**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, brownﬁelds, 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 microelement 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.

**Keywords:**, marginal soils, agricultural management, high carbon amendments, micronutrients, fortification, soil microbiome,

**The problem**

While by 2050 the world's population will exceed 9 billion, the area which can be used for agricultural production will shrink, as a result of global change. Besides the high demands of land for industry and urbanization also climate change and associated increases in global temperature and frequency of extreme weathering events (including prolonged drought periods, floodings and hurricanes), have resulted in serious land use conflicts, which still have to be solved. 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 (Shazad 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.

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 70­85% 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 is 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 and 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). Finally, an excess of mainly inorganic fertilizer to equalize yield will lead to nutrient leaching and new imbalances (De Clerq 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, soil contamination with persistent organic pollutants (POPs), and acidity or salinity (Fig. 1). 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).

**Insert Fig 1 (Textbox) here**

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).

Insert Fig. 1 here

**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, VonCossel 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 CO2 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. 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](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/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](https://www.sciencedirect.com/science/article/pii/S1687850714000119%22%20%5Cl%20%22bib24)). 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).

Insert Fig. 2 here

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 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.

Amending abandoned sites with farm residues or composts can enhance cost-effectiveness on a farm (Fig. 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 CO2 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%o per year, thus helping to mitigate the adverse climatic inﬂuence of anthropogenic CO2 emission (Zydelis et al. 2019, Reichel et al. 2020).

Insert Fig. 3 here

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. 2020).

Insert Fig. 4 here

Insert Fig. 5 here

**Identify and utilize key players of soil life**

Research on ecosystem stability has concentrated on the role of biodiversity for ecosystem health. However, it is increasingly recognized that rather than biodiversity per se the connectivity between key functional groups within a community is decisive (Garlaschelli et al. 2003). In agroecosystems the plant is a major driver in addition to microbes, hence also the right plant genotype needs to be considered (including for example deep rooting plants, use of catchcrops and intercropping or the use of periannual crops. Albeit of ample importance for crop yields, little work has focused on soil microbial community structure and data are difficult to link directly with biogeo­chemical processes that underpin key ecosystem functions essential for plant productivity. A major short­coming was the lack of instrumentation for proper analysis of microbial diversity. Full DNA sequen­cing has only become available recently, through elaborate technology. A second shortcoming is our lack of knowledge on microbial functional ecology, i.e. on the overlapping substrate use by so many micro­organism communities. Key soil processes proceed in high redundancy, to the plant´s benefit. Fertilizer or amendment addition to soils will undoubtedly induce shifts in microbial community structure, with short and long term effects.

Microbes are the major catalysts of nutrient turnover, and microbe-plant interactions are decisive for crop performance and health. 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). 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 et al. 2016). Thanks to their ability to secrete many enzymes, soil microbes mineralize organic nutrients, making a fraction of them available for plants. Some symbiotic microbes also contribute to water uptake or stimulate plant resistance towards pathogens (Rineau and Ladygina, 2011). On the other hand, root pathogens may display detrimental interactions with plants. In fact, soil microbial communities are characterized by their sheer richness in both taxa and functions, whether beneficial or detrimental (Bardgett and Caruso 2020). Many studies show that they seem to be largely functionally redundant as well (Nielsen et al. 2011). Disturbances causing species loss would therefore have only limited functional impact since the disappeared species can be replaced by others with a similar role (Yachi and Loreau 1999). And consequently, soil functions are expected to be quite stable: only disturbances causing a massive species loss may lead to disturbed functioning (Wei 2019). This, however, assumes that all essential soil functions are carried by a large group of species, which may not be the case. Especially so in marginal soils, where many stressors might act in concert to filter the community towards a low-diversity one (Caruso et al. 2011), soil functions may be less stable against environmental changes. We, therefore, need 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). Moreover, stimulating microbial diversity has the extra advantage of decreasing the risk of invasion by pathogen species (Van Elsas et al. 2012).

