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

P. Schröder, Benoit Beckers, S. Daniels, F. Gnädinger, E. Maestri, N. Marmiroli, Michel Mench, R. Millan, M. M. Obermeier, Nadège Oustrière, et al.

To cite this version:

P. Schröder, Benoit Beckers, S. Daniels, F. Gnädinger, E. Maestri, et al.. Intensify production, transform biomass to energy and novel goods and protect soils in Europe-A vision how to mobilize marginal lands. Science of the Total Environment, 2018, 616-617, pp.1101-1123. 10.1016/j.scitotenv.2017.10.209 . hal-02627782

HAL Id: hal-02627782
https://hal.inrae.fr/hal-02627782

Submitted on 26 May 2020

Science of the Total Environment 616–617 (2018) 1101–1123

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Opinion Paper

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

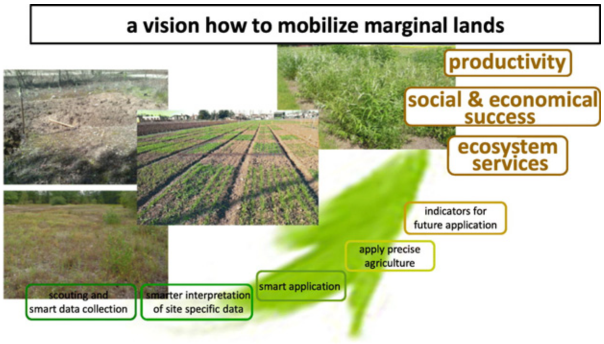
P. Schröder [a],*, B. Beckers [b], S. Daniels [b], F. Gnädinger [a], E. Maestri [c], N. Marmiroli [c], M. Mench [d], R. Millan [e], M.M. Obermeier [a], N. Oustriere [d], T. Persson [f], C. Poschenrieder [g], F. Rineau [b], B. Rutkowska [h], T. Schmid [e], W. Szulc [h], N. Witters [b], A. Sæbø [f]

[a] Helmholtz Zentrum Muenchen, German Research Center for Environmental Health, GmbH, COMI, Ingolstädter Landstrasse 1, D-85764 Neuherberg, Germany.
[b] Hasselt University, Agoralaan Gebouw D, B-3590 Diepenbeek, Belgium
[c] University of Parma, Department of Chemistry, Life Sci. Environm. Sustainability, – Parco Area delle Scienze 11A, I-43124 Parma, Italy
[d] UMR BIOGECO INRA 1202, Bordeaux University, France
[e] CIEMAT - Departamento de Medio Ambiente, Avenida Complutense 40, E-28040 Madrid, Spain
[f] NIBIO - Norwegian Institute of Bioeconomy Research, NO-1431 Ås, Norway
[g] Martl-Hof, Hochwiesweg 6, D-83703 Ostin, Germany
[h] Warsaw University of Life Sciences - SGGW, 02-787 Warsaw, Poland

HIGHLIGHTS

- Challenges for smart intensification of marginal land are manifold
- 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

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 August 2017
Received in revised form 20 October 2017
Accepted 20 October 2017
Available online 11 November 2017

Editor: D. Barcelo

Keywords:
Marginal land
Derelict site
Polluted soil
Precision agriculture
Decision support tool

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. However, since it is estimated that agricultural production systems will have to produce food for a global population that might amount to 9.1 billion by 2050 and over 10 billion by the end of the century, we will require an 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) ameliorated

---

* Corresponding author.
E-mail address: peter.schroeder@helmholtz-muenchen.de (P. Schröder).

https://doi.org/10.1016/j.scitotenv.2017.10.209

Surplus production
Soil amendments

nutritional status in food and feed products, (4) increased sustainability, (5) product traceability and (6) 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 position paper discusses recent developments to indicate how to unlock the potentials of marginal land.

Contents

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 Midwest US is still of topical relevance today and a threatening reminder to protect our valuable production base for nutrition, drinking water supply and important ecosystem services.

All across the world, agriculture is in transition. Until now, conventional farming, influenced by the post-war food requirements, has largely been transformed into integrated and organic, sustainable farming, at least in the EU and advanced countries (Schröder et al., 2008a, 2008b). 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. The share of biofuels has reached 2%, and biomass used for industrial purposes in 2011 was 1.26 million t DM. But the rapidly increasing 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 farms, and new perspectives for the valuable ecosystem services of rural landscapes (De Marsily and Abarca-del-Rio, 2016) and soils (Mol and Keesstra, 2012).

Cascading, upgrading and recycling of bio-based products (SCAR-report, 2015) are visions for a novel circular economy, where the term “waste” has lost its former meaning. However, a sustainable strategy for future agriculture should always be to first use harvests for food and fodder, before utilizing biomass for emerging products (bioplastic, biochemicals, biomaterials, etc.). 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 an energy content of about 269 MTOE (million tons oil equivalent). The current bioeconomy 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). A severe problem that cannot be tackled here is the fact that only 30% of the food produced reaches our stomachs – valuable agricultural goods are lost due to post-harvest problems, discarded due to presumed low quality, or rotten due to lacking distribution channels (SAVE FOOD, 2015). Increased agricultural production will require changes in our general attitude towards food products, smarter use of the available land, and a higher 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 and brownfields with actual or aged pollution. Hence, marginal situations develop as the result of the interaction of a combination of factors (Brouwer et al., 2011). They all have in common that the land has lost its economical and/or ecological viability for the community, a situation that is complicated by the fact that such land is usually further degrading and ceases to contribute ecosystem services.

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, relevant ecosystem services have to be conserved or strengthened. Merging natural with human made solutions will be needed to find a way to make our ecosystems compatible between nature and human use (Keesstra et al., 2018). Hence, challenges for smart intensification exist on many levels, and have to relate to the actual market developments. Farmers, policy makers, as well as all stakeholders including consumers have to contribute to novel solutions.

1.1. Challenges for smart intensification

Having postulated that the best soils should always be used for food production, while less productive fields could serve as production sites for biomass or energy, we have to understand 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 or in the passage from intensive to organic farming, and will threaten yield increases obtained from nutrient enrichment and better use of genetic resources (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 sustainable agriculture with 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; Campbell et al., 2014; 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 management practices at a given site according to soil conditions. Cross-fertilizing with conservation agriculture, such a novel approach will: increase resource use efficiency by producing more with less (ensuring food security), reaching targeted product quality, improve nutritional status in food and feed products, augment sustainability, raise product traceability and minimize negative environmental impacts notably on biodiversity and ecological functions.

Regarding climate change, one of the major challenges for agriculture is to diminish loss of carbon into the atmosphere after changes in soil tillage. Hence, there are numerous attempts to decrease the flux of carbon and nitrogen 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 and biochar), improved rotations, irrigation, bioenergy crops, organic farming, are the most prominent (Smith and Falloon, 2005). The sequestration potential is up to 45 Tg (C) per year.

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, 2002). If this fails, the soil will become marginal, i.e. land will lose its viability with regards to economical or ecological demands of the farmer and the community. 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, 1994).

In this context, a controversial discussion is ongoing whether grassland soils are richer in carbon than soils hosting any other crop types. While some authors find that forage crops store more carbon than any

Fig. 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 (www.bajuwarenhof.de, photo: PS). (B) Right: Historic 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 (source: Geobasisdaten: Bayerische Vermessungsverwaltung). (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 (source: Instituto Geográfico Nacional – IGN, 2016). (D) Below right: Even under constricted topographical conditions (bedrock/sea) in western Norway, recent agricultural settlements consume fertile agricultural areas (photo: AS).

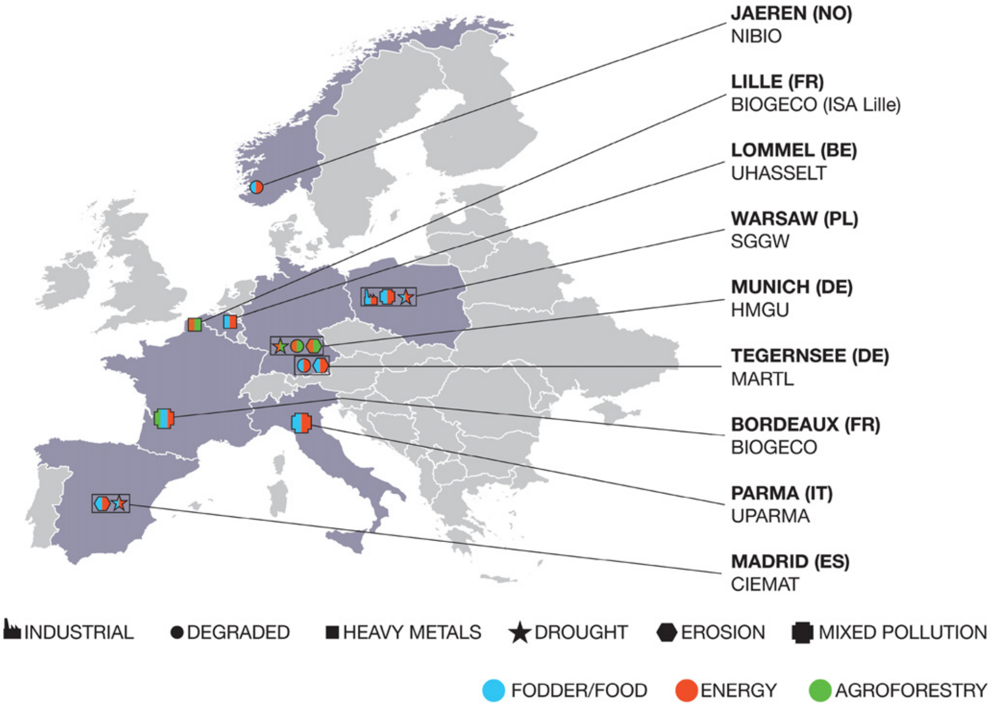


Fig. 2. Location of the study sites in the ERA-NET Cofund Project INTENSE with their main sustainability problems.

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 and Mediterranean Europe, 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 which is non-permanent. Furthermore, improved agricultural management often has a range of other environmental and economic benefits in addition to climate mitigation, and this makes any attempt 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, this position 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 make them unsuitable for agricultural practices and important ecosystem functions (Heimlich, 1989). Across Europe, marginalization caused severe losses of arable land 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. Main causes of soil degradation have been identified to be: overgrazing (35%), agriculture (28%), deforestation (30%), producing fuel wood (7%), and industrialization (4%) (IP/B/AGRI/IC/2009_26, 2009). Similar results were reported by Longobardi et al. (2016). Based on estimates by the European Environment Agency (Bardos et al., 2008), the number of sites where potentially 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 range from €50,000 to €500,000 per site (40% of 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 lose biodiversity (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 grain onto the market (IP/07/1402, 2007). However, in many places the potential yields are not reached although improved practices could probably result in much larger productivity. Hence, marginal lands have recently been recognized for their potential to improve food security and support bioenergy production. Although a promising perspective, environmental issues, concern about losses of ecosystem services, and reduced sustainability have also been discussed in the context of using marginal land (Kang et al., 2013).

Given the large areas of degraded land, 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 is needed to consider marginal, neglected or polluted sites for agricultural production, at least for raw materials and/or bioenergy, if not for feed and food.

2.2. Soil degradation by poor land husbandry

Ancient farmers settled close to their fields and meadows, in 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, roads, industry, settlements, instead of utilizing them for sustainable production. Besides, in industrialized countries where agricultural foods are abundant 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).

