuation estimates the indirect use value of biodiversity and may hence reveal more objective values than the application of stated preference techniques. The indirect use arises from the functioning of the biological system and if useful to humans, it leads to (bundles of) ecosystem services (Farnsworth et al., 2015).

In a first step the parameters defining the ecosystem properties and parameters relating to organisms (e.g. species abundance, species composition, species richness) in their environment (e.g. plant density, soil properties) have to be selected. The dynamic ecological model will then simulate the interaction between organisms and their environment in multiple scenarios by allowing the ecosystem property parameters (related to organisms and environment) to vary (e.g. less or more biological diversity). The implementation of a production function results in the quantification of ecosystem functioning. In the next step, moving from the ecological model to the economic model, a linking function links the results of ecosystem functioning to the ecosystem services delivered (e.g. nutrient cycling to soil quality regulation). The benefits of enhanced ecosystem services are translated into monetary benefits expressed as net added value, using a direct market approach (Net added value may be defined as the market price corrected for production costs (€ ton^{-1}, € m^{-3})). This framework allows for the assessment of the indirect value of biodiversity by linking a production function approach with a direct market approach, thereby attributing an objective monetary value to increased species diversity in the provisioning of a marketable good.

7.3 Functional role-based valuation of biodiversity

When dealing with marginal lands, farmers are confronted with constraining ecosystem properties. Solutions/strategies have to be developed based on a combination of management practices, amendments and crop selection, which value (i) the contribution of biodiversity (i.e. microbial diversity) changes to changes in net farm value, and (ii) the contribution of changes in management practices to changes in delivery of ecosystem services. Figure X shows an overview of the approach.

In the **first stage** of the framework, ecosystem properties are translated to ecosystem functions and changes in services through a production function approach. In a first phase, one generic dynamic simulation model is built for an average site with the use of e.g. the STELLA 10.0.6 model simulating the link between soil organism biodiversity and its subsequent effects on related ecosystem services:

biomass production (food and non-food), soil quality regulation and climate regulation (in Figure 9, comparison along the X-axis, comparison among colours, where microbial diversity is changed).

In a second phase, the effects of drought and low organic matter on the provisioning of soil services are included, resulting in 2 models (average and marginal lands). Average lands are then compared to untreated marginal lands based on the marginal change in delivering soil services. In Figure 9 this is shown by comparing within the blue and orange boxes along the Y-axis (dark colours are compared with medium and light colours).

In a third phase, from the models for average and untreated marginal sites, the model is expanded to include the interaction effects of management options (amendments combined with crops) on soil organisms (in Figure 9, comparison among the green boxes). These options are expected to have a net positive effect on soil organisms as compared to untreated marginal sites, resulting in different provisioning of ecosystem services: (1) differences in changes in soil biodiversity, (2) different potential use of land and biomass during management and (3) new options for potential land use after management. The economic benefit of a management option then depends on the change in delivery of ecosystem services as compared to the situation in an untreated marginal site.

In the **second stage** of the framework, for each service delivered, changes are valued with an ecological function linked to an economic valuation method. E.g. fertility, such as a decrease/increase in N-fluxes, will affect the quantity of fertilizers applied and can be valued using the avoided cost method. The values obtained provide an objective and quantifiable indication of the change in services provided by soil biodiversity and can be considered as an indirect value for the measures applied.

Insert Fig. 9

In the third and **final stage** of the framework, the (private) costs of the strategies are taken into account and consist of preparation, investment, operational and monitoring costs. Moreover, the potential environmental impact reduction is included as a reduced cost. The effectiveness of the strategies in restoring and safeguarding ecosystem services and the role of biodiversity can then be calculated as the net added value of biodiversity and management strategies in agricultural productivity. Model application and validation involves assessing the models accuracy and variability with use of an independent validation dataset. Furthermore, spatial model extrapolation at the regional scale as well as monitoring (over several years) will need to be validated using another extrapolation dataset.

8. Unlock the potential of marginal lands

In our struggle to protect the natural environment and manage the resources of the earth in a sustainable way, soil has been neglected for a long time. Today it is clear that soils are non-renewable resources, under increasing environmental pressure across the world, driven and exacerbated by human activity, such as inappropriate agricultural and forestry practices, urban development, tourism or industrial activities. These activities damage the capacity of soil to continue to perform in its full broad variety of crucial functions and services. Degradation of soils must not be viewed as an isolated problem: it has strong impacts on other areas of common human interest, such as water, human health, climate change, nature and biodiversity protection and food safety. Besides degradation, productivity loss has become a matter of growing concern in our industrialized world. This concern is accentuated by an increasing need for land to meet the demands of the world's ever increasing population. Among the strong drivers of this detrimental situation is the industrialization of food production. We have to outline options for a new form of productivity, in a holistic approach, with emphasis on soil resilience. Otherwise we may soon reach a tipping point where production cannot be made less expensive, without endangering the whole system.

And even more, across the EU, valuable agricultural land has become abandoned due to pollution. Such sites remain unproductive in agricultural and ecological context and will not revert to their former state through good agricultural, rangeland management or forestry practice alone. The ecological and human health risk of contaminated soils may be greatest if erosion continues to relocate soil or if the pollutants are resistant to decomposition. Driven by technology feasibility studies of the mid-1980, the management of contaminated sites has moved from a cost-centred approach in the mid-1970s, to a risk-based approach of the mid-1990s and in the new millennium, where environmental decisions must also fulfil the requirements of a sustainable development. With regard to trace element contaminated soils, a variety of physico-chemical remediation methods has been adopted, including solidification, electrokinetics encapsulation, or soil destructive excavation, followed by washing, pyrolysis or disposal of contaminated soil (Vegter, 2001; Schwitzguébel et al., 2002). In many cases, these strategies have resulted in criticisms with regards to their high cost, energy intensiveness, site destructiveness, associated logistical problems and growing degree of public dissatisfaction (Mench et al., 2003). The implementation of gentle phytoremediation and rehabilitation strategies using crop plants and microorganisms to degrade organic contaminants and to stabilize and/or extract plant available heavy metals from contaminated soil, addresses the above mentioned concerns. It is clear that unless the course is reverted, restoration will not occur and the soil will never again be able to complete its full functions.

From an ecological point of view, the rationale for restoration of degraded or marginal land is to recover lost aspects of local biodiversity and ecosystem resilience. From a pragmatic point of view, it is indispensable to recover or repair ecosystems and their capacity to provide a broad array of services and products upon which human economies and human life quality depends. And with view to immediate problems, it is of ample importance to counteract extremes in climate caused by ecosystem malfunction. Clear-cut evidence is presented in EU papers that growing crops on degraded land, without trying to revert the degradation status, will not be sustainable, and continued land degradation will be unavoidable when we don´t alter the course. Thus, besides scientific progress in understanding soil functioning, it will at the same time be of high importance to mobilize the European Research Area (ERA) to achieve common and well developed strategies to overcome soil degradation problems and to respond to global change issues of high public concern such as restoration of soil life and soil functions and mitigation of soil pollution. Of course this requires sound research and rigorous data analyses in an international context, to provide a data base with highly specific evidence on the one hand, and sufficient broadness on the other to generalize problems and communicate solutions. This is imperative, since many policy makers seem to be unfamiliar with the opportunities for modern, ecologically sound agriculture, or of alternative policies that would enable sustainable farming on marginal and abandoned sites.

