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Discussion

Relaunch cropping on marginal soils by incorporating amendments and beneficial trace elements in an interdisciplinary approach

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ABSTRACT

In the EU and world-wide, agriculture is in transition. Whilst we just converted conventional farming imprinted by the post-war food demand and heavy agrochemical usage into integrated and sustainable farming with optimized production, we now have to focus on even smarter agricultural management. Enhanced nutrient efficiency and resistance to pests/pathogens combined with a greener footprint will be crucial for future sustainable farming and its wider environment. Future land use must embrace efficient production and utilization of biomass for improved economic, environmental, and social outcomes, as subsumed under the EU Green Deal, including also sites that have so far been considered as marginal and excluded from production. Another frontier is to supply high-quality food and feed to increase the nutrient density of staple crops. In diets of over two-thirds of the world's population, more than one micronutrient (Fe, Zn, I or Se) is lacking. To improve nutritious values of crops, it will be necessary to combine integrated, systems-based approaches of land management with sustainable redevelopment of agriculture, including central ecosystem services, on so far neglected sites: neglected grassland, set aside land, and marginal lands, paying attention to their connectivity with natural areas. Here we need new integrative approaches which allow the application of different instruments to provide us not only with biomass of sufficient quality and quantity in a site specific manner, but also to improve soil ecological services, e.g. soil C sequestration, water quality, habitat and soil resistance to erosion, while keeping fertilization as low as possible. Such instruments may include the application of different forms of high carbon amendments, the application of macro- and microelements to improve crop performance and quality as well as a targeted manipulation of the soil microbiome. Under certain caveats, the potential of such sites can be unlocked by innovative production systems, ready for the sustainable production of crops enriched in micronutrients and providing services within a circular economy.

1. The problem

By 2050 the world's population will exceed 9 billion, and global temperatures will have increased so that the world has to face prolonged drought periods and lower water availability. Dramatic, more intense hurricanes (Asia, Florida, even in France/Italy/Greece due to warming of the Mediterranean Sea, etc.) and periods of tremendous floods (last time in central Europe, China, also Thailand/Japan/Vietnam, etc.), as well as rivers running dry result from increased temperatures, and reduction of forests and increase of the interface between natural areas and periurban/agricultural areas promote changes in life cycles of pests and biological auxiliaries.

Moreover, our focus on bioeconomy will change crop production, and it can be expected that agriculture of the future has to produce more raw materials to be used in multiple refinery processes, while reduction of forests and increase of the interface between natural areas and periurban / agricultural areas promote changes in life cycles of pests and biological auxiliaries (Shahzad et al., 2021). And finally, global pollution levels and high impact farming have induced a strong decline in soil quality, making a sustainable use of land more challenging than in the past (FAO, 2017).

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Consequently, one main challenge for agriculture will be to ensure food security and safety under these conditions, and to sustainably produce high-quality crops for an ever-increasing human population. Current estimates suggest a surplus in food production by approximately 70 - 85% is needed (Dhankher and Foyer, 2018).

In 2014, a FAO report shocked the community with a forecast, indicating if current rates of soil degradation would continue, the world's top-soils could be gone within 60 years (https://www.scientific-american.com/article/only-60-years-of-farming-left-if-soil-degradation-continues). While this was certainly a publicity-oriented exaggeration, it made clear that in line with decreasing productivity of arable soils and progressing climate change, agricultural science and practice will have to develop new strategies to increase quantity and quality of food and feed crops around the world. It is also true that the expansion of croplands in recent decades has significantly reduced ecosystem services while it remains a fact that soils are a non-renewable resource. Different aspects of agriculture cause land degradation, contributing to this process in a variety of ways (Schröder et al., 2018). Although it is well established that pedoclimatic conditions should determine the local choice of agricultural management, it is obvious that globalization and commercialized production of seeds induced the opposite and today management is based on combinations of seeds, fertilizers, plant protection agents and machineries, proceeding without too much attention to soil heterogeneity. Hence, soil degradation might be caused by ploughing techniques, clearing of genuine vegetation, improper fallow periods, lack of crop rotations, heavy machines or overgrazing (Tepes et al., 2020). Other challenges to be faced by a modern agricultural production are the reduction of the use of plastics and the even stronger competition with alternative land use, e.g. photovoltaic power plants. Finally, excess application of mainly inorganic fertilizer to equalize yield will lead to nutrient leaching and new imbalances (DeClerq et al., 2018).

But other pressures on farms are equally high, both in terms of ecology and economy: Increasing production costs, implementation of EU taxonomy, low prices paid by supermarket chains, and restrictions for agrochemical use exert significant strain, especially on small farms. As an additional complication, most existing croplands have some low-yielding areas exhibiting physical and chemical problems such as low soil quality, water holding capacity, high compaction, susceptibility to flooding, erosion and acidity or salinity (Fig. 1). In many of the latter sites, costs for the remediation might be balanced through the profitability of the bioresources obtained through nonfood plant cultivation, i.e. biomass energy valorization, followed by biochar production (Marmiroli et al., 2018), or even by phytomining (Sheoran et al., 2009). Approaches like those might lead to a circular system, getting revenues from novel on-farm activities and by-products.

These partially degraded areas are classified as marginally productive croplands (see Textbox 1) and, in addition to idle, abandoned croplands or long-term fallows, represent a considerable fraction of valuable land without proper management (Blanco-Canqui, 2016).

In Europe with its geographical gradient of temperatures and soil types, specific measures leading to sustainable growth of sound agricultural productivity and improved climate change resilience of agroecosystems are needed. This is also mirrored in the EU Green Deal of 2020. Thus, converting marginally productive areas to productive land could enhance both soil services and resilience of the landscape as a whole, and smart enhancement of the production efficiency of such areas is a timely demand, especially under constraints like reduced carbon and nutrient stocks in soil, higher frequency of extreme weather events, or system-inherent limitations such as the typical lack of livestock (and return of manure) in rural areas of Europe.

So far, research on ecosystem stability has concentrated on the role of biodiversity in maintaining ecosystem health: the lower the diversity, the more probable it is that a loss of species is followed by both, a loss of function and connectivity between key functional groups (Garlaschelli et al., 2003). Thus land use intensification has been considered a major reason for the losses of multi-functionality of soil ecosystems due to reduced diversity of species on all trophic levels (Felipe-Lucia et al., 2020).