Degradation processes that can be aggravated by agricultural activity include water and wind erosion, physical and chemical weathering, and salt accumulation (Lal, 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) (Jobbágy and Jackson, 2000) and most of the biological communities responsible for nutrient cycling and maintaining soil structure. Loss of organic matter, soil biodiversity and consequently soil fertility are often

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 Agraria Sperimentale Stuard	IT1	Continental	Alkaline silty-clay	44°48′28″/10°16′28”	60
Særheim	NO1	Oceanic	Glacial moraine	58°46′N/5° 39′E	90
Skiernivice	PL1	Continental	Stagnic Luvisol	51°95′N/20° 15′E	128

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 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 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

Fig. 3. Spain. 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 °C 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 °C 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/100 g. 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 × 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 2400 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 (Table 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 colour, 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.

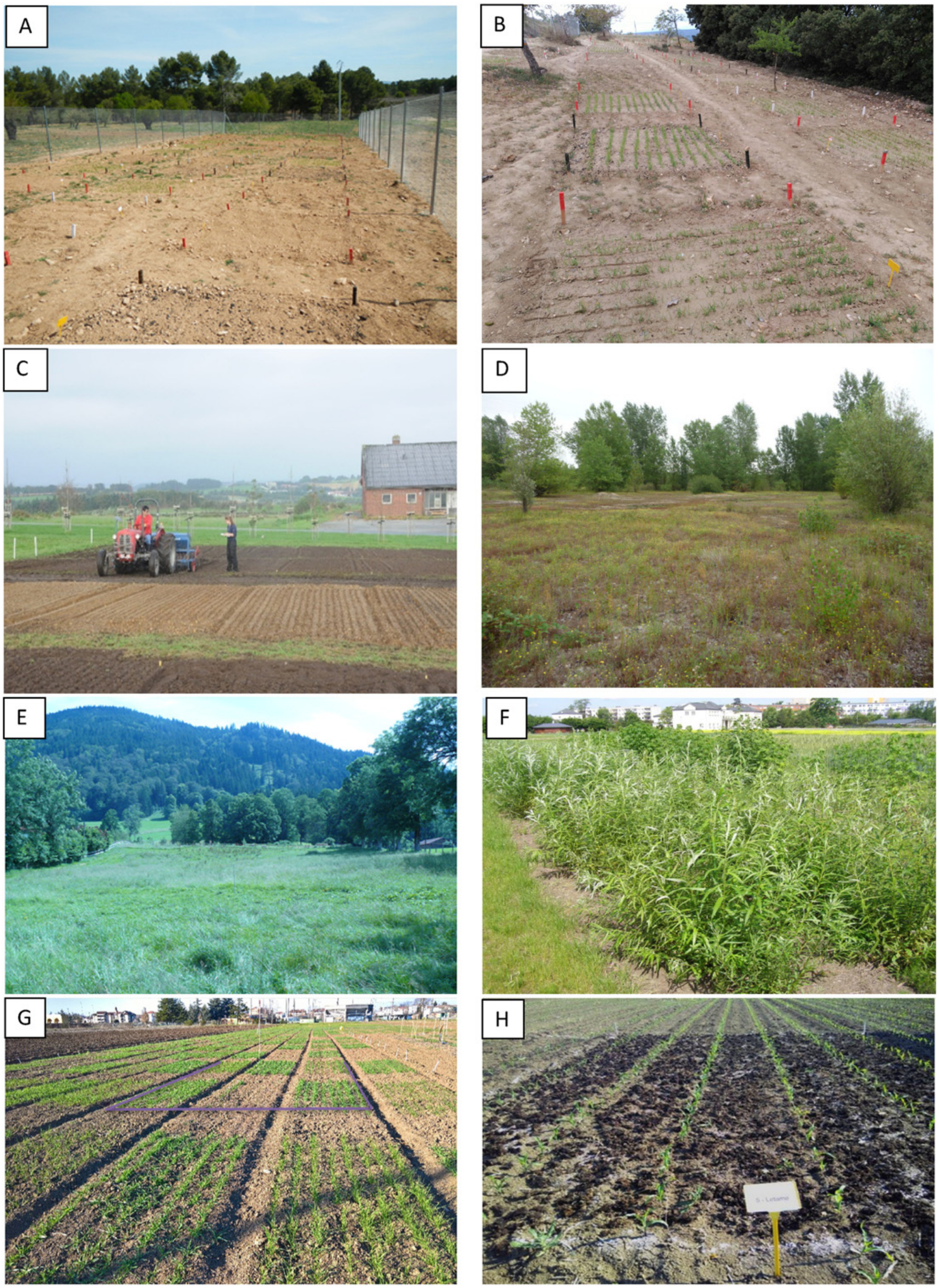
amending organic matter to soils will increase the aggregate formation potential, over-fertilization can lead to an uncoupling of processes that challenge the whole ecosystem and its productivity.

It becomes clear that anthropogenic activities cause soil quality losses over time, which may not revert 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 promote the re-establishment of a functional plant-soil system for the long-term. Methods must aim at the natural rehabilitation potential of soils, integrating existing knowledge on soil resilience functions.

Given the large areas of land 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 in ecologically sound and sustainable ways.

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



(Fig. 2, Table 1). These sites represent problems associated to marginal soils and are characteristic for low productivity, water scarcity, or inappropriate landuse, others are prone to contamination by trace elements or organic pollutants. Their situation is complicated by the fact that mixed and multiple pollution occurs.

4. A toolbox to transform marginal land into productive land

4.1. Detecting the hotspots

Conventional farming of land has 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 within fields. Indeed, when the first yield monitors were operated in the 1990s such differences in sections 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, characterization of soil texture, soil carbon, and plant available water in the soil improved tremendously. 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 the basis for management decisions (Kyratzis et al., 2017). With new generation computers, 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 optimize the use of natural resources such as water and nutrients as well as to 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 use of satellite- or aircraft-borne sensing systems for mapping crop condition and soil quality in arable land. 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 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 conductivity (EM38) are also in use (Heil and 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

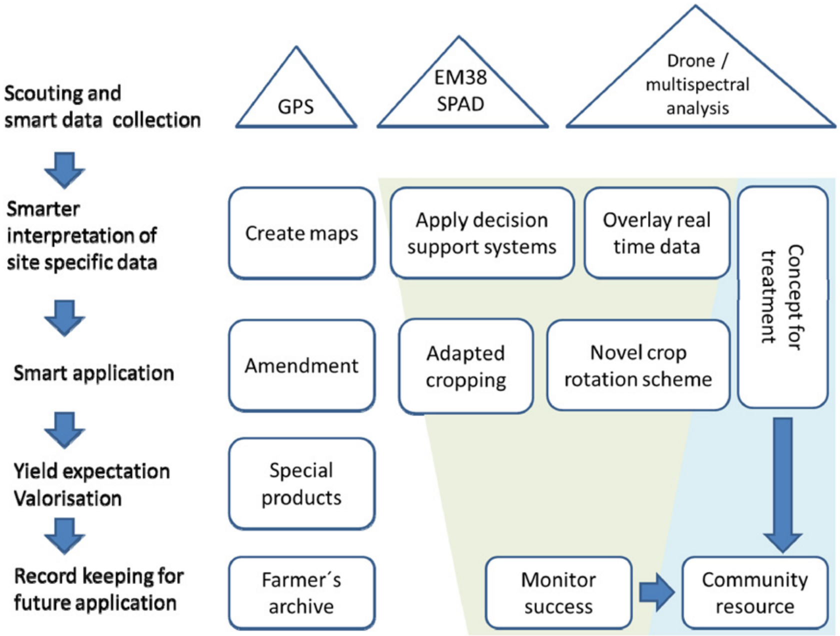


Fig. 4. Using precise tools for management of marginal land. Derived from high-tech precision agriculture solutions, modern sensors allow farmers to obtain a better knowledge about sites, their land, soils and their crops. To date, spatial collection systems are in use for collecting georeferenced data 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; Pádua 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.

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).

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).

Unfortunately, remote sensing is scarcely used for marginal lands (Gibbs and Salmon, 2015), although it would be of significant benefit if applied (Fig. 5). For plants grown on degraded land hyperspectral imageing can be used to determine soil degradation due to erosion (Schmid et al., 2016; Žížala et al., 2017), to identify plant stress due to leachate percolation from landfills (Ferrier et al., 2009), and pesticide contamination (Morari et al., 2013). Statistical methods like data fusion could help to optimize the outputs from tools mentioned above. Future scenarios must allow open and unbiased views on existing technologies, and options for their implementation. It would make a lot of sense to combine practices of integrated farming with ecological, organic and biological approaches, to gain moderate productivity while simultaneously protecting ecosystem services.

4.2. The role of amendments to increase long term productivity

Adding amendments to soils has been farming practice for generations, with the underlying idea that addition of external nutrients or structure building matter would improve soil fertility more or less immediately, or 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 oversimplified concept had been recognized. In itself, the addition of compost is a beneficial act, since it retains water and controls soil temperature, 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 relate to adding organic matter, by that increasing the capacity of the sorption complex, to retain more water in the rhizosphere (Table 2).

4.3. Compost qualities: Reducing pathogens by suppressive composts

The processing of waste organic matter is a common procedure. Almost 50% of the compost produced in Europe is used in agriculture (Sayen and Eder, 2014). With regards to compost qualities, it is important to consider 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 for compost use and quality differ substantially, partly due to differences in soil policies (Table 3).

Sanitary properties are pivotal 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 pathogen populations. The addition of e.g. untreated sewage sludge probably increases the content of pathogens and the risk of crop failure or adverse health effects (Matei et al., 2016). In many EU countries, basic procedures are implemented to achieve hygienization, e.g. by raising the temperature during composting (Supplementary Table 1). In summary, fermentation processes should reach at least 55 °C for 24 h, and fermentation should not last < 12 days.

Besides, the quality of the compost and speed of the composting process is influenced by many factors (Supplement Table 1).

4.4. Municipal slurries

Municipal slurries may differ a lot in quality according to cleaning methodology and to which enterprises and product lines connect to the system. The content of metals should be monitored, even if plant availability may be low (Farrell and Jones, 2009). The treatment of slurry may imply methodology affecting the 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

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.

hygienization of slurry through use of large quantities of lime may increase the pH to very high levels and thus also limit nutrient availability. If enterprises on the slurry net have production that comprises use and leaching of metal(loid)s, then these compounds will follow the stream to the cleaning unit and will be carried to the final slurry. Another worry may be input of organic pollutants from both enterprises, from use and (inappropriate) disposal of pharmaceuticals from private households. Finally, the content of microorganisms should be monitored in municipal slurry. Prior to agricultural use of municipal slurry, the content of metal(loid)s, organic and inorganic pollutants should be checked, and safety guidelines tailored to different soils should be followed, to exclude potentially dangerous waste fractions from application to soils (Antonkiewicz et al., 2017). The responsibility for the slurry quality lies in the enterprises producing it, but the receiver should also have liabilities that the quality is 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 vital 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. At the best, the produced crop biomass will be fed to the animals, by this approaching a closed system. Adequately handled manure 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 reduce the need of mineral nitrogen fertilizers whose industrial production requires large amounts of energy frequently supplied by 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 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 5). Field experiments showed a higher 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 shown that manure affects microbial community composition (Peacock et al., 2001) soil enzyme activity (Liu et al., 2010) and catabolic substrate utilization profile (Sradnick et al., 2013) more than ammonium nitrate or no fertilizer application. However, despite beneficial effects of manure on resource use efficiency and soil productivity, manure application can sometimes impose stress to the environment. In manure and other organic substrates the nutrients are largely bound to compounds that cannot be taken up easily by plants. Thus, their efficient use requires that nutrient availability is synchronized with plant nutrient demand and climatic conditions that favor nutrient uptake in roots. If manure applications are not synchronized, 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, nutrient 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 metal(loid)s (Dach and Starmans, 2005). In addition, manure application to crops with heavy machinery can easily cause soil compaction and entail negative effects on soil physics, biological properties and plant growth (Nawaz et al., 2013).