Whereas conventional farming uses water soluble, chemical fertilizers, the site-adapted farming applies organic matter in the form of crop residues and other wastes or compost or in the later years also biochar, to enhance biogeochemical nutrient cycling, stimulate soil life and its proliferation effectively. Invertebrates and microbial activity are pivotal in the fragmentation and decomposition of dead organic material and turn it into humus, and stable substance. The occurrence of microorganisms in the soil depends on many factors e.g. on soil acidity, organic matter, nutrient availability, air and soil humidity, air and soil temperature, soil water, abiotic stressors, etc. Besides providing the human population with food, fodder and agricultural products, the substantial task for the farmer is to take care in returning nutrients extracted from the soil through harvesting.

Scientific progress of the last decades has resulted in a large number of valuable techniques to assess soils, productivity and ecosystem services. However, little of the new science has been shared with farmers, extension services or even with other specialized agricultural scientists and technicians (Scherr and McNeely, 2008). This seems especially true for applied sciences, dealing with real-life innovations that local people can make to modify ecological impacts of management activities. Agricultural advisory services, even if public or on academic extension services, rarely address landscape management issues (Scherr and McNeely, 2008). But it is now necessary to translate exactly these insights into tools for farmers and stakeholders for site specific assessment and treatment of field sites and knowledge-based practical instructions on a regional scale. This requires that stakeholders are informed about the problem, are correctly consulted, and that they get the best available tools at hand to take action, ideally assisted by scientific guidance (REVIT project, 2007). Thus, applied research for a sustainable and ecologically compatible land use aiming at sufficient food production is ever so important and needs to be disseminated to stakeholders (Schröder et al. 2002, 2003, 2008b). Precise farming techniques will be helpful to re-establish soil life as first priority, and to re-introduce cycling of nutrients. Ecoagriculture approaches will be needed to repair lost functions, and to conserve wildlife (Scherr and McNeely, 2008). Decision support systems considering energy efficiency, variations in climate conditions, cropping systems and production goals between regions will implement regional welfare.

To embrace these goals in marginal land, agricultural and conservation innovators have to pursue strategies to minimize agricultural pollution of natural habitats, manage conventional cropping systems in ways that enhance habitat quality, and design farming systems to mimic the structure and function of natural ecosystems. A reliable strategy is needed to combine and communicate the available tools so that agricultural output is maintained or even increased, production costs stay stable and the market value of the products increases (Scherr and McNeely, 2008). The challenge is no longer simply to maximize productivity of a single crop, but to optimize farming across a far more complex landscape of production, environmental, and social outcomes. When agriculture thrives under the auspices of land-owners educated in sustainable land use, the potential of marginal lands will be unlocked and strengthened, and local stakeholders will defend their region from further degradation and establish economically sound management systems.

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Tables

Table 1

Table 1. List of the study sites in the INTENSE project

Name	Site	Climate	Lithology	Coordinates Lat/Long	Alt.(a.s.l)
Martl-Hof	DE1	Alpine	Calcareous	47°44'36"/11°45'41"	784
Roggenstein	DE2	Continental	Gravel	48°10'49"/ 11°19'07”	540
Buendía	ES1	Mediterranean	Limestone	40°22’10”/2°46’19”	732
Casasana	ES2	Mediterranean	Limest./gypsum	40°31’44”/2°38’11”	954
St.Médard d’Eyrans	FR1	Oceanic	Gravel	44°43′ / 0°30′	3 - 51
Parc aux Angéliques	FR2	Oceanic	Technosol	44° 51′ 20″/0° 33′ 7″	5
MetalEurop	FR3	Oceanic	Clays	50°26´15”/3°10´5.7”	28 - 40
Azienda Stuard	IT1	Mediterranean			
Særheim	NO1	Oceanic	Glacial moraine	58°46'N/ 5° 39'E	90
Skiernivice	PL1	Continental	Stagnic Luvisol	51°95'N/ 20° 15'E	128

Table 2. Ways to improve agricultural suitability of sandy soils permanently or temporarily dry

Methods	expected degree of improvement of the soil		
	High	Medium	Low
Addition of materials with high brevity (silt, clay, etc.).	X		
Addition of permanent organic matter such as. biochar, brown coal	X		
Irrigation	X		
Construction of reservoirs of water		X	
Woodlots			X
Positive balance of organic matter			X

Table 3 Compost criteria for its qualification as product/waste in different European Member States. Compiled from Sayen and Eder (2014).

Country	**Compost status**	**Criteria for the definition of compost status and its use on soil**
Flanders (Belgium)	Product	Requirements on: Input materials; Process conditions; Product characteristics and use
Wallonia (Belgium)	Waste	Among the four classes (A-D) defined by the Government Decree, compost belong to class B and can be used on/in agricultural soil. Within class B, subclasses B1 and B2 are distinguished. The main difference lays in the acceptable metal content.
Germany.	Waste	Requirements established by the bio-waste Ordinance. On a voluntary basis, if certified under the QAS of the RALGZ 251, compost can be put on the market and used as a product
Italy	Waste/Product	Requirements of the Legislative Decree 75/2010 must be fulfilled for compost use as fertilizer. If not, environmental restoration applications can be considered, when limit values of Inter-ministerial Decree 27/7/84 are fulfilled. Otherwise compost is considered as waste.
Poland	Waste/product	According to the Waste Law/Fertilizer Law
Spain	Product	Origin from specific input materials; – Documented life cycle (from waste reception to product selling); – Requirements for compost qualitative characterization.
Norway	Product	Application according to content of heavy metals, the plant's need for nutrients and the kind of products produced in the soil.

Table 4 Availibility of different kinds of urban organic wastes in different European countries

Country	Sources [Mg·year^{-1}]		Fertilizer amounts produced	
	Green wastes	Household bio-wastes	Composts	Digestates
Germany	5 000 000	4 000 000	5 000 000	430 000
Norway	160 000	250 000	112 000	45 000
Poland	549 400	1 896 000	1 154 000	2 000 000*

*Digestates from agriculture biogas plants

Table 5. Relevant properties of main categories of organic amendments as reported in literature (updated January 2017). Green and orange colour indicates positive and negative effects respectively; yellow colour indicates presence of both positive and negative effects; grey colour indicates lack of knowledge.