2. The rationale: unlock the potential of marginal soils

To overcome the dilemmas described above, one strategy could be the enhanced use of the capacities provided by fallow land and marginal soils. Here a (re)activation strategy for the production of food, fodder, or non-food products might be beneficial (Schröder et al., 2018; Von Cossel et al., 2019). It seems well possible to produce relevant amounts of high-quality biomass on marginal soils after improving their physico-chemical properties and nutrient availability. With view of current problems connected to stagnating productivity in rural areas, increasing amounts of waste and CO_2 emissions to the atmosphere, it is high time to develop novel concepts for marginal lands and organic waste fractions. Without management, erodible sites (see Fig. 2) could only store about 1 Mg ha^{-1} yr^{-1} of C in the soil (Gebhart et al., 1994; Follett, 2001; Mi et al., 2014), a number that could be increased under smart farm management, e.g. when soil amendments derived from on-site agricultural by-products and wastes are applied (Urra et al., 2019; Gebremikael et al., 2020). Such agricultural by-products (i.e.

Fig. 1. A (left): Marginal site on a farm in Upper Bavaria; Germany. The farmer abandoned the grassland years ago, since the revenue seemed too small and the management too complicated. The plot is used to park farm equipment and as lairage for the cattle of the farm. The former grassland has been overgrown by weeds like *Rumex*, *Atriplex*, *Ranunculus*, *Solanum* and others and has successively become less attractive for forage or animal husbandry. UAV imagery helps to identify weed density and soil heterogeneity (Photo: P. Schröder). B (right): Former brownfield soil at Saint-Médard d'Eyrans in southern France. The plot belonged to a wood preservation company and is polluted with Cu-PAH contamination, suffers from drought, and has only low organic matter and CEC. After discontinuing industrial activities, the owner was assessing soil remediation with phytomanagement options which proceeds slowly due to the low nutrient availability in the soil, see also table in the supplemental material (Photo: M. Mench).

Textbox 1
Definition of the term "marginality". Excerpted from: Kang et al., 2013, Shortall, 2013, Brown, 2003.

> Textbox 1
>
> Marginal sites may be defined as regions at the rim or border of given prevailing dominant social, economic or political structures and exhibit spatial conditions that make them less or even un-suitable for a particular use than regions in the center of the structures (Shortall 2013). Hence, marginality is always linked to the set of mainstream functions assigned to the central area by certain actors (e.g. agriculture, industry, mining, residential area, etc.). Given this, locations characterized as marginal do not necessarily have to be geographically at the edge of active spaces, resources and information flows. Like brownfields they can even be in the center of former topical hotspots but still only contribute marginally to the quality of an area. Land-owner's perceptions seem to be affected by a combination of unfavorable biophysical (e.g., soil water capacity, temperature variability, and slope) and socioeconomic factors, among which farm size appears to be significant. Hence, the definition of marginality contains a pre-set suitability to integrate into overarching and generally accepted economic and geophysical structures and processes. In an agricultural context, Turley et al. (2010) define marginal lands as sites where:
>
> - cost effective production of high quality crops is not possible under a given set of conditions,
> - break-even economic margins define whether productivity on the land is high enough, and
> - significant change in land use is most likely to be expected.
>
> Still, in current literature, the use of the term "marginal land" is vague, unstable and ambiguous and may not be suitable as definition in scientific context, rather than a loose category of terms used to characterize a given type of land as: abandoned, additional, bad, degraded, fallow, free, idle, inappropriate, unused, unsuitable, spare, under-used, under-utilized, and set aside. Semantically, these terms are ambiguous and fluid, and interesting conceptual issues might be raised about the degrees of freedom such land might have.
>
> The rationale of putting unprofitable, marginal farmland back into more productive use while meeting regional energy demands and ecological goals is an appealing one. Some use a hype about future technologies to raise expectations and tap into stereotypes of scientific progress leading to societal progress (Brown, 2003). Proposing the use of marginal land might raise inappropriate expectations about the production of abundant, sustainable biomass. The potential association of biomass production with marginal land or regarding crops grown there as marginal crops is for sure a hindrance to its development (Shortall 2013). Sites with historical burdens or lower productivity need to be gently remediated for sustainable usage, expecting restricted, but stable yields from well-designed inputs within a circular farm management.

straws, hulls, digestates, spent substrates, etc.) mainly contain primary residues with huge pools of untapped biomass which can, when treated properly, be either converted into bioenergy and bio-based products (i.e. fertilizers, energy, and raw materials) by cascading conversion processes within the circular economy, or applied to poor soils (Fig. 3). Typically, crop lignocellulosic biomass is comprised of about 10–25% lignin, 20–30% hemicellulose, and 40–50% cellulose, ideal as primers for carbon storage in soils (Iqbal et al., 2011). Similarly, biochars with different intrinsic capabilities might be applied, improving the water holding capacity of soils and nutrient retention due to their chemical and electrical properties (Ruotolo et al., 2018). An important side effect of such amendments is the improved potential of the soil biomass to act as a temporal storage pool for nitrogen, phosphorus and other nutrients, as a result of a stable stoichiometry in the microbial biomass (Kamau et al., 2021).

From the point of circular economy, environmental protection and stabilization of organic matter in marginal soils, management of farm waste to produce domestic natural fertilizers is crucial. Systematic introduction of processed organic matter from the farm will improve physical and chemical soil properties, stabilizing yields and soils by fostering soil, microbiota and crop interactions (Schmid et al., 2018). When digestates from biogas production, or composts derived from different sources are returned to fields, carbon backbones, nutrients, and selected microorganisms are added to increase the functional potential and ecosystem services from soils (Nabel et al., 2017) and may induce positive feedback loops, towards improved resilience of a given soil. Thus, increased organic matter (OM) and water storage merged with best practices will produce surplus yields. And when a balanced alliance of perennials and food crops in the existing agricultural landscapes would be established, both, renewable energy security as well as food security could be achieved (Blanco-Canqui, 2016), with positive aspects for biodiversity and multifunctionality of soil ecosystems.