The production of bioenergy may partly decrease the dilemma of overloads. Anaerobic digestion (AD) of manure and other organic feedstocks 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, also due to EU subsidies (Mao et al., 2015). The rest product from AD, digestate, is suitable as 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, during AD the manure undergoes an increase in pH and 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).

Similar to manure, digestate has a positive influence on soil microbial activity and biomass (Chen et al., 2012; García-Sánchez et al., 2015a), 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 et al. (2015) concluded that digestate could enhance soil microbial activity and biomass as compared to manure. Similar to manure, the high proportion of unavailable organically bound nutrients in digestate require scheduled applications, synchronized with plant nutrient demands. 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 ammonia and nitrogen 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 manure application (Goberna et al., 2011).

Digestate, especially when processed from pig or chicken manure, contains higher amounts of metal(loid)s than manure (Demirel et al., 2013; Zhu et al., 2014), which suggests that its application could be a concern, particularly on those soils which already contain trace elements. However, other studies found smaller amounts of metal(loid)s 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 metal(loid)s in soils where they occur in high concentrations (García-Sánchez et al., 2015b).

There are techniques to separate manure and digestate into nitrogen and potassium rich liquid and a phosphorus rich solid phase to facilitate its recycling and adapt its nutrient content to the specific demands of different crop and nutrient status (Möller and Müller, 2012). The solid phase can be dried further and/or pelleted to decrease transportation costs. The liquid phase can be applied using traditional or sophisticated techniques. 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 plant biomass and other kinds of waste of plant or animal origin: applications of biochar resulting from energy production contributes to close 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 also 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 (Agegnehu et al., 2017). 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 Electric Conductivity (EC): 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 favorable 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.

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 nitrogen fertilizers, also climate gases and waste are emitted (Fischedick et al., 2014), and mineral phosphorus production relies on non-renewable limited sources (Scholz et al., 2013). One method of limiting the adverse effects would be adjusting 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 organic amendments (Fig. 6). Fertilizer use efficiency can be optimized by best management practices applying nutrients at correct rate, time, and place - accompanied by adequate agronomic practices (Johnston and Bruulsemab, 2014).

Selecting the right source – it is pivotal to select the right source of fertilizer for achieving individual goals that will meet specific economic, environmental, and social objectives at a given site.

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, i.e. once every four years. Over- or under-application will result in reduced nutrient use efficiency or losses in yield and 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. It should never be applied when soil temperatures are in the range of 0–6 °C or to any substrate above its 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), and following a mapping approach (see Fig. 4).

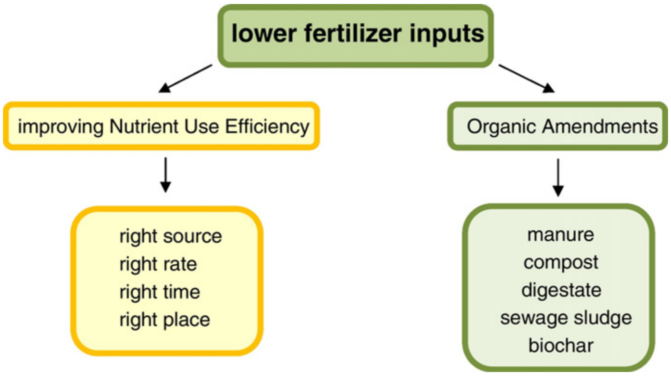


Fig. 6. Methods to reduce the fertilizer input.

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[a]

[a] Digestates from agriculture biogas plants.

Precision agriculture methods like phenotyping with unmanned aerial vehicles (UAV) can help in this respect.

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

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 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, as well as rendzina soils.

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

4.8. A special case: Biological methods for soil remediation

When land is polluted by historical or recent industrial activities or contaminant spills, action has to be taken. Soil contamination due to

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
Technologies for soil remediation. Typically, physical, chemical or biological methods may be applied.

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

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, including removal. 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, 2006). In any case, the aim of remediation is to reduce existing or potential environmental risks, to analyze and assess health and environmental risks to related pollution in the area, and to reduce the risk to a level that guarantees the return of contaminated sites into use as planned (Table 6). Phytoremediation with living plants (or plant-microbe associations) provides a set of options suitable for in situ and ex situ remediation of contaminated soils, sludges, sediments and ground waters through contaminant removal, degradation, sequestration, volatilization or stabilization (Marmiroli and McCutcheon, 2003). It can be used to remove or dissipate various contaminants including trace elements, pesticides, solvents, explosives, petroleum hydrocarbons, polycyclic aromatic hydrocarbons and landfill leachates (Vaněk and Schwitzguébel, 2003; Mench et al., 2003, 2006; 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 received a great deal of attention from regulators, consultants, responsible parties, and stakeholders, and became 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 (Marmiroli and McCutcheon, 2003). The accumulation of contaminants 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, e.g. by supercritical gasification, liquefaction and pyrolysis as potential routes. The first process results in the formation of syngas to produce e.g. heat or electricity, while the other processes lead to biofuel, biochar or 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 trace element recovery from this fraction, or when metal recovery seems not feasible, they are at least concentrated in only a very small mass fraction (needing to be disposed) compared to the initial biomass amount. 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).

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 decreases in soil fertility. After World War II it was replaced by more intensive farming practices with mineral fertilizers, pesticides and new technologies to enhance yield (Tilman et al., 2002). Especially in Northern Europe cereal-based, intensive cropping was used instead of the more balanced cereal-legume-tuber crop rotation 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 resulted in soil fertility decline (FAO, 1993) and increases soil erosion. 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 (Garrison et al., 2014). 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 an elaborate life cycle assessment of crop rotation schemes 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 should contain legumes (mulch or cut) – tuber crops – winter cereal – spring cereal. Undersowing of leguminous species has been proven to be beneficial (Schröder et al., 2008a). 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 amounts 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.

Eco-efficiency could be improved by exchanging cultivars which are dependent on higher fertilization rates with cultivars less dependent to

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	Cooksfoot (mulch or cut) – potatoes - winter wheat – oilseed rape - winter rye	Trost et al., 2014
	Low soil fertility	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.

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 for food and fodder, and even their biofortification (Jablonowski et al., 2017). Therefore crop rotation could enhance yield in low- input cropping systems without increasing environmental burdens, 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

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 cues, e.g. water stress, soil acidity or salinity, nutrient deficiency, frost, soil erosion or compaction, herbivory, pests. In addition, for the gentle remediation options (GRO), they must at the same time tolerate any soil contaminant(s) present (Supplement Fig. 1). 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 trace element (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 (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 within soil microbial communities (Cavani et al., 2016; Foulon et al., 2016; Touceda-González et al., 2017a, b), mesofauna (De Vaufleury et al., 2013), butterflies (Mulder and Breure, 2006) and other 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. One major aim must be 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 rhizodegradation (Taghavi et al., 2005; Barac et al., 2004; Weyens et al., 2009b). 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, Chen et al., 2016). A bioremediation strategy for soils co-contaminated with Cd, DDT, and its metabolites was developed using the Cd-hyperaccumulator *Sedum alfredii* and DDT-degrading microbes (Zhu et al., 2012). 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 production, and safely dispose of rest fractions. In any case, be it organic pollution or excess availability of trace elements, harvested biomass should not be utilized as sources for food or feed.

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

As pointed out above, agricultural management strategies utilizing soil amendments such as compost and biochar mainly seek to improve soil fertility and the underlying ecosystem services by adjusting soil pH and increasing soil nutrient content and retention capacity (Diacono and Montemurro, 2010, Touceda-González et al., 2017a, b). Besides, 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 are stimulated as measured by microbial biomass C, basal respiration measurements and the activity of specific enzymes such as ureases and alkaline phosphatases (Diacono and Montemurro, 2010). In contrast to mineral fertilizers, slow and continuous release of nutrients from degrading compost will support microbial biomass for longer periods of time (Murphy et al., 2007). Similarly, biochars mainly derived from wood and cellulosic materials will stimulate bacteria and mycorrhizal fungi (arbuscular and ectomycorrhizal) by increased nutrient and carbon availability, decreased susceptibility to leaching through adhesion to the biochar, protection against competitors and predators, sorption of toxins and increased resistance against desiccation

(Lehmann et al., 2011). Therefore, both biochar and compost amendments appear a good option to foster the activity of beneficial plant-associated microorganisms.

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

6.1.1. Nutrient cycling and soil nutrient bioavailability

The most prominent impact of microorganisms on soil fertility is their effect on nutrient cycles by fixing or mineralizing nutrients from the gross soil nutrient pool, making them available as biofertilizers (Hayat et al., 2010; Bulgarelli et al., 2013). Well-known mechanisms to promote nutrient 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. Mycorrhizal 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). When acting in concert 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 into plant-accessible HPO_4^{-2} and $H_2PO_4^{-1}$ through microbial production of organic acids (e.g. oxalate) 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 monocots and microorganisms, thus improving iron bioavailability and uptake by roots and microbes (Wandersman and Delepelaire, 2004; Jeong and Guerinot, 2009). So far, broad-scale 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., 2009a, b).

6.1.2. Biosynthesis of phytohormones

Apart from their influence on the mineral cycle, plant-associated microbes can directly trigger plant health and growth through the biosynthesis of various signaling molecules, including homoserine-lactones (Sieper et al., 2013, Götz-Rösch et al., 2015) and phytohormones. Phytohormonal production is frequent in plant-associated bacteria. It ranges from the production of auxins (Spaepen et al., 2007), cytokinins (Arkhipova et al., 2007), gibberellins (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. 7) 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 in triggering the host plant immune system in a process termed induced systemic resistance (ISR) (Ryu et al., 2004). Two well 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 more efficient water and nutrient uptake (Glick et al., 1998; Patten and Glick, 2002; Spaepen et al., 2008). ACC-deaminase activity 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).

6.1.3. 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).

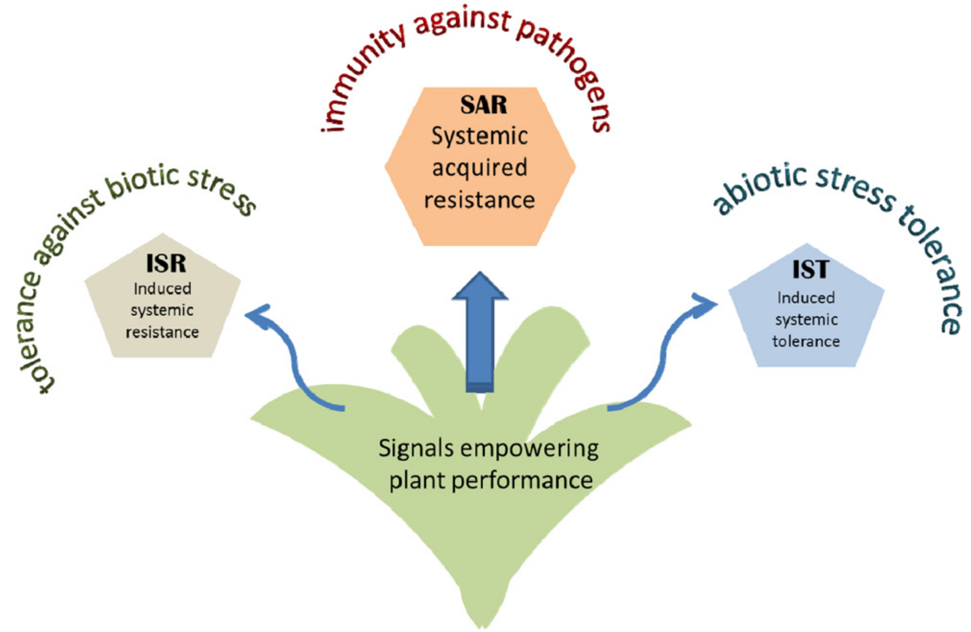


Fig. 7. Role of microbes in empowering plant performance. **ISR** describes a systemic resistance effect triggered by beneficial root-colonizing rhizobacteria in distal not-challenged plant parts of monocotyledons and dicotyledons (De Vleesschauwer et al., 2009; Pieterse et al., 2014). Besides PGPRs, endophytic fungi, and mycorrhizae have been demonstrated to induce resistance against a broad spectrum of pathogens (Balmer et al., 2013). **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.