Properties	COMPOST[1]	ANIMAL MANURE[2]	DIGESTATE (anaerobic digestion)[3]	BIOCHAR[4]
Increase in content of organic matter	increases soil organic matter, humic substances	increases soil organic matter, depends on animal diet	depends on feedstock - humic acids (mainly solid fraction)	affects the stability of existing organic matter
Modification of C:N ratio			low C/N ratio due to digestion	increase
Improvement of water holding capacity	Increases		improves	increases due to surface structure
Supply of nutrients (N, P, etc.) nutrient balance	enhances nutrient supply	leaching of N and P – content differs with animal species	depends on feedstock - mineral N, P (mainly liquid fraction), possible leaching	reduces leaching of nutrients / slow release fertilizer - provides P and K
Modify pH	lowers pH		high pH	increase in soil pH of acidic soils
Modification of cation exchange capacity	Increases			increase in soils with low CEC
Improvement of texture and aggregation state	amelioration of structure and porosity	reduces density	reduces density, increase in aggregate stability	increase in porosity, stability of aggregates
Sequestration of pollutants/contaminants	through humic substances		not reported	can sequester pollutants, but also increase mobility
Addition of pollutants/contaminants	might contain persistent pollutants	micronutrients supplied to animals	might contain persistent pollutants, metals	can contain pollutants, in this case it is not usable
Decrease in salinity	Improvement		can increase salinity with repeated applications	can sequester salts and modify CEC
Soil conservation (e.g. minimise erosion)	remediates degraded soils		still to be investigated	still to be investigated
Increase in microbial biomass	increase	Increase	considerable increase	increase
Increase in microbial diversity	increase or decrease	Increase	significant changes	significant differences
Stimulation of specific microorganisms	no indication	antibiotic resistance	dominance of slowly growing microorganisms	arbuscular and ectomycorrhiza
Increase in enzymatic activities	increase in soil microbial activity	Increase	nitrogen mineralization, other enzymes	reports on increase in enzymatic activities
Increase in diversity of fauna	Limited observations, differing effects		limited observation, increase	Limited observations, differing effects
Effects on plants growth	positive	very positive	positive	mostly positive
Increase of yield	Positive	Positive	fertilizer capacity	reports on increase of crop yield
Increase of product quality	not significant			not assessed
Improve in defense against pathogens	Positive effects			Limited observations, positive effects
Origin, raw materials	biomass from different sources		biomass from different sources	biomass from different sources
Production requirements	requires large amounts of energy, long time			depends on biomass feedstock - importance of temperature

Standardisation of product	Quality assessment differs in the countries	not possible	not possible	just starting
Cost (including transport)	moderate		depends on feedstock	depends on feedstock - high
Positive carbon emission	emissions during composting	emissions of CH_4 and N_2O, NH_3	during digestion GHG emissions, NH_3 emission	could stimulate CO_2 emissions by microbes
Negative carbon emission	carbon sequestration in humic substances		decrease of emissions from manure	removal during growth of biomass, C- sequestration
Legislation, norms on applicability	Differences among countries		can be amendment or fertilizer	limited
Social acceptability	well established	well established	Low	not yet tested
Additional benefits (e.g. energy production)	scalable to farm		production of biogas	reduction of N_2O emissions
Ecosystem services of relevance				

1-Martinez-Blanco et al., 2013; Cesaro et al., 2015; Medina et al., 2015
2-He et al., 2016; Bernal et al., 2009
3-Nkoa, 2014; Möller, 2015
4-Jeffery et al., 2011; Lehmann et al., 2011; Laghari et al., 2016; Tammeorg et al., 2017

Table 6: methods of soil remediation

Technologies	
„Ex-situ”	**„In-situ”**
physical methods	
Incineration	Aeration
Thermal desorption	Soil vapour extraction thermally enhanced
Soil vapour extraction	Electro reclamation
Magnetic segregation of radioactive soil	
chemical methods	
Soil washing	Soil flushing
Solidification/stabilization/sorption/ immobilization	Solidification/stabilization/sorption/chemical immobilization
Dehalogenation	
Solvent extraction	
Chemical and photochemical oxidation/ reduction	
biological methods	
Composting	Bioremediation
Bioreactors/microbiological filters	Phytoremediation
Landfarming	Landfarming
Biopiles	Natural attenuation

Table 7: Examples for crop rotations on marginal soils

Soil type	**Problems/ conditions**	**Rotational scheme**	**Literature**
Sandy soil	Low soil pH (5.5-5.8) Low soil organic matter (SOM) High soil irrigation demand Low soil fertility	Cooksfoot (mulch or cut) – potatoes - winter wheat – oilseed rape - winter rye	Trost et al., 2014
		Oats – winter rye- winter barley – spring barley	Ellmer, 2008
Dry land (Great Plains)	Limited water Cold weather	spring wheat- lentil	Sainju et al., 2006
Thin black Cernozem	Poor grassland, cold weather, ineffective oilseed production	spring wheat–spring wheat–flax–winter wheat spring wheat–flax–winter wheat–field pea	Zentner et al., 2004
Bavarian Tertiary hills (e.g. Scheyern)	Erosion, compaction, intensive agriculture	clover/grass-potatoes-winter wheat-sunflower-clover/grass-winter wheat-winter rye, all with lucerne/clover undersowing	Schröder et al., 2008*a*
Bavarian Tertiary hills (e.g. Roggenstein)	Erosion, compaction, intensive agriculture – focus on Energy plants	Giant wheatgrass – maize/winter wheat – grass legumes. Additional cultures of: Cup plant, Miscanthus, willow, poplar	Chmelikova, personal comm.

INFO-BOX 1

- **BOX 1: The nature of soils**

Soil is the biologically active, unconsolidated surface of the Earth. Well-developed mineral soil consists of 90% mineral and 10% bio-organic substance. The bio-organic part consists of 70-90% humus, 10-30% roots, and an active fraction, constituted of living soil organisms. However, in cool and humid regions, organic soils based on drained bogs can consist of close to 100 % organic materials. Topsoil (0-30 cm) is the most important fraction, since it harbors the main turnover processes. Its basic quality depends on long term stability of humus, soil structure and organismic interactions. Soil fertility and productivity are both determined by a plethora of interconnected features including nutrient balance and release capability in the soil, soil acidity, organic matter content, soil structure, water retention, etc. (Havlin et al., 2013). The long-term functionality of all these soil processes in agricultural systems is highly dependent on healthy microbial activity (Van der Heijden et al., 2008). The soil and plant microbiome, i.e. all microorganisms present in soil, rhizosphere and plant, fulfill crucial roles in ecosystem functioning, nutrient cycling, plant nutrient uptake and disease suppression, which ultimately regulates plant health, physiology and performance (Berendsen et al., 2012; Bulgarelli et al., 2013; Raaijmakers et al., 2008; Bakker et al., 2013; Kiely et al., 2006). Soils promote and support vegetation, and strong relationships exist between habitats of high conservation value and soil properties. When soils are disturbed e.g. by pollutants, poor agricultural techniques or overexploitation, then due regard needs to be given to their restoration and recovery to ensure satisfactory re-establishment of habitats and future sustainable management (Puri, G., 2002). Four basic processes govern all ecosystems: mineral cycle, water cycle, energy flow and community dynamics, all of them have to be in harmony to guarantee the life on Earth. Especially the latter is under scrutiny today, but we are far from understanding which part of the soil diversity is key for soil functioning (Bender et al., 2016). For living beings to thrive, they need effective energy flow to feed them, a water cycle that supplies adequate moisture, and a mineral cycle that supplies vital nutrients. If this is not the case, the system will be imbalanced. If any of these processes is modified by negligence and poor ecosystem husbandry, it will automatically influence all of them, and the system will lose its resilience. Soil as a whole is a limited resource and its health is critical for any sustainable development, it is considered a no-renewable resource. To feed one person per year, 0.26 ha of fertile soil is needed (FAO, 1993)