As has already been discussed in previous work (Schröder et al., 2018; Millán et al., 2019), all agricultural productivity options, to be economically sustainable, have to be regarded as a part of a value chain, in a scheme that has already focused on the reference market for product valorization before starting the reconfiguration of the land. In this context, amending abandoned sites with farm residues or composts can enhance cost-effectiveness on a farm (Figs. 4 and 5), and will also take effect in terms of wider economic, social, and environmental benefits, i.e. local and regional ecosystem services (Constantin et al., 2019), by improving the energy balance and increasing the content of soil organic matter by C sequestration (Gontard et al., 2018). Proper management of agricultural by-products, e.g. by transformation into biogas and energy recovery and production of organic amendments usable to improve the properties of marginal soils will contribute to reduced CO$_2$ emissions, promoting lower C footprints. In line with this, and after careful consideration of site specific conditions of given marginal soils, amendments made from sawdust or lignin could help to implement the recommendation of the French Ministry of Agriculture (Minasny et al., 2017), aiming to increase soil carbon pools by 4‰ per year, thus helping to mitigate the adverse climatic influence of anthropogenic CO$_2$ emission (Žydelis et al., 2019, Reichel et al., 2018).

Soils richer in organic matter can retain more water, which will be important, since drought stress alone will limit the productivity of more than half of the earth's arable land in the next 50 years. With view to novel legislation, and to the protection of waterbodies it will further be essential to introduce well designed N-management, keeping nitrogen in the amended soil and available for plant growth. Rapid N immobilization can occur under field conditions after incorporation of organic C-rich crop residues (Congreves et al., 2013; Reichel et al., 2018).

3. Identify and utilize key players of soil life

Soils have been recognized as ecosystems with the highest biodiversity on Earth, due to the unique variety of ecological niches they provide, which are shaped by the interplay of chemical, physical and biological soil properties (Bardgett and Caruso, 2020). Here soil microbes play a very important role and are often referred to as major architects of soil quality (Thiele-Bruhn et al., 2020). They drive nutrient turnover in soil, support plant growth, play an important role in the safeguarding of drinking water by degrading pollutants and are involved in carbon sequestration (Nannipieri et al., 2020). The most prominent impact of microorganisms on soil fertility in soils under agricultural use is their effect on nutrient availability by fixing or mineralizing nutrients from the

Fig. 2. Agricultural plots with sandy soils and low water holding capacity. A: experimental farm in southern Poland, close to Skirveniece. Although permanently under agricultural management, the site suffers more and more from drought, and productivity has ceased. B: eroded slope in a tertiary hill-area of northern Bavaria, Germany. The plot is on the verge of the tertiary hill lands, the end moraines of the last glacial period. While the hill top is characterized by gravel and sand, the valley part is loamy. The patchy soil quality causes problems in fertilization management and C/N values, see also table in the supplemental material (Photos: W. Szulc, P. Schröder).

gross soil nutrient pool (Hayat et al., 2010; Bulgarelli et al., 2013). Some symbiotic microbes also contribute to water uptake or stimulate plant resistance towards pathogens (Rineau and Ladygina, 2013). Moreover, arbuscular mycorrhiza improves the uptake of micronutrients by plants (Munkvold et al., 2004). However, root pathogens may display detrimental interactions with plants and thus induce serious reductions of yield (Campbell and Noe, 1985).

Taking these important roles of soil microbiota into account, it is not surprising that the last two decades of research on ecosystem services and their resilience have concentrated on the role of (micro)biota and their diversity. It has been increasingly recognized that rather than individual taxa, connectivity and networks between key functional groups (keystone species) within a community determine soil functionality (Garlaschelli et al., 2003).

Microbiomes of highly productive sites have frequently been characterized by a large degree of functional redundancy (Nielsen et al., 2011). Consequently, disturbances causing species loss would have only limited functional impact since the disappeared species might be replaced by others with a similar role (Yachi and Loreau, 1999), which results in the hypothesis that soil functions are expected to be quite stable and only disturbances causing a massive species loss may lead to disturbed functioning (Wei et al., 2019). This assumes that a large group of species carries all essential soil functions - which may not be the case for marginal sites. Even more, several studies have indicated that microbial diversity at marginal sites is lower than in highly productive sites (Schmid et al., 2020; Vuko et al., 2020), mainly when abiotic stressors might act as a filter towards a low-diversity one (Caruso et al., 2011). In addition, activity of microbiota at marginal sites might be strongly impacted due to low concentrations of nutrients (Zhu et al., 2020). This calls for practices to increase microbe-mediated soil functions (enhance their *activity*, for example of mineralization), but also to improve their *stability* (increase their diversity, or beyond that, their functional redundancy for given functions) in marginal soils. Moreover, stimulating microbial diversity has the extra advantage of decreasing the risk of invasion by pathogen species (van Elsas et al., 2012). In many cases focus is given on the response of the soil microbiome towards specific treatments, but surveys of soil mesofauna can be used as additional indicators to assess improvements in soil functionality (Schröder, 2008). This is important since soil fauna is bottom-up regulated by microorganisms and plants, and energy transferred along food webs can either flow through detritus or the plant-based energy channels (Domene, 2016). The detritus-based pathway includes soil animals feeding from microbes (bacterivores or fungivores) and consumers (detritivores), while the plant-based pathway involves plant biomass feeders (herbivores).

pH	C_{org}	N	S	P	Na	Ca	Mg	K
	g·kg^{-1}							
6.7	158,7	12,8	1,49	11,05	1,02	84,57	5,39	10,71

Fig. 3. Pellets produced from spent mushroom substrate, bio-rest from biogas production and straw or brown coal as amendments to topsoils on selected sites. The constituents are mixed according to the requirements of the fertilizer, pressed and dried. The composition of the pellets is kept stable to reach marketable quality. Chemical quality (see table) and levels of potential contaminants are checked on a regular basis.
(Photo: W. Szulc). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Plants provide carbon during growth as exudates or during decay as litter. In this respect root morphology has been considered as an important factor, which does not only influence soil structure but also the distribution of "hotspots" (zones of increased microbial activity, but low diversity) and "coldspots" (zones with low activity and mostly dormant microbes of high diversity). Since the microbes acting as drivers for nutrient turnover in hotspots are recruited from "coldspots" spatial heterogeneity in soil is an important issue which triggers functionality and resilience. Taking the importance of plants as drivers for below ground biodiversity into account, it is obvious that mainly at marginal sites the selection of the right plant and cropping sequences is essential for the activation of the microflora and its functioning. This might include the use of deep rooting plants to mobilize nutrients from deeper soil layers (Thorup-Kristensen et al., 2020), where it has been shown that species like Lucerne, Sunflower, Sugarbeet or Summer wheat might penetrate 5, 2, 3 or 2 m, respectively, into soils and retrieve water from these depths while also introducing root exudates at the same time. Similarly, catchcrops and intercropping can be used to improve the retention of nutrients while periannual crops may promote soil structure development.