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). Since 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, they 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).

6.1.4. Drought, osmotic stress and freezing resistance

Microorganisms, and especially mycorrhiza, also play crucial roles in plant resistance to drought and osmotic stress and the tolerance against episodes of freezing and thawing. Established mechanisms include the mycelium, which has a smaller diameter than root hairs and therefore better access to bound water (Lehto and Zwiazek, 2011) and various mechanisms protecting the mycorrhizal fungus (and therefore also the plant root) from osmotic stress, such as accumulation of osmolytes (mannitol, trehalose); surface hydrophobicity and bacterial secretion of exopolysaccharides (Evelin et al., 2009; Dimpka et al., 2009).

6.1.5. Impact on soil structure and organic matter content

Plant-associated microbes can influence soil structure. The best known examples are arbuscular mycorrhizal fungi improving soil aggregation through two mechanisms. The first 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 (arbuscular mycorrhizal fungi) hyphae (Johnson and Gehring, 2007) both mechanisms are 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).

6.1.6. Soil remediation

Finally, plant-associated microorganisms can also play vital roles in the bio-and phytoremediation of contaminated soils and groundwater (Weyens et al., 2009a). 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 metal(loid)s, the use of plant-associated microorganisms could increase availability, uptake and translocation and decrease phytotoxicity (phytoextraction) and/or contribute to the stabilization of the trace elements in excess (phytostabilization) (Lebeau et al., 2008).

6.2. Diversity versus function: What do we have to know about soil microbes

From all the arguments listed above, it becomes clear that soil microbes contribute to a very significant extent to plant growth on marginal soils. On the other hand, soil amendments that favor microbial activity also have the potential to increase plant growth, through increased mineralization, resistance to plant disease (induced systemic resistance), or drought (induced systemic tolerance) and all other aspects associated with beneficial plant-microbe interaction. As a general rule, we may assume that the more microbes are active, the more they will contribute to soil mineralization processes. Microbes are however sensitive to environmental conditions such as water content, pH or temperature. Hence microbially controlled soil processes are likely to be unstable in a versatile environment, and the loss of a species may lead to the loss of a given soil function. This is where microbial diversity is of importance: the higher it is, the more likely that the loss of a given species (because of a disturbance) is compensated by another one similar in functionality. In this case, this is not the taxonomic diversity per se (Estendorfer et al., 2017) that matters, but rather the functional diversity, defined as the range of processes that a microbial community can contribute to (Heemsbergen, 2004). To measure the contribution of microbial communities in soil processes, both, taxonomic and functional diversity need to be taken into account. High taxonomic diversity could therefore 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 and nitrogen fixation) can be a better ecological indicator of soil microbiological quality than the abundance of specific taxa.

7. Indicators and models – Enabling tools 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, objective 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). This 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 can benchmark benefits for the environment or the 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, an assessment is made to determine how well an agricultural ecosystem is meeting the needs and expectations of its present and future users, in order to elaborate methods to sustainably improve soils within marginal and/or degraded lands. 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 external deposition and off-site effects of emissions resulting from agricultural production, e.g. toxicity of pesticides and their residues towards natural aquatic ecosystems (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 soils and farming situations from contrasting regions across Europe, which are described above (see Figs. 2&3), 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 rule out which scenarios are relevant to investigate.

Both, process-driven dynamic models and conceptual models are useful tools to investigate indicator sensitivity of a system to changed conditions. Notably process-based models have previously been used to evaluate the growth, development and yield of annual and perennial crops 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 et al., 2001; Smith, 2012).

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 phytomanagement 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 to account for both the ecological and the socio-economic sides 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,

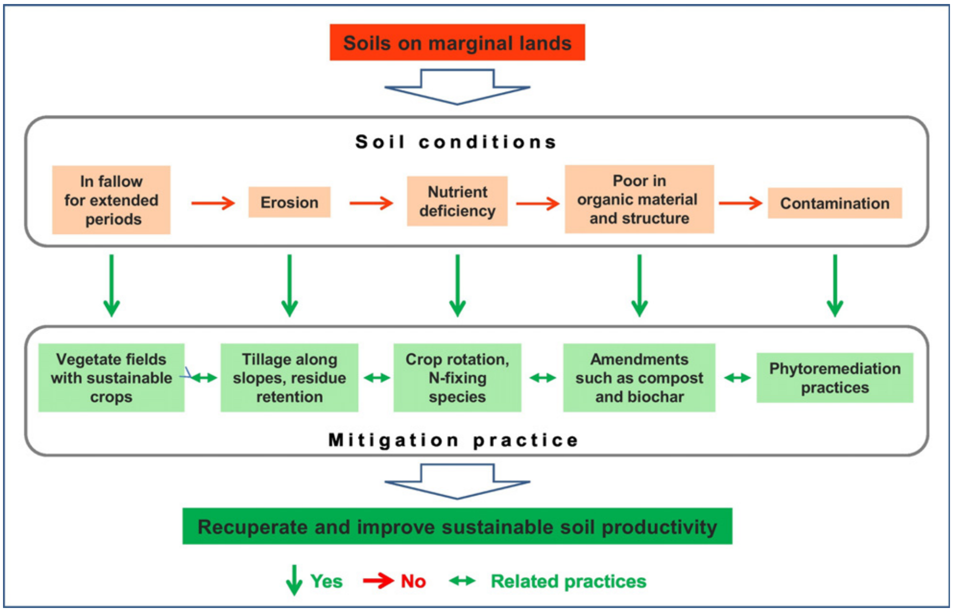


Fig. 8. Decision tree for improving and optimizing the productivity of soils on marginal lands.

functional role-based valuation estimates the indirect 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 related to organisms (e.g. species abundance and composition) 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 to the economic model, a linking function couples 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 is defined as market price corrected for production costs (€ ton^{-1}, € m^{-3})). This framework allows for the assessment of the indirect value of biodiversity, linking production with a 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. Fig. 9 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 biodiversity and its subsequent effects on related ecosystem services: biomass production (food and non-food), soil quality regulation and climate regulation (in Fig. 9, comparison along the X-axis, comparison among colors, 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 Fig. 9 this is shown by comparing within the blue and orange boxes along the Y-axis (dark colors are compared with medium and light colors).

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 Fig. 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. For instance soil 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 changes in services provided by soil biodiversity and can be considered as an indirect value for the measures applied.

In the 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

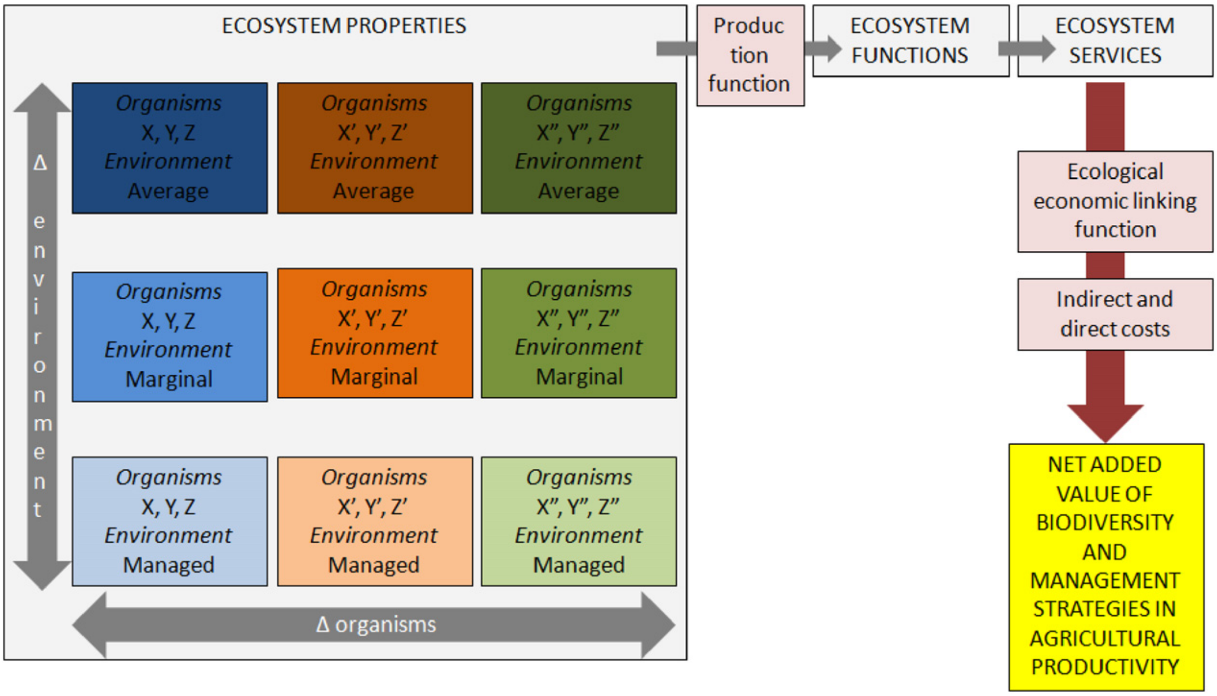


Fig. 9. Interaction effects of management options, amendments combined with crops, on soil organisms. These options are expected to have a net positive effect on soil organisms as compared to untreated marginal sites, resulting in different provisioning of ecosystem services.

impact reduction is included as reduced costs. The effectiveness of 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 for 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 other extrapolation datasets.

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, at least at human time-scale, under increasing environmental pressure across the world, driven and exacerbated by human activity, such as inappropriate agricultural and forestry practices, urban development, tourism or mining and industrial activities. These activities damage the capacity of soils 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 world, 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-1980s, the management of contaminated sites has moved from a cost-centered approach in the mid-1970s, to a risk-based approach of the mid-1990s and in the new millennium, where environmental decisions must also fulfill the requirements of sustainable development. With regard to trace element contaminated soils, a variety of physico-chemical remediation methods has been adopted, including solidification, electrokinetic soil remediation, encapsulation or soil destructive excavation, followed by washing, pyrolysis or disposal of contaminated soil (Vegter, 2001; Virkutyte et al., 2002, 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 (Yao et al., 2012). The implementation of gentle phytoremediation and rehabilitation strategies using 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. For sure, it is a loss of culture and a loss of patrimony if we decide to abandon agriculture in an area.

And regarding 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 if we don't alter the course. Thus, besides scientific progress in understanding soil functioning, it is necessary 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, 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. Decision makers have to recognize that recovery of many other values occurs when smart agriculture is practiced.

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 (Walmsley and Cerdà, 2017). 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 local 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. Eco-agriculture 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.

9. Conclusions

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.

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 to establish economically sound management systems.

Acknowledgements

The authors are partners in the FACCE-SURPLUS project INTENSE and gratefully acknowledge financial support by the FACCE-JPI Programme SFS-05-2015: Strategies for crop productivity, stability and quality, grant number 652515.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.209.

References

Abubaker, J., Cederlund, H., Arthurson, V., Pell, M., 2013. Bacterial community structure and microbial activity in different soils amended with biogas residues and cattle slurry. Appl. Soil Ecol. 72, 171–180.

Agegnehu, G., Srivastava, A.K., Bird, M.I., 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Appl. Soil Ecol. 119, 156–170.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., ... Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33.

Antonkiewicz, J., Kołodziej, B., Bielińska, E.J., 2017. Phytoextraction of heavy metals from municipal sewage sludge by *Rosa multiflora* and *Sida hermaphrodita*. Int. J. Phytorem. 19 (4), 309–318.