Figure 1

Figure 1: Typical examples for agricultural settlements on high yield lands. (A) Left: reconstruction of 6th-7th century Bajuvaric settlements in fertile plains close to Munich (photo: PS). (B) Right: BayernAtlas map of typical agricultural landscape close to Straubing, Bavaria, where those settlements were typically located in the middle of the fertile land, riverbanks, colluvial valleys and where still farm communities thrive (CC BY-ND, 2017). (C) Below left: Land use pattern in North western Spain – soil heterogeneity and topography lead to scattered land use and abandonment in case of drought stress (Instituto Geográfico Nacional, 2016). (D) Below right: Even under constricted topographical conditions (bedrock/sea) in western Norway, recent agricultural settlements consume fertile agricultural areas (photo: AS)

Figure 2

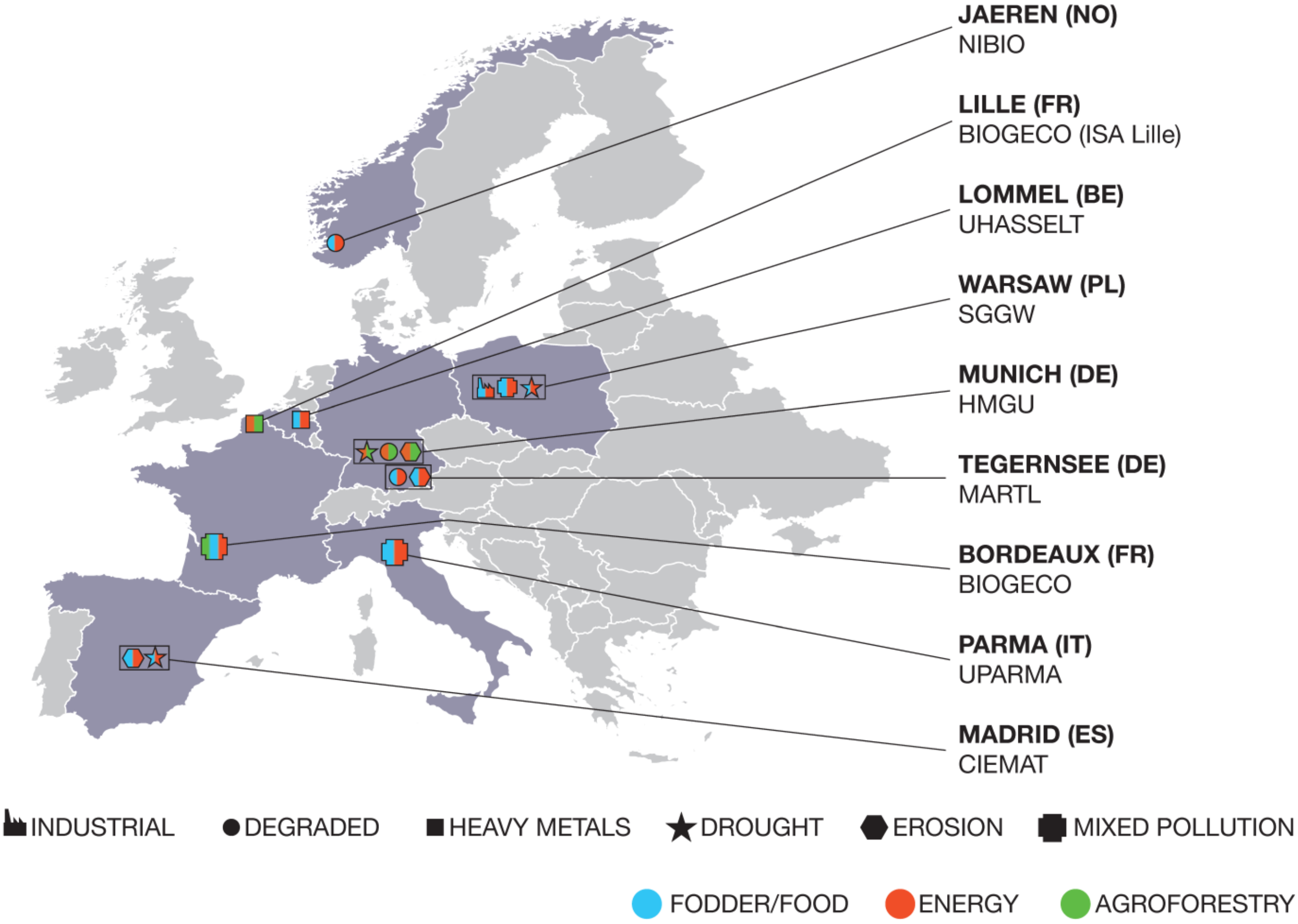
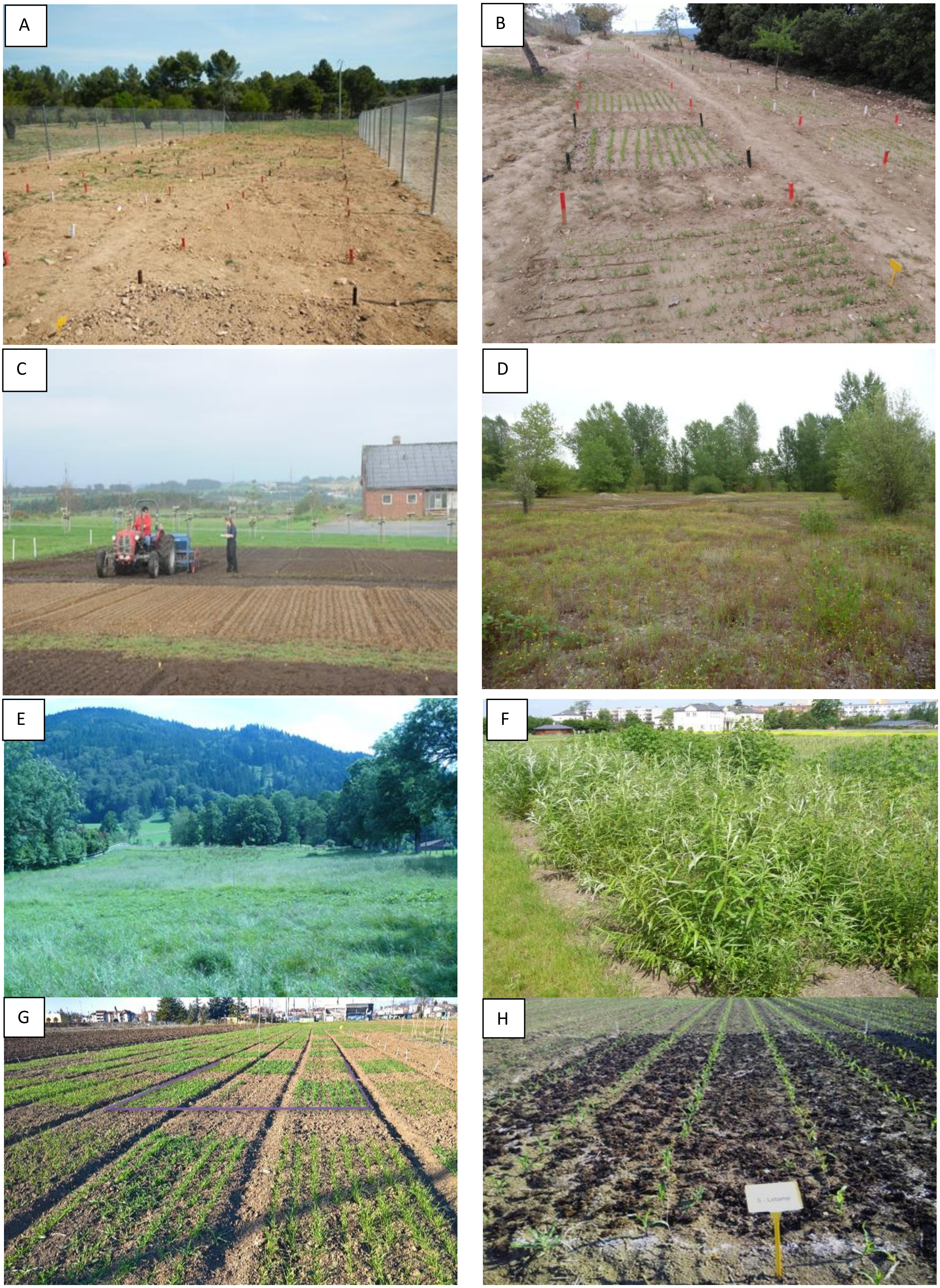