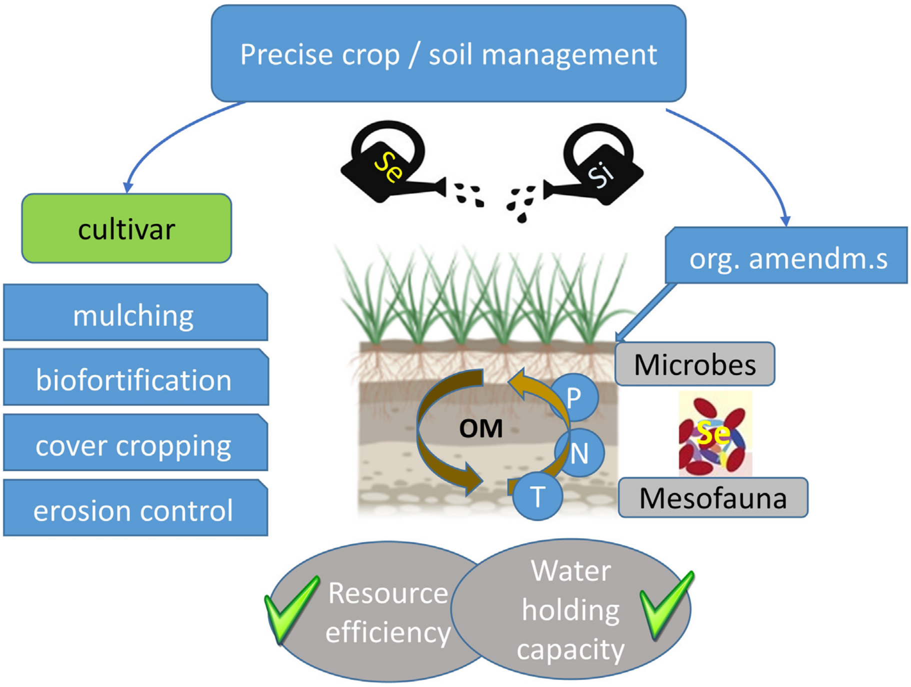

Fig. 4. Precise crop and soil management and targeted amendment of beneficial elements like selenium (Se) and/or silicium (Si) will improve plant performance and influence agricultural resource efficiency and water holding capacity. T: trace metal(loid)s, P: phosphorus, N: nitrogen, and OM: organic matter.

Fertilization is another important factor to trigger microbial diversity and activity pattern. The stoichiometry of nutrients, mainly the ratio of C:N:P, acts as a driver by which microbial processes are activated (Rineau et al., 2013; Reichel et al., 2018; Esmaeilzadeh-Salestani et al., 2021). While application of fertilizers in many regions is combined with irrigation, e.g. as fertigation or chemigation, the projected systems would be rainfed. Still, in high productive soils the use of inorganic fertilizers will induce the utilization of carbon to maintain a stable stoichiometry of the microbial biomass (Reichel et al., 2018). However, since available carbon is often one of the limiting factors at marginal sites, the use of inorganic fertilizers might be critical, as it will not induce microbial activities in a significant manner and result in leaching of nutrients to deeper soil layers and the groundwater (Zhao et al., 2011).

Organic fertilizers like manure could be considered, since here carbon is applied together with nutrients like N and P. However due to the labile nature of the applied carbon, manure might not be sustainable to manage marginal sites as it induces a flush of microbial activity resulting in a loss of carbon in form of CO_2 (Das et al., 2017). Furthermore, together with the nutrients also microbiota from the gut of the animals is applied to soil, which could result in an increase of potential human pathogens in such soils (Ekman et al., 2021). Compost amendments might be a good alternative, but they bear the risk of contamination with pollutants like heavy metals or μ-plastics (Watteau et al., 2018). Similarly, the quality of compost material may be differing as it strongly depends on the origin of the parent materials (Hasan et al., 2012). The addition of high carbon amendments (e.g. saw dust or biochar) could also be a solution, as it will stabilize physico-chemical soil structure, and induce a sustainable increased activity of the soil microbiome due to a continuous slow release of easy degradable carbon from the applied matrix as a matter of decay. Substrate availability might be modulated by clay contents, mineralogy, and soil carbon content (Guimarães et al., 2013). In addition, managing soil mineral N after harvest during times without sufficient winter crop N-uptake is of ample importance to reduce N-losses and improve the field N use efficiency (Zhang et al., 2015). In a previous study (Obermeier et al., 2019) it had been shown that the successful transformation of a marginal grassland to arable land via a transitional nitrogen fixing phase was successful when a leguminous crop was used to incorporate nitrogen by

Fig. 5. Field trial with compost amendment at a former wood preservation site, St-Médard d'Eyrans, France. Short rotation coppice (black poplar and willows) in year 6 after the compost incorporation into the soil and transplantation of mycorrhizal trees. Soil is remediated and prepared to multiple uses, see also table in the supplemental material (Photos: M. Mench).

biological fixation, and green manure. During growth of *V. faba* a strong enrichment of nitrate-N and total biological nitrogen was observed, and the later incorporation of the leguminous plant residues (Ordóñez-Fernández et al., 2018) led finally to the high amount of 50 μg nitrate-N g^{-1} dw (150 kg N/ha) which is already sufficient as a starter for crop cultivation. Available soil N will be immobilized after application of decomposable, C-rich organic residues with wide C:(N:P) ratios, such as wheat straw or amendments with mixed C-sources (Cheshire, 1999, Reichel et al., 2018). Even if changes in soil C-stocks might not be significant in the first few years after establishment, depending on the initial soil C-levels (Evers et al., 2013; Schmer et al., 2012), conditioning marginal soils with such amendments will obviously lead to stabilize nutrient cycling, reestablish trophic levels within food chains, better water availability, and yield security.