Arkhipova, T.N., Prinsen, E., Veselov, S.U., Martinenko, E.V., Melentiev, A.I., Kudoyarova, G.R., 2007. Cytokinin producing bacteria enhance plant growth in drying soil. Plant Soil 292, 305–315.

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., ... Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Chang. 3, 827–832.

Bakker, P.A., Berendsen, R.L., Doornbos, R.F., Wintermans, P.C., Pieterse, C.M., 2013. The rhizosphere revisited: root microbiomics. Front. Plant Sci. 4, 165.

Balmer, D., Planchamp, C., Mauch-Mani, B., 2013. On the move: induced resistance in monocots. J. Exp. Bot. 64 (5), 1249–1261.

Bani, A., Echevarria, G., Sulçe, S., Morel, J.L., 2015. Improving the agronomy of *Alyssum murale* for extensive phytomining: a five-year field study. Int J Phytorem. 17 (2), 117–127.

Barac, T., Taghavi, S., Borremans, B., Provoost, A., Oeyen, L., Colpaert, J.V., et al., 2004. Engineered endophytic bacteria improve phytoremediation of water-soluble, volatile, organic pollutants. Nature. Australas. Biotechnol. 22, 583–588.

Bardos, P., Chapman, T., Andersson-Sköld, Y., Blom, S., Keuning, S., Polland, M., Track, T., 2008. Biomass production on marginal land. Biocycle 49 (12), 50–52.

Beesley, L., Marmiroli, M., 2011. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environ. Pollut. 159 (2), 474–480.

Beesley, L., Marmiroli, M., Pagano, L., Pigoni, V., Fellet, G., Fresno, T., ... Marmiroli, N., 2013. Biochar addition to an arsenic contaminated soil increases arsenic concentrations in the pore water but reduces uptake to tomato plants (*Solanum lycopersicum* L.). Sci. Total Environ. 454, 598–603.

Bell, S., Morse, S., 2008. Sustainability Indicators: Measuring the Immeasurable? Earthscan, New York

Bender, S.F., Wagg, C., van der Heijden, M.G., 2016. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol. 31 (6), 440–452.

Berendsen, R.L., Pieterse, C.M., Bakker, P.A., 2012. The rhizosphere microbiome and plant health. Trends Plant Sci. 17 (8), 478–486.

Berg, G., 2009. Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture. Appl. Microbiol. Biotechnol. 84, 11–18.

Berg, G., Fritze, A., Roskot, N., Smalla, K., 2001. Evaluation of potential biocontrol rhizobacteria from different host plants of *Verticillium dahliae* Kleb. J. Appl. Microbiol. 91, 963–971.

Bernal, M.P., Alburquerque, J.A., Moral, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. Bioresour. Technol. 100, 5444–5453.

Boerema, A., Rebelo, A.J., Bodi, M.B., Esler, K.J., Meire, P., 2016. Are ecosystem services adequately quantified? J. Appl. Ecol. 54 (2), 358–370.

Bottini, R., Cassán, F., Piccoli, P., 2004. Gibberellin production by bacteria and its involvement in plant growth promotion and yield increase. Appl. Microbial Biotech 65.

Branca, G., McCarthy, N., Lipper, L., Jolejole, M.C., 2011. Climate-smart agriculture: a synthesis of empirical evidence of food security and mitigation benefits from improved cropland management. Mitigation of Climate Change in Agriculture Series. 3, pp. 1–42.

Bräuer, I., 2003. Money as an indicator: to make use of economic evaluation for biodiversity conservation. Agric. Ecosyst. Environ. 98, 483–491.

Brouwer, F., Baldock, D., Godeschalk, F., Beaufoy, G., 2011. Marginalisation of Agricultural Land in Europe. LSIRD NAPLIO Conference Papers. The James Hutton Institute http://www.macaulay.ac.uk/livestocksystems/nafplio/proceedings/brouwer.htm#Brouwer (accessed Oct. 18, 2017).

Bulgarelli, D., Schlaeppi, K., Spaepen, S., Ver Loren van Themaat, E., Schulze-Lefert, P., 2013. Structure and functions of the bacterial microbiota of plants. Annu. Rev. Plant Biol. 64, 807–838.

Cabell, J.F., Oelofse, M., 2012. An indicator framework for assessing agroecosystem resilience. Ecol. Soc. 17, 18.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil/plant system: a review. Ann. Appl. Biol. 162, 145–173.

Campbell, E.E., Johnson, J.M.F., Jin, V.L., Lehman, R.M., Osborne, S.L., Varvel, G.E., Paustian, K., 2014. Assessing the soil carbon, biomass production, and nitrous oxide emission impact of corn stover management for bioenergy feedstock production using DAYCENT. BioEnergy Re. 7, 491–502.

Castell, A., Salzeder, G., Schmidt, M., Urbatzka, P., 2015. Einfluss der Fruchtfolge auf Ertrag und Qualität von Winterweizen in viehhaltenden und viehlosen Betriebssystemen-Ergebnisse eines Dauerfeldversuches. 13. Wissenschaftstagung Ökologischer Landbau, Hochschule für Nachhaltige Entwicklung Eberswalde, 17. - 20. März 2015.

Cavalli, D., Cabassi, G., Borrelli, L., Geromel, G., Bechini, L., Degano, L., Marino Gallina, P., 2016. Nitrogen fertilizer replacement value of undigested liquid cattle manure and digestates. Eur. J. Agron. 73, 34–41.

Cavani, L., Manici, L.M., Caputo, F., Peruzzi, E., Ciavatta, C., 2016. Ecological restoration of a copper polluted vineyard: long-term impact of farmland abandonment on soil biochemical properties and microbial communities. J. Environ. Manag. 182, 37–47.

Cesaro, A., Belgiorno, V., Guida, M., 2015. Compost from organic solid waste: quality assessment and European regulations for its sustainable use. Resour. Conserv. Recycl. 94, 72–79.

Chalot, M., Brun, A., 1998. Physiology of organic nitrogen axquisition by ectomycorrhizal fungi and ectomycorrhizas. FEMS Microbiol. Rev. 22, 21–44.

Che-Castaldo, J.P., Inouye, D.W., 2015. Interspecific competition between a non-native metal-hyperaccumulating plant (*Noccaea caerulescens, Brassicaceae*) and a native congener across a soil-metal gradient. Aust. J. Bot. 63, 141–151.

Chen, R., Blagodatskaya, E., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Kuzyakov, Y., 2012. Decomposition of biogas residues in soil and their effects on microbial growth kinetics and enzyme activities. Biomass Bioenergy 45, 221–229.

Chen, F., Huber, C., Schröder, P., 2016. Fate of the sunscreen oxybenzone in *Cyperus alternifolius* based hydroponic culture: uptake, biotransformation and phytotoxicity. Chemosphere 182, 638–646.

Christie, M., Hanley, N., Warren, J., Murphy, K., Wright, R., Hyde, T., 2006. Valuing the diversity of biodiversity. Ecol. Econ. 58, 304–317.

Chu, H., Lin, X., Fujii, T., Morimoto, S., Yagi, K., Hu, J., Zhang, J., 2007. Soil microbial biomass, dehydrogenase activity, bacterial community structure in response to long-term fertilizer management. Soil Biol. Biochem. 39, 2971–2976.

Compant, S., Duffy, B., Nowak, J., Clément, C., Barka, E.A., 2005. Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. Appl. Environ. Microbiol. 71, 4951–4959.

Contesto, C., Desbrosses, G., Lefoulon, C., Béna, G., Borel, F., Galland, M., et al., 2008. Effects of rhizobacterial ACC deaminase activity on Arabidopsis indicate that ethylene mediates local root responses to plant growth-promoting rhizobacteria. Plant Sci. 175, 178–189.

Cui, H., Hense, B.A., Müller, J., Schröder, P., 2015. Short term uptake and transport process for metformin in roots of *Phragmites australis* and *Typha latifolia*. Chemosphere 134, 307–312.

Dach, J., Starmans, D., 2005. Heavy metals balance in polish and Dutch agronomy: actual state and previsions for the future. Agric. Ecosyst. Environ. 107, 309–316.

Daniels, S., Witters, N., Beliën, T., Vrancken, K., Vangronsveld, J., Van Passel, S., 2017. Monetary valuation of natural predators for biological pest control in pear production. Ecol. Econ. 134, 160–173.

De Marsily, G., Abarca-del-Rio, R., 2016. Water and food in the twenty-first century. Surv. Geophys. 37 (2), 503–527.

De Vaufleury, A., Gimbert, F., Gomot, L., 2013. Bioaccumulation, bioamplification des polluants dans la faune terrestre-Un outil pour la biosurveillancedes écosystèmes: Un outil pour la biosurveillance des écosystèmes. EDP sciences, ADEME.

De Vleesschauwer, D., Chernin, L., Höfte, M.M., 2009. Differential effectiveness of *Serratia plymuthica* IC1270-induced systemic resistance against hemibiotrophic and necrotrophic leaf pathogens in rice. BMC Plant Biol. 9:9. https://doi.org/10.1186/1471-2229-9-9.

Demirel, B., Göl, N.P., Onay, T.T., 2013. Evaluation of heavy metal content in digestate from batch anaerobic co-digestion of sunflower hulls and poultry manure. J. Mater. Cycles Waste Manage. 15, 242–246.

Deng, L., Li, Z., Wang, J., Liu, H., Li, N., Wu, L., ... Christie, P., 2016. Long-term field phytoextraction of zinc/cadmium contaminated soil by sedum plumbizincicola under different agronomic strategies. Int. J. Phytoremediation 18 (2), 134–140.

Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. Agron. Sustain. Dev. 30, 401–422.

Dimpka, C., Weinand, T., Asch, F., 2009. Plant-rhizobacteria interactions alleviate abiotic stress conditions. Plant Cell Environ. 32, 1682–1694.

Dixon, R., Kahn, D., 2004. Genetic regulation of biological nitrogen fixation. Nat. Rev. Microbiol. 2, 621–631.

EEA, 1999. Environment in the European Union at the Turn of the Century. 1999. European Environment Agency. http://reports.eea.europa.eu/92-9157-202-0/en.

EEA, 2012. Annual Report 2011 and Environmental Statement 2012. European Environment Agency, Copenhagen (Denmark).

Ellmer, F., 2008. Soil Organic Matter of a Sandy Soil Influenced by Agronomy and Climate.

Estendorfer, J., Stempfhuber, B., Haury, P., Vestergaard, G., Rillig, M.C., Joshi, J., Schröder, P., Schloter, M., 2017. The influence of land use intensity on the plant-associated microbiome of *Dactylis glomerata* L. Front. Plant Sci. (21 June 2017).

European Parliamentary Research Service, 2016. Precision agriculture and the future of farming in Europe. Scientific Foresight Study PE581.892. https://doi.org/10.2861/020809.

Evelin, H., Kapoor, R., Giri, B., 2009. Arbuscular mycorrhizal fungi in alleviation of salt stress: a review. Ann. Bot. 104, 1263–1280.

FAO, 1993. The State of Food and Agriculture. Rome (Italy): FAO Agricultural Series (26). ISBN 92-5-103360-9.

FAO, 1994. Food and Agriculture Organization of the United Nations. World Soil Resources Reports, Rome (Italy) ISBN (92-5-103595-4).

Farnsworth, K.D., Adenuga, A.H., de Groot, R.S., 2015. The complexity of biodiversity: a biological perspective on economic valuation. Ecol. Econ. 120, 350–354.

Farrell, M., Jones, D.L., 2009. Heavy metal contamination of a mixed waste compost: metal speciation and fate. Bio/Technology 100 (2009), 4423–4432.

