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Research Article

Sustainable intensification of agricultural production: a review of four soil amendments

Nachhaltige Intensivierung der landwirtschaftlichen Produktion: ein Überblick vier verschiedener Bodenzusätze

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Summary

Dwindling natural resources, growing population pressure, climate change, and degraded soils threaten agricultural production. In order to feed the growing world population, we have to develop strategies to sustainably intensify current agricultural production while reducing the adverse effects of agriculture. Currently, a number of amendments have come into focus for improving structure and fertility of soils. Zeolites, biochar (BC), lime, and nitrification inhibitors (NIs) are reviewed for their properties. Zeolites and BC share many characteristics, such as a high cation exchange capacity (CEC), high specific surface area, and high porosity. Lime, on the other hand, works above all through its buffering capacity and can improve aggregate stability. Although the latter amendments change soil physicochemical characteristics, NIs do not act on soil properties but constrain a chemical/enzymatic reaction directly. These amendments are potential strategies to mitigate ongoing soil degradation and to secure soil fertility, under the global challenges. While the ecological effects of these soil amendments are studied intensively, the extent to which they can contribute to sustainable intensification is not fully explored. We want to contribute to the debate by providing an overview that seeks to integrate ecological evidence with the agronomic perspective.

Keywords: soil health, climate change, food security, environmental protection, nitrogen cycling

Zusammenfassung

Schwindende natürliche Ressourcen, steigender Druck durch Bevölkerungswachstum, der Klimawandel und degradierte Böden gefährden die landwirtschaftliche Produktion. Um die wachsende Weltbevölkerung zu ernähren, müssen wir Strategien entwickeln, um die landwirtschaftliche Produktion nachhaltig zu intensivieren, dabei aber gleichzeitig die negativen ökologischen Auswirkungen der Landwirtschaft verringern. Zurzeit fokussieren Bemühungen für die Verbesserung der Bodenstruktur und -fruchtbarkeit auf Zusätze wie zum Beispiel Zeolite. Hier werden vier solche Zusätze – Zeolite, Biokohle, Kalk und Nitrifikationsinhibitoren – vorgestellt. Zeolite und Biokohle sind insofern ähnlich, als beide über eine hohe Kationenaustauschkapazität, eine hohe spezifische Oberfläche und eine hohe Porosität verfügen. Kalk hingegen wirkt durch seine hohe Pufferkapazität pH-regulierend und kann Bodenaggregate stabilisieren. Während die vorhin genannten Bodenzusätze auf die physiko-chemischen Parameter der Böden wirken, wirken Nitrifikationsinhibitoren selbst nicht direkt auf Bodeneigenschaften, beeinflussen aber direkt eine chemische/enzymatische Reaktion. Der Einsatz dieser verschiedenen Zusätze ist eine mögliche Strategie, um die voranschreitende Bodendegradation hintanzuhalten und die Bodenfruchtbarkeit in Anbetracht der oben erwähnten globalen Herausforderungen zu erhalten. Während die ökologischen Effekte dieser Zusätze intensiv untersucht werden, wird die agronomische Perspektive vernachlässigt. Ohne diese ist allerdings eine Abschätzung des Beitrags dieser Zusätze zu einer nachhaltigen Intensivierung der Landwirtschaft nicht möglich. Dieser Artikel möchte einen Überblick über ökologische Auswirkungen geben und einige agronomische Erwägungen zur Diskussion stellen.

Schlagworte: Bodengesundheit, Klimawandel, Ernährungssicherheit, Umweltschutz, Stickstoffkreislauf

1. Dwindling natural resources, a growing population and climate change: the need for sustainable intensification of agricultural production

We face more challenges than ever, such as climate change, key nutrient elements peaking, and an ever-growing world population; but the boundaries of our planet remain unchanged. With more than 9 billion people to feed by 2050 (UN DESA, 2015) and to provide energy for, we urgently need to render the ways we use natural resources more sustainable. The past strategy of simply expanding the agriculturally used area is only possible to a very limited extent as fertile soils are becoming increasingly scarce. Therefore, we will have to sustainably intensify production on land that is already under cultivation (Figure 1). In the context of agriculture, other aspects of sustainable intensification are protecting or regenerating natural resources (Pretty, 1997) and increasing the provision of environmental services while reducing adverse effects (Garnett and Godfray, 2012; Schiefer et al., 2016). The way in which the authors use "sustainable intensification" is broader than "ecological intensification". The Food and Agriculture Organization of the United Nations (FAO), for example, defines ecological intensification as "a knowledge-intensive process that requires optimal management of nature's ecological functions and biodiversity to improve agricultural systems performance, efficiency and farmers' livelihoods" (FAO, 2013). While ecological aspects are stressed in this definition, economic and especially social aspects are underrepresented. In search for a more holistic term, the authors prefer to use sustainable here instead of ecological, because "sustainable" encompasses not only ecological soundness but also economic affordability as well as social acceptability (Becker, 1997).