Finally the use of microbial inocula might be a possibility to increase the functional repertoire of marginal soils. Microbial inocula have been used in agriculture since a long time mainly to increase the number of symbiotic bacteria in soil during the cultivation of legumes. More recently, also other functional traits, for example related to the biocontrol of pathogens are introduced into soil by inoculation of microbiota to soil successfully (Malusá et al., 2012). In this context, discussion is ongoing whether synthetic consortia could be beneficial to deliver a broader spectrum of functions into soil (Vorholt et al., 2017). Even the transplantation of microbiota from soils with good soil quality has been used mainly for the recultivation of sites (Schmid et al., 2020). All these approaches require however that the inoculated microbiota find their ecological niches to ensure their survival in soil. This requires mainly for marginal sites an in depth understanding of the physiology of the applied microorganisms to develop the fitting niches e.g. by application of the optimal plants or the best fitting fertilizers mirroring the nutrient requirements of the respective bio fertilizers (Hayat et al., 2010; Bulgarelli et al., 2013). Similarly, acquisition of micronutrients by arbuscular mycorrhiza (AM) plants depends on the AM fungal genotype in the symbiosis (Munkvold et al., 2004), hence one could hypothesize that the nutrient composition in a plant would be a consequence of functional compatibility with the AM symbiosis (Ravnskov and Larsen, 2016). Thanks to their ability to secrete many enzymes, soil microbes mineralize organic nutrients, making a fraction of them available for plants.

4. Enhance product quality

There are concepts to generally use marginal sites mainly for agroforestry and bioenergy plants etc., to spare the use of highly productive sites for crop production (Zou et al., 2019). Adding high carbon amendments is an important step for sustainable management of such sites, but on many marginal sites micronutrients are also growth limiting factors and should be added. Hence, it should be possible to raise gross productivity on soils of lower performance, in a site specific manner for edible crop production, and increase in parallel crop resilience and quality, the latter especially in terms of micronutrient content. In many cases, nutrient availability seems to cause low crop quality (Rashid and Ryan, 2004). Such increases in product quality can eventually be obtained by applying biofortification techniques for food and fodder (Table S1). Surveys across the EU have shown that micronutrient intake of the population is insufficient (Mensink et al., 2013). Consequently, some authors suggest a food-chain approach to meet the micronutrient demands of livestock and humans. This requires inter-disciplinary collaboration between stakeholders in agriculture, environment and health (Watson et al., 2012). With view to application techniques, biofortification, like every fertilization model, could not be proposed outside a precision agriculture approach considering also the nanoparticle formulation of many chemicals (Tarafder et al., 2020).

Agronomic options to enhance product quality and integrated nutrition chain management by adding micronutrients are advocated by several organizations as immediate strategies to address this topic since micronutrient-biofortified fodders and food can improve animal and human nutrition and health (Fan et al., 2008; Garg et al., 2018; Novoselec et al., 2018). In this context, it is ever so important that the risk of overfertilisation should be considered. Gentle biofortification will address this and lead to the final aim of providing healthier nutrition. Accordingly, Pompano and Boy (2021) provide unequivocal evidence that biofortification of staple foods with essential trace elements, in this case Zn, provides low doses of the dietary required element regularly and consistently over time. The results of their meta-analysis suggest that such a low-dose, long-duration zinc intervention may reduce multiple risk factors for type 2 diabetes (T2D) and CVD (cardiovascular disease) related to both glycemic control and lipid metabolism (Pompano and Boy, 2021). It is likely that even a modest increase in dietary zinc intake from the consumption of biofortified crops, shifting probands from the lowest intake quantile to a middle quantile, could have a meaningful effect on their risk of developing T2D or other chronic diseases (Pompano and Boy 2020).

To date supplying staple crops with micronutrients is standard in some regions (Welch and Graham, 2004; Dimkpa and Bindraban, 2016), and might be an option for novel approaches on marginal lands (Foley et al., 2021; Trippe and Pilon-Smits, 2021; Buturi et al., 2021).

4.1. Zn

Zn deficiency is widespread and estimated to affect a huge proportion of the world's population of both developing and highly developed countries. It is primarily caused by the consumption of considerable amounts of products of cereal origin with Zn content substantially lower than in animal products. Bread wheat is the basis of the diet of 35% of the global population (Cakmak and Kutman, 2018). It is estimated that at the global scale, even 50% of wheat is cultivated on soils with insufficient Zn availability for plants. In such conditions, plants cannot fully use their capacity for Zn uptake and accumulation, resulting in reduced content of the element in the grain. Zinc concentration in the soil solution significantly decreases with an increase in soil pH, contributing to a decrease in the mobility of the element and its availability for plant roots. Like high soil pH, low soil moisture and low content of organic matter considerably limit Zn availability for plants (Rengel, 2015; Rutkowska et al., 2015). In Europe, Zn deficits occur in calcareous soils (Calcisols) in Austria, Bulgaria, Cyprus, France, Greece, Portugal, Spain, and Turkey, but also in sandy soils in France, Ireland, the Netherlands, Poland, Portugal, Sweden, and Switzerland (Sinclair and Edwards, 2008). If we consider that micronutrient deficit is more pronounced when it occurs in soils suffering from marginality symptoms, it might be an option for the improvement of such sites to start amending them with lacking minerals to reach better crop quality. For local populations, daily micronutrient intakes necessary to support health and immune function may be higher than recommended uptake levels (Gombart et al., 2020). Aiming at a final return of empoverished sites to productivity justifies their preparation for this goal even in early stages of the conversion process.

The success of biofortification depends on several variables such as the elemental species of choice, the mode of application, and the crop species. Zinc has been in the focus of nutritionists for a long time, since it is essential in all organisms as a cofactor of over 300 enzymes and plays critical structural roles in many proteins, including countless transcription factors (Palmgren et al., 2008). According to a WHO report, Zn deficiency ranks fifth among important health risk factors (Palmgren et al., 2008). Many studies have emphasized that Zn occupies a dynamic role in cellular signaling pathways, controlling insulin signaling transduction and glycaemia (Kambe et al., 2014). ZnT8 plays an indispensable role in supplying zinc to insulin granules in b-cells to form insulin-Zn crystals. In a line of Znt8-KO mice, the dense core of Zn-insulin crystals is lost because of lacking zinc. Hence, while adequate Zn content could well enhance crop productivity, Zn-enriched cereals would potentially also generate major health benefits. Moreover, Zn biofortification, while being successful at increasing Zn bioavailability in grains, also does not interfere with the bioavailability of other micronutrients such as iron, manganese, or copper in wheat flour (Liu et al., 2017).