Feest, A., Aldred, T.D., Jedamzik, K., 2010. Biodiversity quality: a paradigm for biodiversity. Ecol. Indic. 10, 1077–1082.

Ferrier, G., Frostick, L.E., Splajt, T., 2009. Application of geophysical monitoring techniques as aids to probabilistic risk-based management of landfill sites. Geogr. J. 175 (4), 304–314.

Finger, R., Buchmann, N., 2015. An ecological economic assessment of risk-reducing effects of species diversity in managed grasslands. Ecol. Econ. 110, 89–97.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., ... Tanaka, K., 2014. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Minx, J.C. (Eds.), Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Foulon, J., Zappelini, C., Durand, A., Valot, B., Blaudez, D., Chalot, M., 2016. Impact of poplar-based phytomanagement on soil properties and microbial communities in a metal-contaminated site. FEMS Microb. Ecol. 92 (10).

Gamfeldt, L., Hillebrand, H., Jonsson, P.R., 2008. Multiple functions increase the importance of biodiversity for overall ecosystem functioning. Ecology 89, 1223–1231.

Garcia-Sánchez, M., Garcia-Romera, I., Cajthaml, T., Tlustoš, P., Száková, J., 2015a. Changes in soil microbial community functionality and structure in a metal-polluted site: the effect of digestate and fly ash applications. J. Environ. Manag. 162, 63–73.

García-Sánchez, M., Siles, J.A., Cajthaml, T., García-Romera, I., Tlustoš, P., Száková, J., 2015b. Effect of digestate and fly ash applications on soil functional properties and microbial communities. Eur. J. Soil Biol. 71, 1–12.

Gardi, C., Visioli, G., Conti, F.D., Scotti, M., Menta, C., Bodini, A., 2016. High nature value farmland: assessment of soil organic carbon in Europe. Front. Environ. Sci. (4), 47.

Garrison, A.J., Miller, A.D., Ryan, M.R., Roxburgh, S.H., Shea, K., 2014. Stacked crop rotations exploit weed-weed competition for sustainable weed management. Weed Sci. 62, 166–176.

German Advisory Council Global Change, 1994. World in Transition: The Threat to Soils. Flagship Report 1994. Verlag (Bonn), Economica (ISBN 3-87081-055-6).

Gibbs, H.K., Salmon, J.M., 2015. Mapping the world's degraded lands. Appl. Geogr. 57, 12–21.

Glick, B., Penrose, D., Li, J., 1998. A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. J. Theor. Biol. 190, 63–68.

Glick, B.R., Todorovic, B., Czarny, J., Cheng, Z., Duan, J., McConkey, B., 2007. Promotion of plant growth by bacterial ACC deaminase. CRC Crit. Rev. Plant Sci. 26, 227–242.

Goberna, M., Podmirseg, S.M., Waldhuber, S., Knapp, B.A., García, C., Insam, H., 2011. Pathogenic bacteria and mineral N in soils following the land spreading of biogas digestates and fresh manure. Appl. Soil Ecol. 49, 18–25.

Götz-Rösch, C., Sieper, T., Fekete, A., Schmitt-Kopplin, P., Hartmann, A., Schröder, P., 2015. Influence of bacterial N-acyl-homoserine lactones on growth parameters, pigments, antioxidative capacities and the xenobiotic phase II detoxification enzymes in barley and yam bean. Front. Plant Sci. https://doi.org/10.3389/fpls.2015.00205.

Govasmark, E., Stäb, J., Holen, B., Hoornstra, D., Nesbakk, T., Salkinoja-Salonen, M., 2011. Chemical and microbiological hazards associated with recycling of anaerobic digested residue intended for agricultural use. Waste Manag. 31, 2577–2583.

Havlin, J.L., Tisdale, S.L., Nelson, W.L., 2013. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. Upper Saddle River, NJ: Pearson Prentice Hall. 8 pp. 97–141.

Hayat, R., Ali, S., Amara, U., Khalid, R., Ahmed, I., 2010. Soil beneficial bacteria and their role in plant growth promotion: a review. Ann. Microbiol. 60, 579–598.

Haynes, R., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosyst. 51, 123–137.

He, L.Y., Ying, G.G., Liu, Y.S., Su, H.C., Chen, J., Liu, S.S., Zhao, J.L., 2016. Discharge of swine wastes risks water quality and food safety: antibiotics and antibiotic resistance genes from swine sources to the receiving environments. Environ. Int. 92, 210–219.

Heemsbergen, D.A., 2004. Biodiversity effects on soil processes explained by interspecific functional dissimilarity. Science 306 (80), 1019–1020.

Heil, K., Schmidhalter, U., 2017. Improved evaluation of field experiments by accounting for inherent soil variability. Eur. J. Agron. 89, 1–15.

Heimlich, R.E., 1989. Metropolitan agriculture: farming in the city's shadow. J. Amer. Plan. Assoc. 55 (4), 457–466.

Heuer, H., Schmitt, H., Smalla, K., 2011. Antibiotic resistance gene spread due to manure application on agricultural fields. Curr. Opin. Microbiol. 14, 236–243.

Insam, H., Gómez-Brandón, M., Ascher, J., 2015. Manure-based biogas fermentation residues – friend or foe of soil fertility? Soil Biol. Biochem. 84, 1–14.

Instituto Geográfico Nacional – IGN, 2016. Orthoimagene from the 13 June 2016 [Online]. (Available: http://centrodedescargas.cnig.es/CentroDescargas/index.jsp - Accessed 18August 2017).

IP/07/1402, 2007. Cereals: Council approves zero set-aside rate for autumn 2007 and spring 2008 sowings. Press Release of the European Commission (Brussels).

IP/B/AGRI/IC/2009_26, 2009. The challenge of deterioration of agricultural land in the EU and in particular in Southern Europe – The response through EU agricultural policy instruments. Press Release of the European Commission (Brussels).

Ippolito, J.A., Spokas, K.A., Novak, J.M., Lentz, R.D., Cantrell, K.B., 2015. Biochar elemental composition and factors influencing nutrient retention. Biochar for Environmental Management: Sci. Tech. Implem, pp. 139–163.

Jablonowski, N.D., Kollmann, T., Nabel, M., Damm, T., Klose, H., Müller, M., ... Dahmen, M., 2017. Valorization of Sida (*Sida hermaphrodita*) biomass for multiple energy purposes. GCB Bioenergy 9 (1), 202–214.

Janssen, J., Weyens, N., Croes, S., Beckers, B., Meiresonne, L., Van Peteghem, P., ... Vangronsveld, J., 2015. Phytoremediation of metal contaminated soil using willow: exploiting plant-associated bacteria to improve biomass production and metal uptake. Int. J. Phytorem. 17 (11), 1123–1136.

Jeffery, S., Verheijen, F.G., Van Der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144 (1), 175–187.

Jeong, J., Guerinot, M.L., 2009. Homing in on iron homeostasis in plants. Trends Plant Sci. 14, 280–285.

Jin, J., Kang, M., Sun, K., Pan, Z., Wu, F., Xing, B., 2016. Properties of biochar-amended soils and their sorption of imidacloprid, isoproturon, and atrazine. Sci. Total Environ. 550, 504–513.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436.

Johnson, N.C., Gehring, C.A., 2007. Mycorrhizas: Symbiotic mediators of rhizosphere and ecosystem processes. Pages 73–100. In: Cardon, Z., Whitbeck, J. (Eds.), The Rhizosphere: An Ecological Perspective. Academic Press, New York.

Johnston, A.M., Bruulsemab, T.W., 2014. 4R nutrient stewardship for improved nutrient use efficiency. Protein Eng. 83, 365–370.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Kai, M., Haustein, M., Molina, F., Petri, A., Scholz, B., Piechulla, B., 2009. Bacterial volatiles and their action potential. Appl. Microbiol. Biotechnol. 81, 1001–1012.

Kang, S., Post, W.M., Nichols, J.A., Wang, D., West, T.O., Bandaru, V., Izaurralde, R.C., 2013. Characteristic conditions of marginal soils are representative marginal lands: concept, assessment and management. J. Agric. Sci. 5 (5), 129–139.

Karadeniz, A., Topcuoğlu, Ş.F., İnan, S., 2006. Auxin, gibberellin, cytokinin and abscisic acid production in some bacteria. World J. Microbiol. Biotechnol. 22, 1061–1064.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., ... Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Keenleyside, C., Tucker, G., McConville, A., 2010. Farmland Abandonment in the EU: an Assessment of Trends and Prospects. Institute for European Environmental Policy, London.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009.

Kidd, P., Mench, M., Álvarez-López, V., Bert, V., Dimitriou, I., Friesl-Hanl, W., Neu, S., 2015. Agronomic practices for improving gentle remediation of trace element-contaminated soils. Int. J. Phytoremediation 17 (11), 1005–1037.

Kiely, P.D., Haynes, J.M., Higgins, C.H., Franks, A., Mark, G.L., Morrissey, J.P., et al., 2006. Exploiting new systems-based strategies to elucidate plant-bacterial interactions in the rhizosphere. Microb. Ecol. 51, 257–266.

Krechel, A., Faupel, A., Hallmann, J., Ulrich, A., Berg, G., 2002. Potato-associated bacteria and their antagonistic potential towards plant-pathogenic fungi and the plant-parasitic nematode *Meloidogyne incognita* (Kofoid & White) Chitwood. Can. J. Microbiol. 48, 772–786.

Krogstad, T., Sogn, T.A., Asdal, Å., Sæbø, A., 2005. Influence of chemically and biologically stabilized sewage sludge on plant-available phosphorous in soil. Ecol. Eng. 25 (1), 51–60.

Kulak, M., Nemecek, T., Frossard, E., Gaillard, G., 2013. How eco-efficient are low-input cropping systems in Western Europe, and what can be done to improve their eco-efficiency? Sustain. For. 5 (9), 3722–3743.

Kyratzis, A.C., Skarlatos, D.P., Menexes, G.C., Vamvakousis, V.F., Katsiotis, A., 2017. Assessment of vegetation indices derived by UAV imagery for durum wheat phenotyping under a water limited and heat stressed mediterranean environment. Front. Plant Sci. 8, 1114.

Laghari, M., Hu, Z., Mirjat, M.S., Xiao, B., Tagar, A.A., Hu, M., 2016. Fast pyrolysis biochar from sawdust improves the quality of desert soils and enhances plant growth. J. Sci. Food Agric. 96 (1), 199–206.

Lal, R., 1989. Agroforestry systems and soil surface management of a tropical alfisol. Agrofor. Syst. 8 (2), 97–111.

Lasanta, T., Arnáez, J., Oserín, M., Ortigosa, L.M., 2001. Marginal lands and erosion in terraced fields in the mediterranean mountains. A case study in the Camero Viejo (Northwestern Iberian System, Spain). Mountain Res. Develop 21 (1), 69–76 (2001).

Lebeau, T., Braud, A., Jézéquel, K., 2008. Performance of bioaugmentation-assisted phytoextraction applied to metal contaminated soils: a review. Environ. Pollut. 153, 497–522.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – a review. Soil Biol. Biochem. 43, 1812–1836.

Lehto, T., Zwiazek, J.J., 2011. Ectomycorrhizas and water relations of trees: a review. Mycorrhiza 21, 71–90.

Lehtomäki, A., Björnsson, L., 2006. Two-stage anaerobic digestion of energy crops: methane production, nitrogen mineralisation and heavy metal mobilisation. Environ. Technol. 27, 209–218.

Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158 (3), 173–180.

Longobardi, P., Montenegro, A., Beltrami, H., Eby, M., 2016. Deforestation induced climate change: effects of spatial scale. PLoS One 11 (4), e0153357.