Figure 2: Location of the study sites in the ERA-NET Cofund Project INTENSE with their main sustainability problems


A
B
C
D
E
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G
H

Legend to Figure 3

Spain (Fig 3 A, B)

The test sites (ES1 and ES2) are in Central Spain in the Autonomous region of Castilla La Mancha, under Mediterranean climate with a continental character. Site ES1 is located next to the town of Buendía (Fig. 3A) in the province of Cuenca 135 km northeast of Madrid. The relief is hilly and the site is gently sloping. The mean annual temperature and precipitation is 14 ºC and 610 mm, respectively. The lithological substrate is mainly formed from the Inferior Miocene with red clays, gypsum clays and gypsum. Soils have a clay loam texture with a pH of 8.4 and an abundance of $CaCO_3$ of 30%. The site is within a mosaic of forests, abandoned land and agricultural use. The forest areas are mainly pine trees and areas with Mediterranean underbrush containing a mix of oak and pine (*Q. ilex* and *P. halepensis*). Site ES2 (Fig. 3B) is located near the town of Casasana in the province of Guadalajara 130 km northeast of Madrid. The surrounding relief is hilly and the site is undulating with a gentle slope. The mean annual temperature and precipitation is 14 ºC and 457 mm, respectively. The lithological substrate is mainly formed of Miocene clays, marls and white sand. The soils have a silty clay loam texture with a pH of 7.8 and an abundance of $CaCO_3$ of 22% with a presence of gypsum. The natural vegetation of the area is Mediterranean underbrush made up of oak (*Q. ilex* and *Q. faginea*) and poplar along streams (*Populus sp*.). In both test sites agricultural activity used to include: cereal crops (wheat, barley, oats), legumes (chickpea, bean, lentil), vineyards, olive groves, fruit trees (almond, walnut, cherry, apple, pear), hemp, sumac, melon and pasture for sheep and goats. However, due to low productivity of the land and diminished population in the rural areas after migration to the big cities in the sixties and seventies, vast stretches of land have been abandoned and become marginal lands.

Norway

A field experiment was established at Særheim, Norway (58°46'N; 5° 39'E; about 90 m asl) in the autumn of 2016 on a site, which has been cultivated with variable intensity for about hundred years (Fig. 3C). The site has continuously received manure, in particularly large amounts during the last 50 years. The climate is oceanic with cool summers and mild winters, and an annual precipitation of approximately 1200 mm. A weather station is installed approximately 100 m from the experiment. The moraine soil of glacial origin at the site has an organic matter of approximately 7 % and phosphorous content of approximately 5 mg/100g. In addition to plots with the original soil, a glacial deposited soil / moraine sandy soil with low organic (approximately 1 %) and nutrient content from a nearby site replaced the upper A-horizon soil layer (about 25 cm) on half of the experimental area. Timothy grass (*Phleum pratense*) (cv Grindstad) and tall fescue (*Festuca arundinacea*) (cv Swaj) were seeded at a rate of 35 kg ha^{-1} in September 2016. A complementary seeding was carried out on April 19, 2017 to ensure sufficient plant coverage. Four soil amendment treatments: 1) separated dry fraction pig manure, and mineral fertilizers, 2) separated dry fraction digestate from pig manure and mineral fertilizers, 3) mineral fertilizers and 4) biochar, separated dry fraction pig manure, and mineral fertilizer, were incorporated into the experimental soils before sowing. Each combination of soil, grass species and amendment was replicated four times on plots with an area of 3 m x 7 m. Soils physical properties and nutritive content were analyzed at the establishment of the experiment. Soil samples for analysis of soil microbial activity and functionality were taken at the same time. Soil nutrients and microbial activity and functionality will be analyzed at least yearly. Plant biomass, leaf area index biomass and quality variables will be measured repeatedly during 2017 and 2018.

France

St Médard d'Eyrans (FR1): The wood preservation site (6 ha) is located in southwest France (Fig. 3D) nearby Bordeaux, and has been used for over a century to preserve and store timbers, posts, and utility poles (Mench and Bes, 2009). The industrial facility dates back to 1846. Creosote, Cu sulfate (from 1913 to 1980), CCA (from 1980 to 2006), and Cu hydroxycarbonates with benzylalkonium chlorides (since 2006) were used successively. Established vegetation and site characteristics are detailed in Bes et al. (2010). Anthropogenic soils are developed on an alluvial soil (Fluviosol, Eutric Gleysol). Soil investigation pits (0–1.5 m) revealed major contamination of topsoils by Cu and its spatial variation (65 to 2,400 mg Cu kg^{-1} soil DW) whereas total As and Cr, i.e., 10–53 mg As and 20–87 mg Cr kg^{-1} in topsoils, were relatively low in all soil layers. Several phytomanagement options, i.e. high yielding crops (sunflower- tobacco crop rotation, barley), short-rotation coppice (willows, poplar, and false indigo), Miscanthus, vetiver, and mixed tree stands (poplar/ scots pine; *Cytisus striatus*/*Salix caprea*, *S. viminalis*). Soil amendments are assessed: compost and dolomitic limestone, alone and in combination, compost with iron grit, basic slags, biochar, compost pellet, separated dry fraction and dry fraction digestate from pig manure.