4.2. Se

Selenium content in soils is primarily determined by the bedrock from which the soil developed. Its content depends on soil origin and geological history, mineralogy, type and texture, organic matter content, and eventually deposition (Hartikainen, 2005; Mehdi et al., 2013). More than 80% of the global selenium resources are accumulated in Chile, the USA, Canada, China, Zambia, Zaire, Peru, the Philippines, Australia, and Papua New-Guinea. Soils developed from igneous, sedimentary, and metamorphic rocks are usually poor in Se. Particularly soils in countries of Central-East and North Europe are characterized by low selenium content, and plants providing the basis of the diet, such as cereals, or fodder plants, e.g. grasses, contain insufficient amounts of Se (Krustev et al., 2019; Lopes et al., 2017; Gupta and Gupta, 2017). Insufficient Se content in crops is also related strongly to soil properties such as pH, Eh, organic matter content, or clay particles, influencing Se mobility (Trippe and Pilon-Smits, 2021). Alkaline soils are dominated by more mobile forms of Se^{6+} (selenians). Soils with neutral and acidic reaction are dominated by selenites (Se^{4+}) which, due to strong sorption by oxy-hydroxides, are characterized by considerably lower mobility in the soil (Tolu et al., 2014; Schiavon et al., 2020). Evidence arises that climatic conditions have an impact on Se content in plants. Selenium content in grains of cereals cultivated in dry climate is higher than in humid climate, probably related to the resistance of selenium to leaching, particularly from sandy soils (Garousi, 2017; Jones et al., 2017).

Because of the chemical similarity between Se and sulfur (S), the behavior of Se in higher plants is closely related to sulfur metabolism. Some plant endophytes accumulate selenium from soil and provide it to the plant, in turn benefiting plant's growth. These selenobacteria may improve selenium biofortification in crops even under drought stress. Above all, Se seems to play a role in increasing activities of glutathione peroxidases (GPX) contributing to the detoxification of reactive oxygen species, since it participates in the active site of these enzymes. GPX activities appear quite active in plants subjected to various abiotic stresses such as drought, salinity and metal(loid) toxicity (Viciedo et al., 2019). Selenium has also been shown to exert effects on human health, and biofortified food can prevent the onset of diseases related to low intake of this micronutrient (Alfthan et al., 2015; Vinceti et al., 2018). Although speculated in the beginning, several clinical studies did not support a role for Se in the development of T2D (diabetes), since groups who received Se or placebo for 3 years did not show any differences, and fasting blood glucose concentrations were higher for those in placebo groups compared to Se-treated groups (Jacobs et al., 2019).

4.3. Fe

The primary cause of iron deficit is diet based on products rich in starch, and poor in mineral elements, including Fe, such as rice, wheat flour or potatoes (Connorton and Balk, 2019). Agricultural soils show relatively high content of iron in a range from 20 to 40 g kg^{-1} but the availability for plants is low. Depending on the physico-chemical properties of soils, even 92% of Fe in soil can occur in forms unavailable for plants. High soil pH, presence of free calcium carbonates, and low content of organic matter contribute to this effect, and cause Fe deficit in plants (Connolly and Guerinot, 2002). In Europe, the problem particularly concerns calcareous soils in the south of the continent (Colombo et al., 2014; Zahedifar, 2020). In wholegrain products, Fe content is similar to that in animal products. In cereal grains, however, Fe primarily accumulates in the embryo and aleurone that are removed during grinding of grain for flour. Plant products also contain anti-nutritional polyphenols and phytic acid, limiting absorbing of iron in the digestive system (Connorton and Balk, 2019).

4.4. I

The diet of EU residents also shows deficits of iodine. Content of I in soils is variable. Soils of coastal regions are richer in the element than those located far from the sea, or soils from mountain areas. Organic matter content in the soil also affects iodine content. Organic (peat) soils and soils with high content of organic matter are higher in I than sandy mineral soils (Fuge and Johnson, 2015). Iodine is not essential for plants, and can be toxic at higher concentrations. Its content in plant tissues is generally low, not exceeding 1 mg kg^{-1} dry mass. Such low levels are not sufficient to meet the nutritional needs of humans and animals, although plant products still constitute the primary source of the element (Duborská et al., 2020; Fuge and Johnson, 2015). Many countries undertake obligatory fortification of salt in iodine, according to research of the Iodine Global Network (Brough et al., 2016), but deficits of the element still occur. One of the reasons for the decreasing iodine intake in European countries is the increasing consumption of "trendy salt" (e.g. crystal salt from the Himalayas or sea salt), leading to iodine deficits in Germany, Norway, Finland, Lithuania, Ukraine, and Estonia.

4.5. Si

Silicon amendments are known to enhance plant resistance to stressors such as drought and pathogen attacks (Vaculík et al., 2020), which are especially critical in marginal soils, where plants are already mobilizing resources to face pollution or low organic matter (Fig. 6). Moreover, drought (Stocker, 2014) and pathogen prevalence (Scheffers et al., 2016) are expected to be among the main threats to crops under a future climate. Silicon (Si) amendments appear well suited to improve crop quality and climate adaptation, and reduce the need for agrochemicals because not only should crop yield increase, but water consumption by evapotranspiration be reduced (Szulc et al., 2015), and crops stay active at lower soil water potential (stronger suberization of the endodermis). The latter would also favour retention of non-essential metal(loid)s in the roots and promote food safety. The advantages of Si fertilization have been recognized only few decades ago, and Si has finally (Drechsel et al., 2015) been upgraded by the International Plant Nutrition Institute (IPNI) as important and beneficial mediator of plant health (www.ipni.net/nutrifacts). Due to the advancement of genomics and the discovery of Si transporters, new opportunities have become available to characterize accumulator and non-accumulator plants on the basis of specific molecular features (Coskun et al., 2018). Any case, the water potential of Si-applied drought-stressed plant leaves is elevated, suggesting improved drought resistance (Zhu and Gong, 2014). Beneficial Si effects include also decrease in seedborne, soilborne, and foliar diseases caused by biotrophic, hemibiotrophic, and necrotrophic plant pathogens, due to Si influence on host resistance, i.e. incubation period, lesion size, and lesion number (Debona et al., 2017). It might be expected that amended plants allocate less energy to fight drought stress, leading to increased pathogen resistance and enhanced biodegradation of xenobiotics by soil microbes in the rhizosphere. Importantly, silicon also contributes to reducing the greenhouse effect and to enhance soil organic content through stable carbon sequestration. At present, one of the most promising mechanisms of biogeochemical sequestration of carbon in soil is its occlusion in plant phytoliths (PhytOC). Phytoliths are mainly composed of silica (SiO_2 - 6691%), and their amount in plants is positively correlated with Si availability (Song et al., 2012, 2013, 2014). During the production of phytoliths in plant tissues, 0.5 to 6% of organic carbon is incorporated into their structures. Phytoliths are among the most stable and recalcitrant organic carbon fractions in soil (Zhang et al.,

Fig. 6. example for a fully automated plant-soil ecotron with options to simulate climate extremes. Hasselt University, Belgium. Photo: F. Rineau.