Lubkowski, K., 2016. Environmental impact of fertilizer use and slow release of mineral nutrients as a response to this challenge. Polish J. Chem. Tech. 18 (1), 72–79.

Mao, C., Feng, Y., Wang, X., Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renew. Sust. Energ. Rev. 45, 540–555.

Marmiroli, N., McCutcheon, S.C., 2003. Making phytoremediation a successful technology. In: McCutcheon, S.C., Schnoor, J.L. (Eds.), Phytoremediation: Transformation and Control of Contaminants. Wiley-Interscience, Inc., Hoboken, pp. 75–107 (ISBN 0-471-39435-1).

Marmiroli, M., Pietrini, F., Maestri, E., Zacchini, M., Marmiroli, N., Massacci, A., 2011. Growth, physiological and molecular traits in Salicaceae trees investigated for phytoremediation of heavy metals and organics. Tree Physiol. 31 (12), 1319–1334.

Martínez-Blanco, J., Lazcano, C., Christensen, T.H., Muñoz, P., Rieradevall, J., Møller, J., ... Boldrin, A., 2013. Compost benefits for agriculture evaluated by life cycle assessment. A review. Agron. Sustain. Dev. 33 (4), 721–732.

Matei, P.M., Sánchez-Báscones, M., Bravo-Sánchez, C.T., Martín-Ramos, P., Martín-Villullas, M.T., García-González, M.C., ... Martín-Gil, J., 2016. Hygienization and control of *Diplodia seriata* fungus in vine pruning waste composting and its seasonal variability in open and closed systems. Waste Manag. 58, 126–134.

McLaughlin, D., Kinzelbach, W., 2015. Food security and sustainable resource management. Water Resour. Res. 51 (7), 4966–4985.

Medina, J., Monreal, C., Barea, J.M., Arriagada, C., Borie, F., Cornejo, P., 2015. Crop residue stabilization and application to agricultural and degraded soils: a review. Waste Manag. 42, 41–54.

Mench, M., Bes, C., 2009. Assessment of ecotoxicity of topsoils from a wood treatment site. Project supported by the French Agency for Environment and Energy (ADEME), Department of Polluted Soils and Sites, Angers, France (No. ADEME 05 72 C0018/INRA 22000033). Pedosphere 19.2 (2009). pp. 143–155.

Mench, M., Bussière, S., Boisson, J., Castaing, E., Vangronsveld, J., Ruttens, A., De Koe, T., Bleeker, P., Assunção, A., Manceau, A., 2003. Progress in remediation and revegetation of the barren Jales gold mine spoil after in situ treatments. Plant Soil 249, 187–202.

Mench, M., Vangronsveld, J., Beckx, C., Ruttens, A., 2006. Progress in assisted natural remediation of an arsenic contaminated agricultural soil. Environ. Pollut. 144, 51–61.

Mench, M., Schwitzguébel, J.P., Schröder, P., Bert, V., Gawronski, S., Gupta, S., 2009. Assessment of successful experiments and limitations of phytotechnologies: contaminant uptake, detoxifycation and sequestration, and consequences for food safety. Environ. Sci. Pollut. Res. 16, 876–900.

Mench, M., Lepp, N., Bert, V., Schwitzguébel, J.P., Gawronski, S.W., Schröder, P., Vangronsveld, J., 2010. Successes and limitations of phytotechnologies at field scale: outcomes, assessment and outlook from COST action 859. J. Soils Sediments 10, 1039–1070.

Mesa, V., Navazas, A., González-Gil, R., González, A., Weyens, N., Lauga, B., ... Peláez, A.I., 2017. Use of endophytic and rhizosphere bacteria to improve phytoremediation of arsenic-contaminated industrial soils by autochthonous *Betula celtiberica*. Appl. Environ. Microbiol. 83 (8), e03411–16.

Mol, G., Keesstra, S.D., 2012. Soil science in a changing world. Curr. Opin. Environ. Sustain. 4, 473–477.

Moldan, B., Hak, T., Kovanda, J., Havranek, M., Kuskova, P., 2004. Composite indicators of environmental sustainability. OECD World Forum on Key Indicators, Palermo, 10–13 November 2004, proceedings. (see http://www.oecd.org/dataoecd/43/48/33829383.doc).

Möller, K., 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. Agron. Sustain. Dev. 35 (3), 1021–1041.

Möller, K., Müller, T., 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. Eng. Life Sci. 12, 242–257.

Morari, F., Loddo, S., Berzaghi, P., Ferlito, J.C., Berti, A., Sartori, L., ... Mosca, G., 2013. Understanding the effects of site-specific fertilization on yield and protein content in durum wheat. Precision Agriculture'13 (pp. 321–327). Wageningen Acad. Publishers, NL.

Mulder, C., Breure, A.M., 2006. Impact of heavy metal pollution on plants and leaf-miners. Env. Chem. Lett. 4 (2), 83–86.

Murphy, D.V., Stockdale, E.A., Brookes, P.C., Goulding, K.W.T., 2007. Impact of microorganisms on chemical transformations in soil. Soil Biological Fertility. Springer Netherlands, Dordrecht, pp. 37–59.

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309.

Németh, T., 2006. Nitrogen in the soil-plant system, nitrogen balances. Cereal Res. Commun. 61–64.

Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. Agron. Sustain. Dev. 34, 473–492.

Nsanganwimana, F., Waterlot, C., Louvel, B., Pourrut, B., Douay, F., 2016. Metal, nutrient and biomass accumulation during the growing cycle of *Miscanthus* established on metal-contaminated soils. J. Plant Nutr. Soil Sci. 179 (2), 257–269.

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56, 377–400.

OECD, 1974. OECD Environmental Indicators – Development, measurement and use. Paris (France).

OECD, 1993. Environmental Indicators for Environmental Performance Reviews Paris (France).

Olfs, H.W., Blankenau, K., Brentrup, F., Jasper, J., Link, A., Lammel, J., 2005. Soil- and plant-based nitrogen-fertilizer recommendations in arable farming. J. Plant Nutr. Soil Sci. 168, 414–431.

Oustriere, N., Marchand, L., Galland, W., Gabbon, L., Lottier, N., Motelica, M., Mench, M., 2016. Influence of biochars, compost and iron grit, alone and in combination, on copper solubility and phytotoxicity in a Cu-contaminated soil from a wood preservation site. Sci. Total Environ. 566, 816–825.

Oustriere, N., Marchand, L., Lottier, N., Motelica, M., Mench, M., 2017. Long-term Cu stabilization and biomass yields of Giant reed and poplar after adding a biochar, alone or with iron grit, into a contaminated soil from a wood preservation site. Sci. Total Environ. 579, 620–627.

Pádua, L., Vanko, J., Hruška, J., Adão, T., Sousa, J.J., Peres, E., Morais, R., 2017. UAS, sensors, and data processing in agroforestry: a review towards practical applications. Int. J. Remote Sens. 38 (8–10), 2349–2391.

Panagos, P., Van Liedekerke, M., Yigini, Y., Montanarella, L., 2013. Contaminated sites in Europe: review of the current situation based on data collected through a European network. J. Environ. Public Health 2013.

Papageorgiou, E.I., Markinos, A.T., Gemtos, T.A., 2011. Fuzzy cognitive map based approach for predicting yield in cotton crop production as a basis for decision support system in precision agriculture application. Appl. Soft Comput. 11 (4), 3643–3657.

Park, J.H., Choppala, G.K., Bolan, N.S., Chung, J.W., Chuasavathi, T., 2011. Biochar reduces the bioavailability and phytotoxicity of heavy metals. Plant Soil 348 (1–2), 439.

Patten, C.L., Glick, B.R., 2002. Role of *Pseudomonas putida* indoleacetic acid in development of the host plant root system. Appl. Environ. Microbiol. 68 (8), 3795–3801.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57.

Peacock, A.G., Mullen, M., Ringelberg, D., Tyler, D., Hedrick, D., Gale, P., White, D., 2001. Soil microbial community responses to dairy manure or ammonium nitrate applications. Soil Biol. Biochem. 33 (7), 1011–1019.

Pieterse, C.M., Zamioudis, C., Berendsen, R.L., Weller, D.M., Van Wees, S.C., Bakker, P.A., 2014. Induced systemic resistance by beneficial microbes. Annu. Rev. Phytopathol. 52, 347–375.

Ping, L., Boland, W., 2004. Signals from the underground: bacterial volatiles promote growth in Arabidopsis. Trends Plant Sci. 9, 263–266.

Puri, G., 2002. Soil restoration and nature conservation, Scottish Natural Heritage (150). SSN: 1358 5843. Edinburgh.

Qambrani, N.A., Rahma, M.M., Won, S., Shim, S., Ra, C., 2017. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: a review. Renew. Sust. Energ. Rev. 79, 255–273.

Raaijmakers, J.M., Paulitz, T.C., Steinberg, C., Alabouvette, C., Moënne-Loccoz, Y., 2008. The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant Soil 321, 341–361.

Reeves, R.D., Baker, A.J.M., 2000. In: Raskin, I., Ensley, B.D. (Eds.), Metal-accumulating plants. In: Phytoremediation of Toxic Metals – Using Plants to Clean Up the Environment, pp- 193–229. John Wiley and Sons, New York.

REVIT Project, 2007. Working towards more effective and sustainable brown field revitalisation policies. Interreg IIIB Project http://www.revit-nweurope.org/selfguidingtrail/27_Stakeholder_engagement_a_toolkit-2.pdf.

Rizwan, M., Ali, S., Qayyum, M.F., Ibrahim, M., Zia-ur-Rehman, M., Abbas, T., Ok, Y.S., 2016. Mechanisms of biochar-mediated alleviation of toxicity of trace elements in plants: a critical review. Environ. Sci. Pollut. Res. 23 (3), 2230–2248.

Rodríguez, H., Fraga, R., 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnol. Adv. 17, 319–339.

Ruttens, A., Boulet, J., Weyens, N., Smeets, K., Adriaensen, K., Meers, E., ... Witters, N., 2011. Short rotation coppice culture of willows and poplars as energy crops on metal contaminated agricultural soils. Int. J. Phytoremediation 13 (sup1), 194–207.

Ryu, C., Farag, M.A., Hu, C., Reddy, M.S., Wie, H., Paré, P.W., et al., 2003. Bacterial volatiles promote growth in Arabidopsis. Proc. Natl. Acad. Sci. U. S. A. 100, 4927–4932.

Ryu, C., Farag, M.A., Hu, C., Reddy, M.S., Kloepper, J.W., Paré, P.W., 2004. Bacterial volatiles induce systemic resistance. Plant Physiol. 134 (3), 1017–1026.

Sainju, U.M., Lenssen, A., Caesar-Tonthat, T., Waddell, J., 2006. Tillage and crop rotation effects on dryland soil and residue carbon and nitrogen. Soil Sci. Soc. Am. J. 70, 668–678.

Sauvêtre, A., Schröder, P., 2015. Uptake of carbamazepine by rhizomes and endophytic bacteria of *Phragmites australis*. Front. Plant Sci. 6, 83. https://doi.org/10.3389/fpls.2015.00083.

Sauvêtre, A., May, R.G., Schröder, P., 2017. Metabolism of carbamazepine in plant roots and endophytic rhizobacteria isolated from *Phragmites australis*. J. Hazard. Mater. 324, 85–95.

SAVE FOOD, 2015. Global Initiative on Food Loss and Waste Reduction. FAO http://www.fao.org/3/a-i4068e.pdf (accessed Oct. 18th, 2017).

Sayen, H., Eder, P., 2014. End-of-Waste Criteria for Biodegradable Waste Subjected to Biological Treatment (Compost & Digestate): Technical Proposals. Publications Office of the European Union, Brussels (Luxembourg).

Scarlat, N., Dallemand, J.F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: policies and facts. J. Environ. Dev. 15, 3–34.