Intensive agricultural systems are characterized by a higher resource input than extensive systems, but this type of intensification is often accompanied by focalization on few crops or even monocultures and by heavy use of fertilizer and pesticide (Figure 1). This, in turn, reduces soil biodiversity and threatens ecosystem functions in the long run. A more ecological approach seeks to keep soil biodiversity high, reduce nutrient losses from the system, and improve nutrient use efficiency rather than simply increasing the amount of nutrients supplied externally (Figure 1).

Proper ecosystem functioning is suggested to rely on a subset of basic organisms, such as fungi, bacteria, and soil fauna, with no further impact by increasing numbers of organisms. This might be due to some functional redundancy among species. However, this hypothesis is currently under debate (Nielsen et al., 2011; Bender et al., 2016). Reductions in soil biodiversity can have strong consequences on ecosystem functions. Soil microorganisms have many functions, such as soil aggregation, carbon sequestration, organic matter decomposition, or nutrient cycling, as well as nutrient supply to plants. The often alarmingly low biodiversity in intensive agricultural land use systems compared to natural ecosystems could have resulted in species losses or functional groups that are crucial for ecosystem functioning (Tuck et al., 2014; Tsiafouli et al., 2015; Bender et al., 2016).

Water resources are decreasing; inputs such as mineral nutrients, in particular phosphorus, are limited. Farmers are under enormous economic pressure to intensify production, but also work in an environmentally friendly manner. Past unsustainable intensification methods have already caused degradation, for example, on soils whose quality is key for agricultural production. Soil degradation includes several phenomena such as acidification, erosion, salinization, and contamination (FAO, 2015). We urgently require new, better adapted strategies for sustainable land management and optimization of production processes. Here, we will compare different amendments that can serve to improve soil structure and fertility and give an overview of the underlying mechanisms. While we will focus on environmental aspects, we strongly advocate for equally taking economic and social constraints and implications into account when considering interventions in agriculture.

2. Challenges in agriculture today: inefficient fertilizer use, soil compaction, and pest and disease control

Agriculture does not only suffer from environmental challenges such as water scarcity, decreasing soil fertility, and climate change, but it also adds to environmental problems, for example, by inefficiently using fertilizers. This can lead to nutrient leaching and greenhouse gas (GHG) emissions. Global inorganic fertilizer consumption has quadrupled in the past 50 years (FAO, 2011). The majority of this, nearly 70%, is lost from the production systems. By 2050, the use of nitrogen fertilizers is expected to double once more, further spurring environmental pollu-