Parc aux Angéliques (Chaban-Delmas and Borifer sub-sites, FR2): The Chaban-Delmas site (4.5 ha) is located in southwest France (Tab. 2), in Bordeaux downtown, at the outlet of the Chaban-Delmas bridge, on the right bank of the Garonne River. This former harbor dock is a brownfield site. From October 2009 to December 2012, it was used as a repository of material stocks and machinery required for the bridge construction. The Bordeaux city has decided to convert it into an urban park. The technosol developed over embankments displays a sandy texture with high total TE concentrations (in mg kg^{-1} DW; Zn [392–7899], Cd [1.7–9], Cu [140–2838], As [41–182], Pb [301–1306], and Ni [20–114]) and PAH concentrations (26–163 mg kg^{-1} DW) in soils exceeding the background values for French sandy soils, under alkaline conditions (pH>8). Such soil contamination is the legacy of former industrial and harbor activities located on the Garonne riverbanks. Plots are phytomanaged with herbaceous plant species, i.e. alfalfa (*Medicago sativa*), ryegrass (*Lolium perenne*), *Bromus sterilis, Festuca pratensis*), alone and in combination with poplars (*Populus nigra*).

Evin-Malmaison (FR3): Agricultural plots are located at Evin-Malmaison, at roughly 1 km from a former Pb/Zn smelter, Metaleurop Nord (Nsanganwimana et al., 2016). The site landscape is highly anthropized with residential suburbs, agricultural and woodlands, and transport networks (Fig. 3 D). The soil is a clay sandy loam dominated by silt (53%), and with a slightly alkaline pH. The total carbonate, organic carbon, total nitrogen, and P_2O_5 contents are higher in topsoil than in deep horizons. The soil metal contamination is restricted to ploughed horizon (0–30 cm). Topsoil is mainly contaminated by Cd, Pb, and Zn at concentrations (mg kg^{-1}) of 14.1 ±1.4, 731±67 and 1000 ±88, respectively. These concentrations are 33, 23 and 15-fold (for Cd, Pb, and Zn, respectively) higher than regional background concentrations in uncontaminated agricultural topsoils (Sterckeman et al., 2002). Compost, either initial state or pelleted, and biochar were applied. Hemp was cultivated in 2017.

Germany

Martlhof (784 m a.s.l.), a traditional small dairy farm, was founded in 2016 on former extensively used grassland between Tegernsee and Schliersee, next to the Alps (Fig 3E). The mean annual precipitation in this region is 991 mm, the mean annual temperature 7.5 °C. The relief is gently sloping and the soils have a sandy loam texture with a pH ranging from 5.7 to 7.0. Martlhof is an ongoing small-scale farm aiming to increase its value creation by implementing aspects of circular bioeconomy. Besides producing fodder for dairy, pigs and horses, it operates a pyrolysis reactor to recycle plant residues and produce energy, heat and biochar. A fully randomized field plot with 48 different plots was implemented at Martlhof to study (a) the microbial diversity changes due to the conversion situation, (b) the health and performance of crops in unfertilized, and organically fertilized plots, and (c) the biomass production on the plots in comparison to the original grassland. In the first growing season, all plots were homogeneously fertilized with organic fertilizer (pig and sheep manure) and subsequently sown with *Vicia faba*, to equalize the initial soil situation. Crop rotation using maize, fodder beet, and barley, with *V. faba* as intercrop will be set up in Martlhof, with an additional group of *Miscanthus* plots (as permanent crop). Martlhof will utilize maize, beets and barley as fodder, and *Miscanthus* as energy crop and for biochar production. Results of a basic inventory on soil parameters show high homogeneity of the soils under the plots, but also differences in fertilization status due to overgrazing. Pelleted compost as well as digestates are used to fertilize this plot experiment.

Poland

The experimental station of Skierniewice was founded in 2002 on the long-term fertilizer experiments of an experimental field from 1921. The mean annual precipitation in this region is 528 mm and the mean annual temperature 8.0 °C. Field I (Skierniewice) and Field II (Miedniewice) are covered with soils of glacial origin, on ground moraine. The dominant types of these soils are stagnic luvisols (about 90% of Field I and about 60% of Field II). The substratum is loamy sand (14-17% of silt) to a depth of 40 cm and loam in deeper soil layers with a low total organic carbon content of 0.6 – 0.75%. Field I covers an area of 27.83 ha, including 25 ha of arable land. Irrigation is needed because of the low water holding capacity and the low mean annual precipitation. Maize, Timothy grass and tall fescue are planted to examine effects of varied fertilization on crops and environment in different crop rotation systems (Fig 3F). Different fertilizers including organic wastes (e.g. pelletized compost from spent mushroom substrate, bio-rest from biogas production and straw) are applied as soil amendments to discover differences in plant growth, biomass yield and microbial diversity. The on-site produced pellets are provided for some field experiments conducted in the INTENSE project.

Italy

Azienda Agraria Sperimentale Stuard (Fig 3G,H) is a small experimental farm sized 20 ha, operating since 1983, located in the upper Po valley, at the center of an alluvial substrate with varying weaving (from gravel to clay), put in place by significant flooding events related to the major watercourses of the area (Taro, Parma, Baganza). In the region, the mean annual temperature is 12.5°C (ranging from -2 to 29 in 2016) and the mean annual precipitation is 842 mm. This is a relatively stable area, from historical times no longer affected by sediment yields, in which the soils have had time to differentiate significantly from the substrate of origin (medium-to-moderate tessitural floods). On the farm there is a moderate variability in soil characteristics mainly related to variations in the soil profile. The plot area is located in the central-western sectors of the farm, where soils have agronomic qualities mainly affected by high silt content. They are moderately alkaline and have superficial horizons, about 50 cm thick, of olive-brown color, lime clay, very limestone and very deep, 30-70 cm thick, light brown olive, strongly calcareous. These soils fall into the utmost fine, mixed, mesic Ustochrepts according to the Soil Taxonomy and the Haplic Calcisols according to the FAO Legend. There are no significant physical limitations to the development of radical apparatus. The characteristics of the structural elements determine favorable conditions for the entire soil volume to be rooted. The presence of an ancient soil buried with features favorable to rooting allows plant roots to deepen without problems. Clay content, despite the high amount of silt that is always present, results in ties of sufficient intensity between the soil particles: The stability of the structure is generally good and crusts are formed only after intense rains. The randomized experimental plots are planted with maize rotated with barley and supplemented with biochar from wood material, compost as pellet, organic fertilizer (manure) and mineral fertilizers.