SCAR-report, 2015. Sustainable Agriculture, Forestry and Fisheries in the Bioeconomy. A Challenge for Europe. Standing Committee on Agricultural Research. Publisher: European Commission. Editor, Barna Kovacs ISBN: 978-92-79-47538-2.

Scherr, S.J., 1999. Soil Degradation: A Threat to Developing-Country Food Security by 2020? (Vol. 27). Intl. Food Policy Res. Inst., Washington.

Scherr, S.J., McNeely, J.A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes. Philos. Trans. R. Soc. B 363, 477–494.

Schmid, T., Rodríguez-Rastrero, M., Escribano, P., Palacios-Orueta, A., Ben-Dor, E., ... Chabrillat, S., 2016. Characterization of soil erosion indicators using hyperspectral data from a mediterranean rainfed cultivated region. IEEE J. Select. Topics Appl. Earth Observ. Remote Sensing 9 (2), 845–860.

Schmidhalter, U., Maidl, F.X., Heuwinkel, H., Demmel, M., Auernhammer, H., Noack, P.O., Rothmund, M., 2008. Precision farming—adaptation of land use management to small scale heterogeneity. In: Schröder, P., Pfadenhauer, J., Munch, J.C. (Eds.), Perspectives for Agroecosystem Management - Balancing Environmental and Socio-Economic Demands. Elsevier, pp. 121–199.

Scholz, R.W., Ulrich, A.E., Eilittä, M., Roy, A., 2013. Sustainable use of phosphorus: a finite resource. Sci. Total Environ. 461–462, 799–803.

Schröder, J., 2005. Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresour. Technol. 96, 253–261.

Schröder, P., Collins, C., 2002. Conjugating enzymes involved in xenobiotic metabolism of organic xenobiotics in plants. Int. J. Phytoremediation 4 (4), 247–265.

Schröder, P., Huber, B., Olazábal, U., Kaemmerer, A., Munch, J.C., 2002. Land use and sustainability: FAM research network on agroecosystems. Geoderma 105, 155–166.

Schröder, P., Huber, B., Munch, J.C., 2003. Making modern agriculture sustainable: FAM research network on agroecosystems. J. Soils Sediments 3 (4), 223–226.

Schröder, P., Huber, B., Reents, H.J., Munch, J.C., Pfadenhauer, J., 2008a. Outline of the Scheyern project. In: Schröder, P., Pfadenhauer, J., Munch, J.C. (Eds.), Perspectives for Agroecosystem Management - Balancing Environmental and Socio-Economic Demands. Elsevier, pp. 3–16.

Schröder, P., Pfadenhauer, J., Munch, J.C., 2008b. Perspectives for Agroecosystem Management – Balancing Environmental and Socio-Economic Demands. Elsevier, Amsterdam, NL.

Schwitzguebel, J.P., van der Lelie, D., Baker, A., Glass, D.J., Vangronsveld, J., 2002. Phytoremediation: European and American trends, success, obstacles and needs. JSS 2, 91–99.

Shah, F., Nicolás, C., Bentzer, J., Ellström, M., Smits, M., Rineau, F., et al., 2015. Ectomycorrhizal fungi decompose soil organic matter using oxidative mechanisms adapted from saprotrophic ancestors. New Phytol. 209 (4), 1705–1719.

Sharma, A., Johri, B.N., 2003. Growth promoting influence of siderophore-producing pseudomonas strains GRP3A and PRS9 in maize (*Zea mays* L.) under iron limiting conditions. Microbiol. Res. 158, 243–248.

Sieper, T., Forczek, S., Matucha, M., Krämer, P., Hartmann, A., Schröder, P., 2013. *N*-acyl-homoserine lactone uptake and systemic transport in barley rest upon active parts of the plant. New Phytol. 201 (2), 554–559.

Smith, P., 2012. Soils and climate change. Curr. Opin. Environ. Sustain. 4, 539–544.

Smith, P., Falloon, P., 2005. Carbon sequestration in European croplands. SEB Exp. Biol. Ser. 2005, 47–55.

Spaepen, S., Van der Leyden, J., Remans, R., 2007. Indole-3-acetic acid in microbial and microorganism-plant signaling. FEMS Microbiol. Rev. 31, 425–448.

Spaepen, S., Dobbelaere, S., Croonenborghs, A., Van der Leyden, J., 2008. Effects of *Azospirillum brasilense* indole-3-acetic acid production on inoculated wheat plants. Plant Soil 312, 15–23.

Sradnick, A., Murugan, R., Oltmanns, M., Raupp, J., Joergensen, R.G., 2013. Changes in functional diversity of the soil microbial community in a heterogeneous sandy soil after long-term fertilization with cattle manure and mineral fertilizer. Appl. Soil Ecol. 63, 23–28.

Sterckeman, T., Douay, F., Proix, N., Fourrier, H., Perdrix, E., 2002. Assessment of the contamination of cultivated soils by eighteen trace elements around smelters in the North of France. Water Air Soil Pollut. 135 (1), 173–194.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289–307.

Taghavi, S., Barac, T., Greenberg, B., Borremans, B., Vangronsveld, J., van der Lelie, D., 2005. Horizontal gene transfer to endogenous endophytic bacteria from poplar improves phytoremediation of toluene. Appl. Environ. Microbiol. 71, 8500–8505.

Tammeorg, P., Bastos, A.C., Jeffery, S., Rees, F., Kern, J., Graber, E.R., Cordovil, C.M.D.S., 2017. Biochars in soils: towards the required level of scientific understanding. Journal of Env. J. Environ. Eng. Landsc. Manag. 25 (2), 192–207.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671.

Touceda-González, M., Álvarez-López, V., Prieto-Fernández, Á., Rodríguez-Garrido, B., Trasar-Cepeda, C., Mench, M., ... Kidd, P.S., 2017a. Aided phytostabilisation reduces metal toxicity, improves soil fertility and enhances microbial activity in Cu-rich mine tailings. J. Environ. Manag. 186, 301–313.

Touceda-González, M., Prieto-Fernández, Á., Renella, G., Giagnoni, L., Sessitsch, A., Brader, G., ... Galazka, R., 2017b. Microbial community structure and activity in trace element-contaminated soils phytomanaged by gentle remediation options (GRO). Environ. Pollut. 231, 237–251.

Toy, T.J., Foster, G.R., Renard, K.G., 2002. Soil Erosion: Processes, Prediction, Measurement, and Control. John Wiley & Sons, Hoboken, NY.

Trost, B., Ellmer, F., Baumecker, M., Meyer-Aurich, A., Prochnow, A., Drastig, K., 2014. Effects of irrigation and nitrogen fertilizer on yield, carbon inputs from above ground harvest residues and soil organic carbon contents of a sandy soil in Germany. Soil Use Manag. 30 (2), 209–218.

Tsuchisaka, A., Yu, G., Jin, H., Alonso, J.M., Ecker, J.R., Zhang, X., et al., 2009. A combinatorial interplay among the 1-aminocyclopropane-1-carboxylate isoforms regulates ethylene biosynthesis in *Arabidopsis thaliana*. Genetics 183, 979–1003.

UNFPA, 2011. Annual Report: Delivering Results in a World of 7 billion, New York.

Van der Ent, S., Van Wees, S.C.M., Pieterse, C.M.J., 2009. Jasmonate signaling in plant interactions with resistance-inducing beneficial microbes. Phytochemistry 70, 1581–1588.

Van der Heijden, M.G.A., Bardgett, R.D., van Straalen, N.M., 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol. Lett. 11, 296–310.

Van der Lelie, D., Schwitzguébel, J.P., Glass, D.J., Vangronsveld, J., Baker, A., 2001. Peer reviewed: assessing phytoremediation's progress in the United States and Europe. Environ. Sci. Technol. 35 (21):446A–452A. https://doi.org/10.1021/es012543u.

Vaněk, T., Schwitzguébel, J.P., 2003. Plant biotechnology for the removal of organic pollutants and toxic metals from wastewaters and contaminated sites. In: Sasek, V., Glaser, J.A., Baveye, P. (Eds.), The Utilization of Bioremediation to Reduce Soil Contamination: Problems and Solutions. Springer, pp. 285–293.

Vegter, J.J., 2001. Sustainable contaminated land management: a risk-based land management approach. Land Contamin. Theatr. Rec.Theatr. Rec. 9 (1), 95–100.

Virkutyte, J., Sillanpaa, M., Latostenmaa, P., 2002. Electrokinetic soil remediation - critical overview. Sci. Total Environ. 289, 97–121.

Vlot, A.C., Dempsey, D.M.A., Klessig, D.F., 2009. Salicylic acid, a multifaceted hormone to combat disease. Annu. Rev. Phytopathol. 47, 177–206.

Vuolo, F., D'Urso, G., De Michele, C., Bianchi, B., Cutting, M., 2015. Satellite-based irrigation advisory services: a common tool for different experiences from Europe to Australia. Agric. Water Manag. 147, 82–95.

Vyslouzilova, M., Tlustos, P., Száková, J., 2003. Cadmium and zinc phytoextraction potential of seven clones of *Salix* spp. planted on heavy metal contaminated soils. Plant Soil Environ. 49 (12), 542–547.

Walmsley, A., Cerdà, A., 2017. Soil microfauna and organic matter in irrigated orchards under Mediterranean climate. Biol. Agric. Hortic. 33, 1–11.

Wandersman, C., Delepelaire, P., 2004. Bacterial iron sources: from siderophores to hemophores. Annu. Rev. Microbiol. 58, 611–647.

Weyens, N., van der Lelie, D., Taghavi, S., Newman, L., Vangronsveld, J., 2009a. Exploiting plant–microbe partnerships to improve biomass production and remediation. Trends Biotechnol. 27, 591–598.

Weyens, N., van der Lelie, D., Taghavi, S., Vangronsveld, J., 2009b. Phytoremediation: plant-endophyte partnerships take the challenge. Curr. Opin. Biotechnol. 20, 248–254.

White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crop Res. 124, 357–368.

World Economic Forum, 2002. Environmental Sustainability Index. An Initiative of the Global Leaders of Tomorrow Environment Task Force. Yale Center for Environmental Law and Policy, New Haven, CT, USA.

Yang, J., Kloepper, J.W., Ryu, C.M., 2009. Rhizosphere bacteria help plants tolerate abiotic stress. Trends Plant Sci. 14, 1–4.

Yao, Z., Li, J., Xie, H., Yu, C., 2012. Review on remediation technologies of soil contaminated by heavy metals. Procedia Environ Sci 16, 722–729.

Zentner, R.P., Plafond, G.P., Derksen, D.A., Nagy, C.N., 2004. Effects of tillage method and crop rotation on non-renewable energy use efficiency for a thin black Chernozem in the Canadian prairies. Soil Tillage Res. 77 (2), 125–136.

Zhang, C., Kovacs, J.M., 2012. The application of small unmanned aerial systems for precision agriculture: a review. Precis. Agric. 13 (6), 693–712.

Zhu, Z.Q., Yang, X.E., Wang, K., Huang, H.G., Zhang, X., Fang, H., ... He, Z.L., 2012. Bioremediation of Cd-DDT co-contaminated soil using the Cd-hyperaccumulator *Sedum alfredii* and DDT-degrading microbes. J. Hazard. Mater. 235, 144–151.

Zhu, N.M., Qiang, L., Guo, X.J., Hui, Z., Yu, D., 2014. Sequential extraction of anaerobic digestate sludge for the determination of partitioning of heavy metals. Ecotoxicol. Environ. Saf. 102, 18–24.

Žížala, D., Zádorová, T., Kapička, J., 2017. Assessment of soil degradation by erosion based on analysis of soil properties using aerial hyperspectral images and ancillary data, Czech Republic. Remote Sens. 9 (28), 2–24.