The addition of slowly degrading residues with high carbon to nitrogen ratio will stabilize physico-chemical soil structure, and when metabolically available labile C-compounds are introduced to the system, the biochemical soil properties will change. Enhanced availability of organic matter will increase microbial biomass and enzyme production and therefore promote processes related to soil organic matter decompo­sition/ mineralization/ humification. Many microbial processes are governed by the availability of organic C and N (Rineau et al. 2013, Reichel et al. 2018). When N-availability is higher than microbial demands, C will be limiting, leading to an increase in N-mineralization. Vice versa, when the available C exceeds microbial demands, N and P are the limiting factors resulting in increased respiration and net N and P immobilization. Substrate availability for these processes is modulated by clay contents, mineralogy, and soil C. If C gets scavenged in the soil matrix, microbes cannot access it to satisfy their nutritional demands, limiting microbial growth (Guimarães et al., 2013). On the other hand, if C and nutrient pools are not protected by soil structures, they are more readily available for microbial attack (Guimarães et al. 2013). This means that 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 (NUE), achieving a similar quantity of N in the harvested crop with less N-input (Zhang et al. 2015). 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 et al. 1999, Reichel et al. 2019). 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, better water availability, and yield security.

With this in mind, it becomes clear that, if our final goal is to predict soil response to given conditions and amendments, we should not only focus on microbial community structure, but also on the functions they perform. If the former has been intensely investigated in the past 20 years, the latter remains a developing field. To date, the most frequently used method to characterize microbial community structure is metabarcoding, using the 16S rRNA gene as marker for bacteria and the ribosomal ITS region for fungi (de Beeck et al. 2015). Identified reads can be assigned to microbial genera, drawing a picture of not only which ones are present but in which proportion. Some functional information can be gained by clustering OTUs into functional groups, such as symbionts (Rhizobia and arbuscular mycorrhizal fungi), saprotrophs, or root pathogens. Approaches on microbial functions are less straightforward. Diversity for specific functions (such as N mineralization) can be assessed through community-level physiological profiling (Rutgers et al. 2016). More specific functions, for example the mineralization of a given organic source, such as soil peptide material, may be followed by enzyme assays, describing potentials for activity. In small plots, rhizotrons or lysimeters, crop growth can be followed, root exudate patterns, and C-sequestration of amended vs. control plots can be recorded (Fig. 6). When PGPR are identified, this will aid to judge the potential to produce healthy plants, and we could use metadata to correlate microbial functions to parameters that can be measured by remote or proximal sensing in the field. Surveys of soil mesofauna can be used as additional indicators to assess improvements in soil functionality (Schröder 2008).

Insert Fig. 6 here

**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 (Zhou et al. 2019). Adding high carbon amendments are an important step for sustainable management of such sites. On many marginal sites micronutrients are a growth limiting factor 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. 2021).

Agronomic options to enhance product quality 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). Accordingly, Pompano and Boy (2020) 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 and CVD (cardiovascular disease) related to both glycemic control and lipid metabolism (Pompano and Boy 2020).

To date supplying staple crops with micronutrients is standard in some regions (Welch and Graham 2004, Dimpka 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). 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).

**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 2020). It is estimated that at the global scale, even 50% of wheat is cultivated on soils with low 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).

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. 2015). 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).

**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 Se6+ (selenians). Soils with neutral and acidic reaction are dominated by selenites (Se4+) 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. 2020). 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 (Alfthahn 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. 2018).

**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 (Conolly 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).

**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. 2020), 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.

**Si** - silicon amendments are known to enhance plant resistance to stressors such as drought and pathogen attacks (Vaculik 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, 2013) 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](http://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 (SiO2 - 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. 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 CO2 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 via biofortification of edible parts of plants (Martin and Bettencourt 2018), see supplementary Table 1.

**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 et al. 2016, Kang et al. 2018, Schimmelpfennig 2017, Newton et al. 2012).

**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 poor, degraded or polluted land management and increased plant production, 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, and more efficient management of 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 its 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 (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 toward 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 (Tab.1).

Insert Table 1 here

**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, 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. Practicioner´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).

Insert Fig. 7 here

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 mobilise 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. Any of these would be a great way of utilizing neglected land and transitioning it into gentle production.

**Acknowledgement:** All authors are partners in the BioFoodOnMars Project funded by the EU-FACCE-JPI. Authors are grateful for the financial support obtained from the national funding organizations, and for the support by the FACCE-office.

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