2019), resulting in lifetimes of 200 to 1000 years, and the amount of carbon bound in PhytOC of 7.28.8 kg/ha/year, may represent 30% of the total amount of organic carbon stored in the soil. Globally, PhytOC production in agricultural ecosystems is 16–44 Tg CO_2 per year, of which more than 80% originates from cereals. Thus, they have a high potential for long-term carbon sequestration (Baveye and White, 2020).

Novel data suggest that silicon is also an essential trace element in mammalian nutrition and an indispensable factor in bone development and connective tissue health (Martin and Bettencourt, 2018). Several potential dietary sources have been identified, but since silicon availability from foods is low, it may be prudent to increase intake from edible parts of plants via biofortification (Martin and Bettencourt, 2018), see Supplementary Table 1.

5. Integration of primary production and end-user demands

Sustainable management options for crop production are often perceived as burdensome and non-profitable by landowners and stakeholders, especially when the general public perception of climate change or a malnutrition scenario seems erroneously distant in the future. However, the actual successful marketing of novel food labels representing organically produced or vegetarian food demonstrates positively how mindful a significant proportion of the end users have become when it is about daily nutrition and the key factors driving agricultural systems. This in mind it will be necessary to demonstrate the potential ecological and economic value resulting from the optimization of biomass production on set-aside or marginal soils, from site adapted fertilization and adaptation to climate change, from the use of new tools for assessing crop performance, and from the use of by-products as valuable fertilizers. This will of course have impact on the socioeconomic indicators of the system.

As a well-established approach, field sites with crop rotations adapted to the regional markets for biomass, food and green products can aid to demonstrate success / failure of options and at the same time adjust technology readiness levels to be reported to stakeholders. With a positive attitude for farming, local products can be negotiated to end-users (food and feed) or local processing industries (fibers, biomass, etc.) to ensure small carbon footprints. It must be understood that production on marginal lands may not be profitable in the beginning, unless other ecosystem services are included in the economic analysis. The conversion of marginal soil into grasslands can stop soil degradation, increase organic carbon accumulation in a long time period, while establishment of short rotation coppice in marginal soils could stimulate soil degradation (Kazlauskaite-Jadzevice et al., 2020). In essence, the argument that marginal lands will always be marginal due to their low productivity and adverse soil conditions can be rebutted in front of the public, opening the view to novel options of soil improvement through circular bioeconomy, a local “no-waste” management strategy, and increased ecosystem services.

The estimation of multiple ecosystem services in sustainable land management for crop production can valorize the implementation of these managing strategies, demonstrating their suitability and effectiveness beyond the typically used monetary terms, as they take into account wider economic, environmental, social and cultural benefits that can be provided from the soil ecosystem. Any case, the ecosystem functions (i.e., soil conservation, C sequestration, safeguarding of drinking water, environmental quality, and biodiversity) provided can be incentives to establish more production plans for marginal lands. This in view, new options to increase the amount of food and feed production and resilience of agroecosystems to climate changes in Europe can be developed (Blanco-Canqui, 2016, Kang et al., 2013, 2018, Zhao et al., 2011, Schimmelpfennig, 2017, Newton et al., 2012).

6. Impact

Experimental data on biomass yields and other ecosystem services from the different types of marginal lands are few. Similar to the action plans connected to the agriculture 4.0 concept (Rose et al., 2021), tools have to be delivered to farmers to systematically change agricultural practices, using a combination of techniques, plants and management, aiming to increase high quality food and biomass production in a holistic approach.

A focus on plant-soil-microbe interactions in marginal lands will affect bioeconomy in the EU. Farmers will gain access to novel solutions, especially related to management of poor and degraded land and increased plant production on such sites, in an environmentally-friendly manner. Of course mixed plantations, and the inclusion of patches of perennials in degraded portions of existing croplands would create a multifunctional mosaic of perennial crops and food crops, including improved wildlife habitat and diversity, soil C sequestration, and soil and water quality, all of them contributing to the overall agricultural landscape diversification. On a regional scale the first goal should be to optimize regional selection of biofortification methods for plants, integrated nutrition chain management and more efficient distribution of

Table 1
Potential indicators and key-factors for the improvement of marginal soils. The indicators are markers of accomplishment/progress of system recovery. They represent specific, observable, and measurable accomplishments or changes in the agro-ecosystem that show the progress made towards achieving the relaunch of crop production in the given work plan. Involvement of stakeholders is advised to include practitioner's knowledge and experience.

Indicator	Measurable/quantifiable key-factor
Soil aggregation indices	Aggregate formation, soil texture, percentage of erosion protection
Soil physico-chemical properties	pH, bulk density,CEC, available forms of macro and micronutriens, traditional agronomic measure
Nutrient cycling	NPK, weathering of minerals, soil formation
CNP	Carbon/nitrogen/phosphorus contents, SOM, dynamics of sequestration
Contamination	Total and extractable contaminants (if any), against national threshold levels
Water	Water holding capacity, water retention, filtration, readily dispersible clay
Biodiversity	Diversity of species, including microbial diversity and PGPR occurrence
Crop quality	Plant health/growth/yield, pathogen attack to crops – quantify crop losses
Yields, harvest	Return of investment (for farmer, for community (estimate))
List of ecosystem services before/after the project	By counting, but also ranking services
"Value" of soil, crops, diversity	Market price, but also esthetical or environmental value
Farmer satisfaction	With type of management, within the community, with customers

water in agriculture through its more effective use by plants (Schiavon et al., 2020).