Figure 4

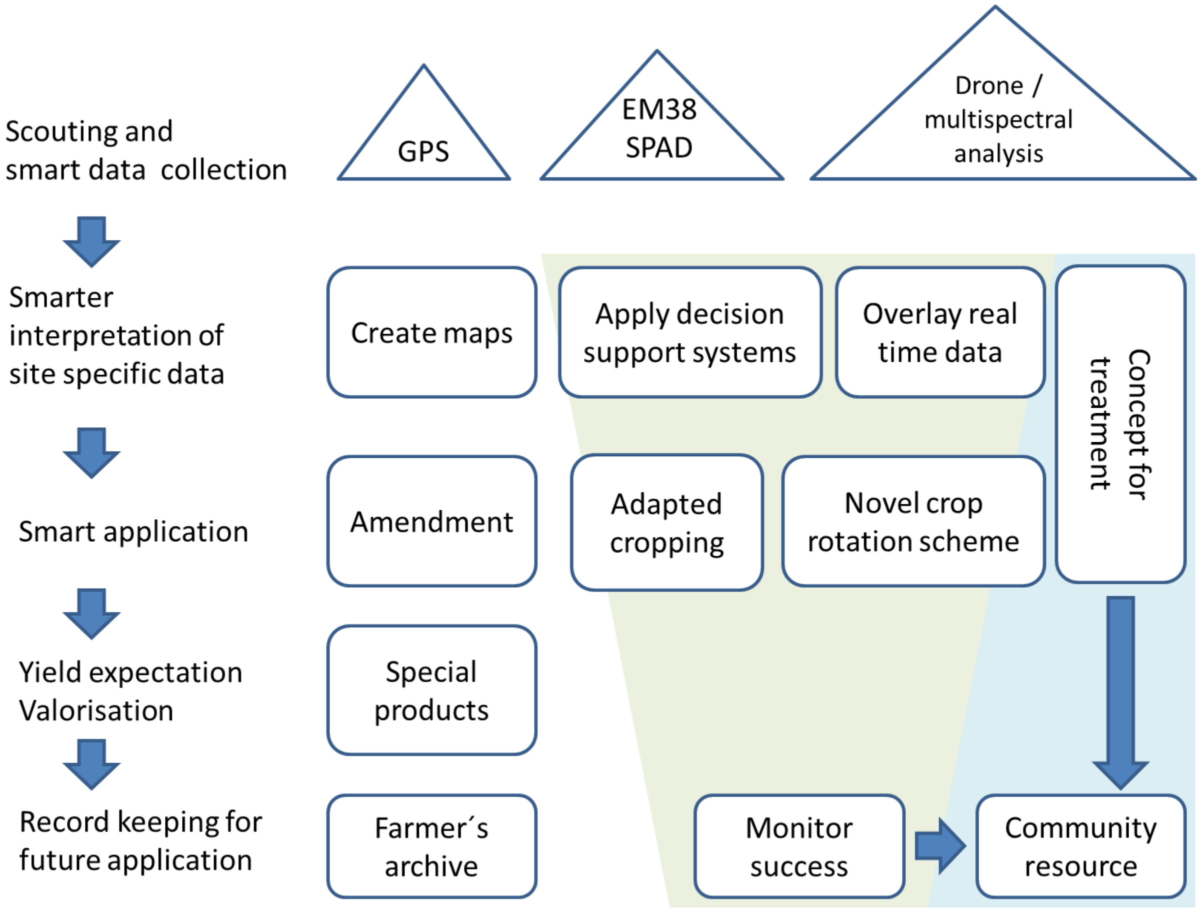

Fig. 4: Using precise tools for management of marginal land. Derived from high-tech precision agriculture solutions, modern sensors allow farmers to obtain a better knowledge about sites, their land, soils and their crops. To date, spatial collection systems are in use for collecting georeferenced data by making use of hand held (SPAD) or vehicle-borne (EM38) sensors and measuring devices that send wireless data to a managing unit. Remote sensing with satellites or airborne vehicles (e.g. UAVs - unmanned aerial vehicles, Zhang and Kovacs, 2012) and proximal on-field sensing attached to agricultural machines can be used to obtain hyperspectral imaging to monitor the physiological status of the vegetation (Morari et al., 2013; Padua et al., 2017). Many presently available precision farming tools can be utilized to unlock the marginal soil´s potential. Smart combination of methods is the key.

Figure 5

Fig 5: Aerial picture of the experimental plot at the Martl-Hof, Bavaria, taken with an XR6 Drone and a Sony α6000 camera in RGB mode from 100 m distance. Crop types, quality of the grassland, animal distribution (right edge) and soil features can easily be distinguished (© PS).

Figure 6

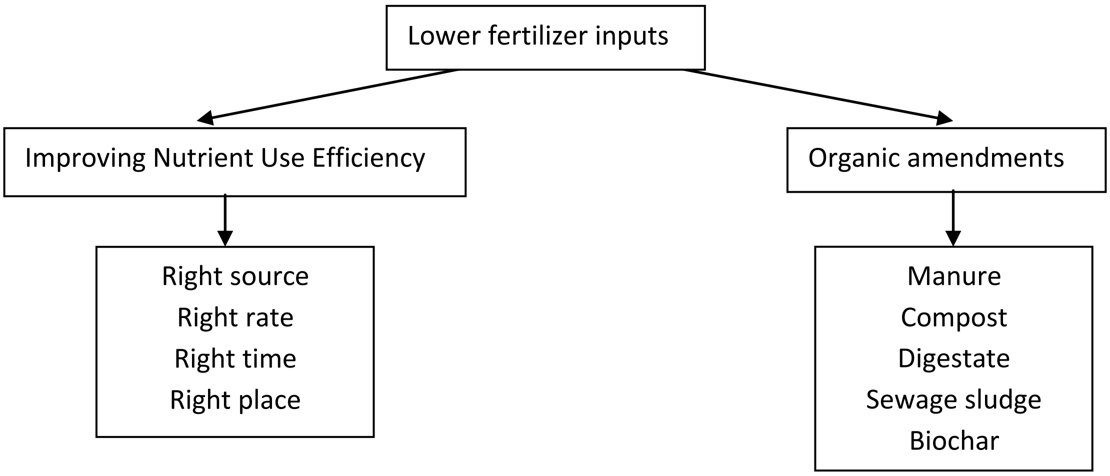

Figure 6. Methods to reduce the fertilizer input

Fig. 7

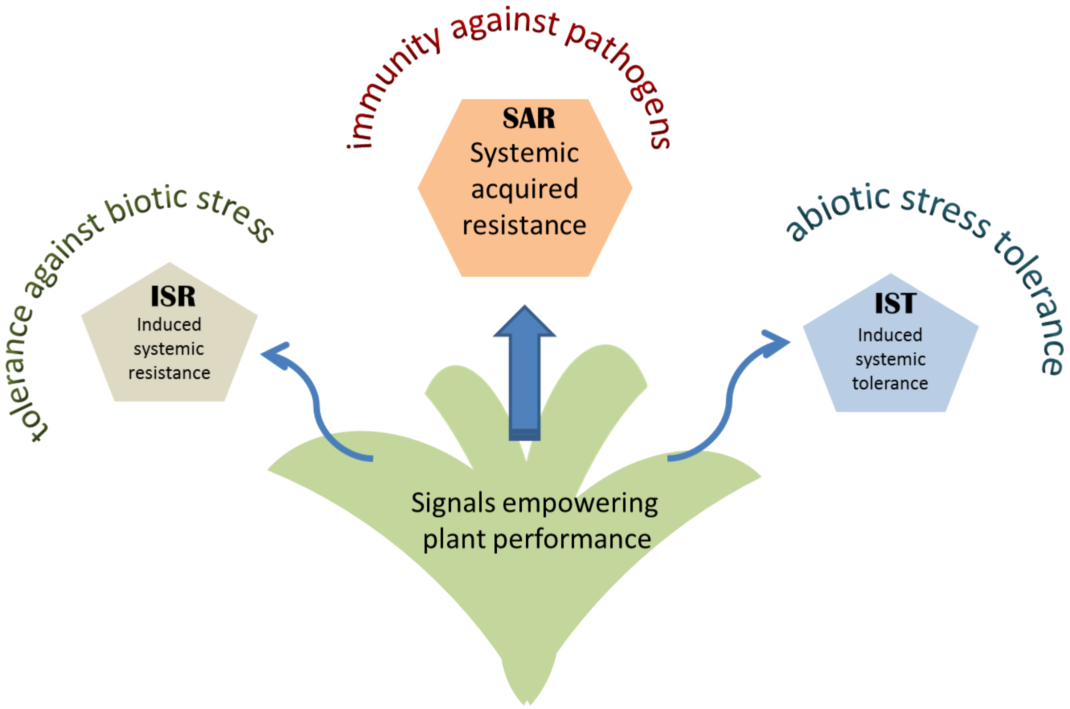

Figure 7: Role of microbes in empowering plant performance.