Consequently, when local food supply and security increases, citizens concern for food quality and environmental safety can be addressed by explaining the novel rationale of production. Overall, this will help to generate a sustainable income situation and increased productivity at the farm level, by using amendments of low cost (Datnoff and Rodrigues, 2005), that in principle reduce the use of pesticides, on land that had been set-aside. Many approaches have tried to qualitatively and quantitatively describe soil and site quality, and to translate soil fertility to land users and owners. Soil fertility is the capacity to support plant growth. It is the component of overall soil productivity that deals with available nutrient status, and its ability to provide nutrients out of its own reserves and through external applications for crop production. There are three main components of soil fertility: Physical, chemical and biological. The level of soil fertility results from the inherent characteristics of the soil and the interactions that occur between these three components during crop management. Thus, discussions based on field data are needed to better understand the real potential of marginal lands (Blanco-Canqui, 2016) and options of phytomanagement to improve ecosystem services and opportunities of using this land for non-food production (Burges et al., 2018). Most of the time, indicators have been defined that serve to standardize a certain status before or after a measure (Schröder et al., 2019). Improvement of sites, and movement towards circular economy can eventually be characterized by factors of soil multi-functionality to support the sustainable use of soil resources (Greiner et al., 2017) and other indicators (Drobnik et al., 2018), that ideally derive from discussions with farmers, stakeholders, and agronomists (Table 1).

7. Outlook

With view to the increasing land use conflicts, it will be of high importance to achieve common strategies to respond to global change issues of high public concern such as food, feed and fiber plants. In addition to the sustainability aspect, cost effectiveness, reliability, long-term sustainability, resilience and reasonable input of resources are characteristics of this approach that is exploiting well established as well as new technologies. Derived from indicator networks like those described above (or more elaborate ones) and from available computerized measurements, a practical toolbox addressing resilient agricultural systems should become available as an end-product,

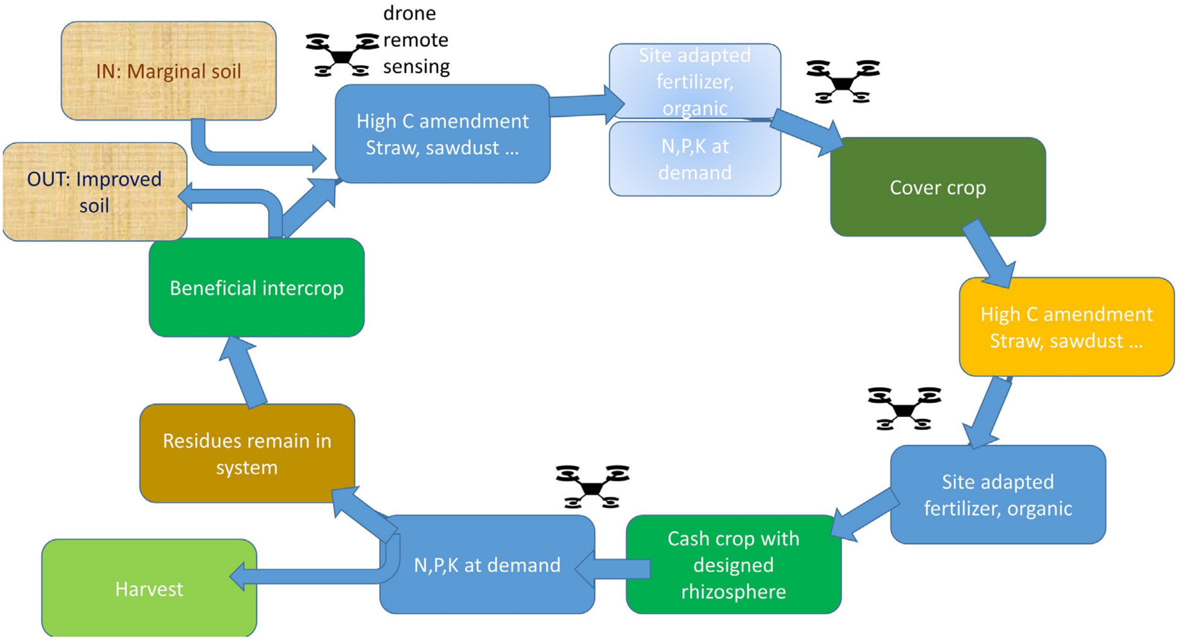

Fig. 7. Food, fodder and biomass production on re-installed soils with limited productivity. After thorough analysis, essential soil processes will be re-activated by crop rotation with favourable combinations, and by amendments of compost or green manure derived material that can be applied in a precise manner, e.g. as pellets, for that, farm residues will be incorporated to initiate soil formation: biochar, biofortifying elements and manure. In consequence, water retention will be enhanced. Future directions: select crops with special endophytes and initiate resilient rhizosphere communities.

describing sustainable intensification of agriculture under increasing stress of climate change, with a recommendation of which crop rotation to use, which amendments to apply and how to preserve biodiversity and ecosystem services, translated to national languages and distributed to farmers and stakeholders (Fig. 7). In this context, it is important to bridge the contrasting expectations connected to the use of marginal lands, to avoid the costly price of hype, overselling and disillusionment. Practitioner's involvement is of utmost importance to build constructive engagement that bases on scientific facts of soil functioning, including constant oscillation between present and future results, between present problems and future solutions. It is important to point out the underlying longer-term value of soil recovery and to attenuate unrealistic or impracticable short-term expectations (Brown, 2003).

Thus, a second, more ecology-driven toolbox with a set of advanced methods to characterize the microbiota and nutrient turnover should be produced, describing new pests and disease outbreaks and other environmental pressures, and how to improve plant health by inoculating with beneficial microbes. Such a toolbox is fundamental to forecasting the incentives and obligations that will be necessary to mobilize the necessary resources for a particular measure to be realised in the field situation.

As research agendas and data sets mature, it can also be expected that novel agro-ecology and climate problems will become more apparent and need to be solved. Much of the initial momentum and investment might still be utilized in terms of general soil improvement measures, and niche applications, which in the medium term will not entirely substitute present ways of doing and thinking about crop and soil management. In the end, good parts of valuable land would be ready for an improved new use. Perhaps grasses would be established for pasture, biomass plants would thrive, specialty crops would be cultivated or short coppice perennials would have already gained several years of growth. Overall, the system would focus on smarter agricultural management based on enhanced nutrient efficiency and resistance to pests/pathogens combined with a greener footprint. Any of these would be a great way of utilizing neglected land and transitioning it into gentle production.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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