ISR describes a systemic resistance effect triggered by beneficial root-colonizing rhizobacteria in distal not-challenged plant parts of monocotyledons and dicotyledons (De Vleesschauwer et al., 2009; Pieterse et al., 2014). Besides PGPRs, endophytic fungi, and mycorrhizae have been demonstrated to induce resistance against a broad spectrum of pathogens (Balmer et al., 2012).
SAR represents a systemic induced immune response of plants, contributing to a durable and broad spectrum resistance to a vast majority of harmful microbes, such as bacteria, fungi, or viruses (Vlot et al., 2009). SAR is mainly induced by a local infection of necrotizing pathogens in systemic plant tissue and mobile alarm signals are sent to activate systemic resistance in distal pathogen-free foliage.
IST is the induced resistance due to abiotic stresses like heat, drought, light or the contact to trace metals (Yang et al., 2009). The border between IST and ISR may be fluent since organic molecules and fungal/microbial elicitors also play a role in both resistance types.

Fig. 8

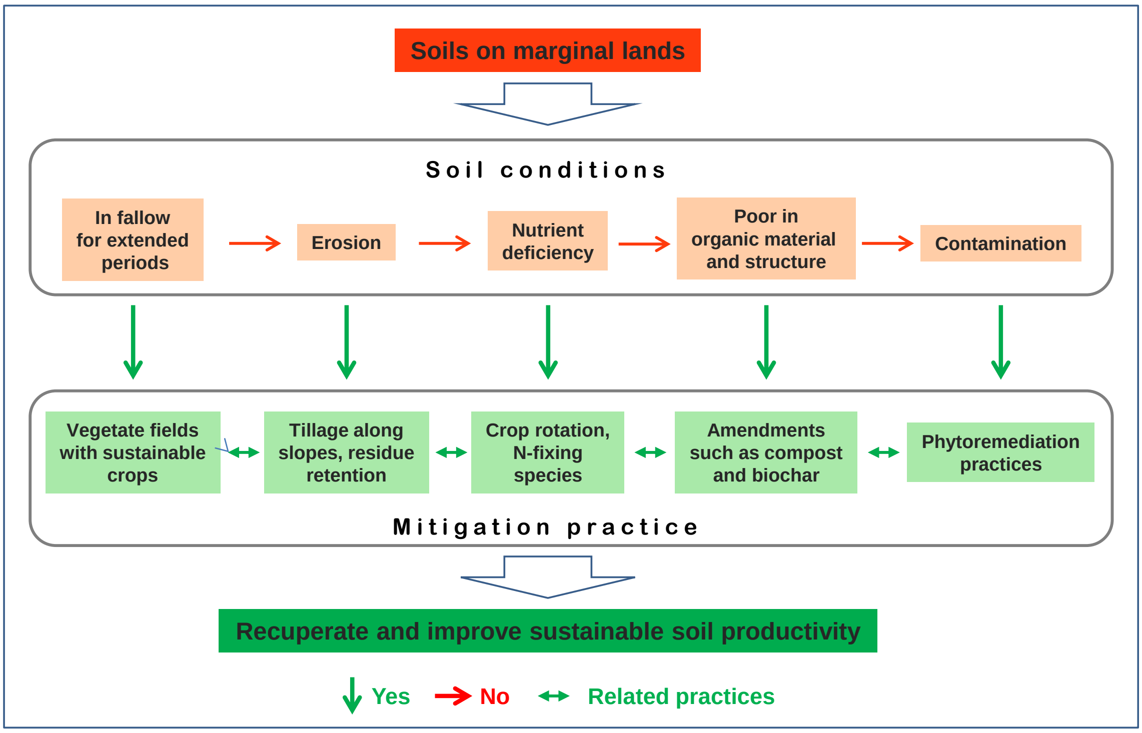

Fig. 8. Decision tree for improving and optimizing the productivity of soils on marginal lands.

Figure 9

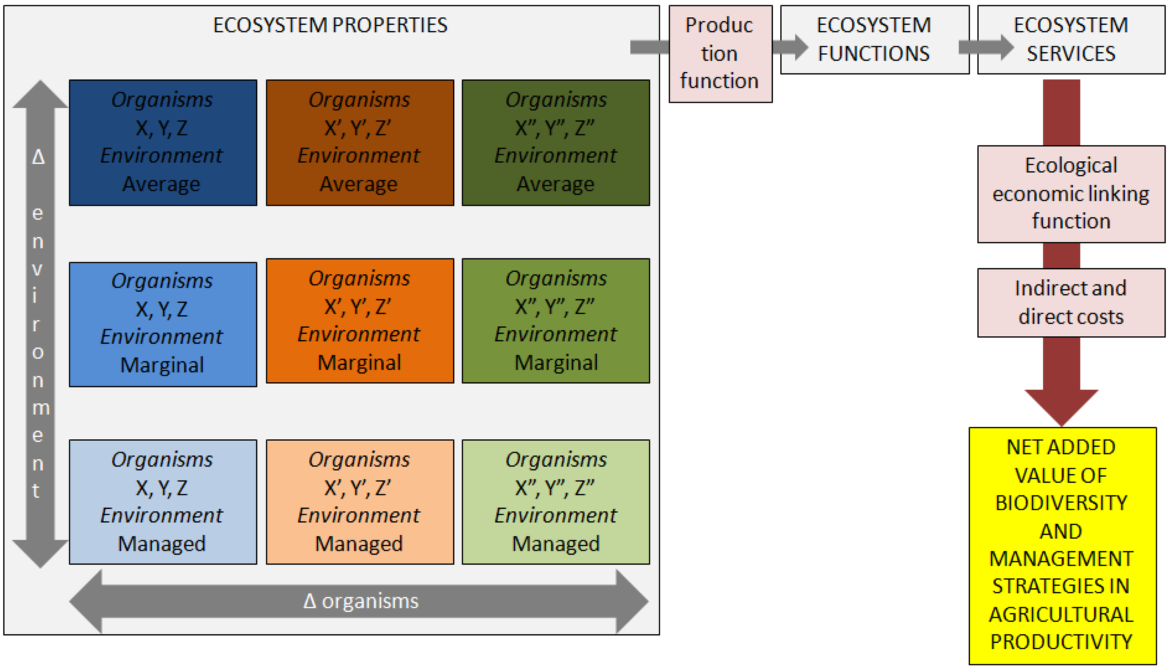

Figure 9: Interaction effects of management options, amendments combined with crops, on soil organisms. These options are expected to have a net positive effect on soil organisms as compared to untreated marginal sites, resulting in different provisioning of ecosystem services