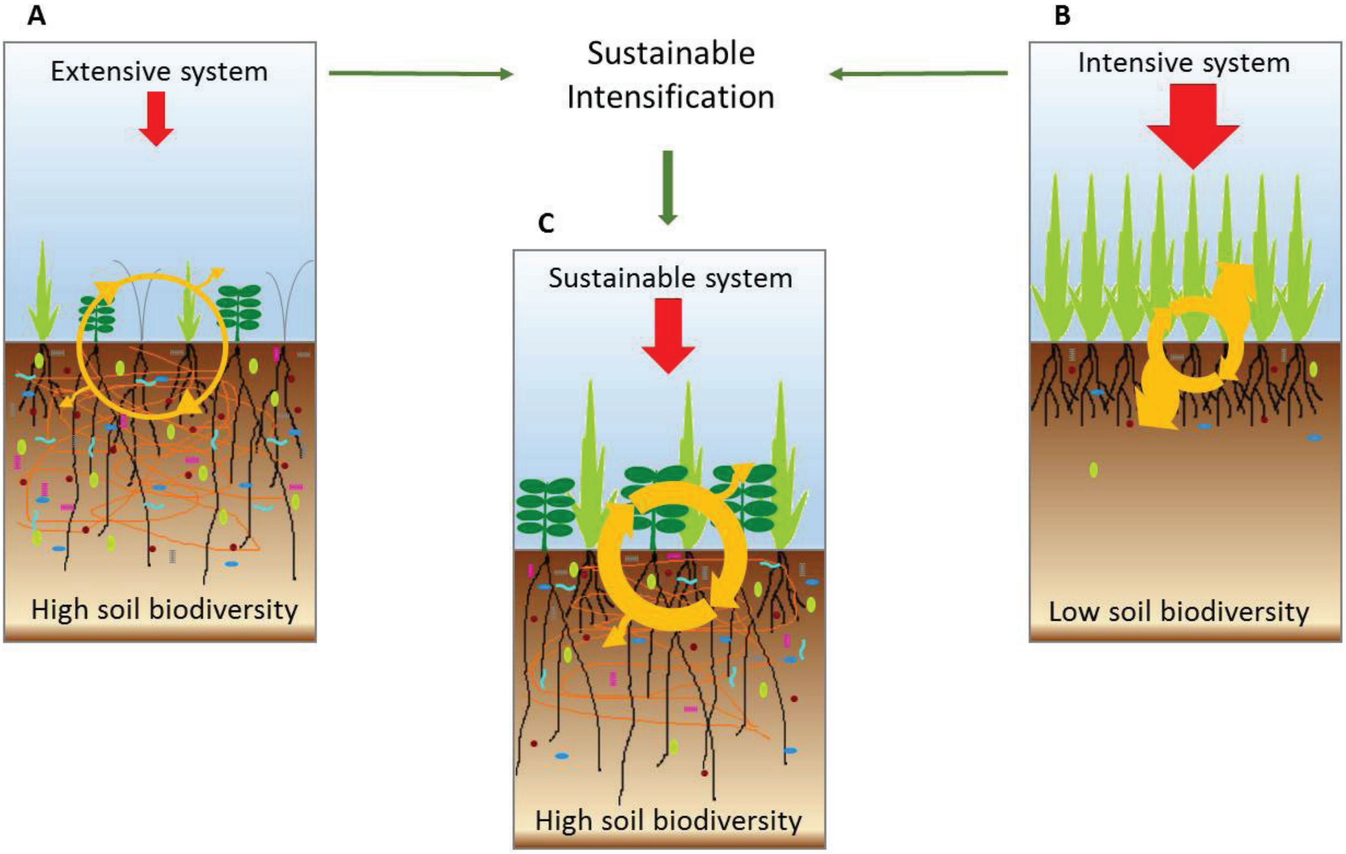

Figure 1. Management intensity and regulatory processes by soil biodiversity (modified from Bender et al., 2016). Arrows indicate the relation of resource inputs, losses, and soil regulatory processes conducted by soil microbes. (a) The extensive system is characterized by low resource inputs and losses and shows rich soil life, a high rate of internal regulatory processes, and low production. (b) The intensive system is characterized by high resource inputs and outputs and has a depleted soil life, a low rate of internal regulatory processes, but high production. (c) Ecological intensification in the ideal case integrates traits of both systems and leads to a sustainable system that is characterized by moderate resource inputs and has a rich soil life, a high rate of soil regulatory processes, low nutrient losses, and high productivity.
Abbildung 1. Managementintensität und regulatorische Prozesse durch Biodiversität im Boden (modifiziert nach Bender et al., 2016). Pfeile zeigen die Zuführung von Ressourcen und das Ausmaß von Verlusten und Bodenregulationsprozessen, die von Bodenmikroben durchgeführt werden. A) Das extensive System zeichnet sich durch geringe Ressourceneinträge und -verluste aus und zeigt eine reiche Bodenlebensdauer, eine hohe Rate an internen Regulierungsprozessen und eine geringe Produktion. B) Das intensive System zeichnet sich durch hohe Ressourceneinträge und -verluste aus und weist ein erschöpftes Bodenleben, eine geringe Rate an internen Regulierungsprozessen, aber eine hohe Produktion auf. C) Ökologische Intensivierung im Idealfall integriert Merkmale beider Systeme und führt zu einem nachhaltigen System, das sich durch moderate Ressourceneinträge auszeichnet und ein reichhaltiges Bodenleben, eine hohe Rate an Bodenregulationsprozessen, geringe Nährstoffverluste und hohe Produktivität aufweist.

tion (Galloway et al., 2008). Nitrification is the dominant process in N cycling in typical aerobic agricultural systems. Its product, nitrate, is the main form in which plants take up N from their environment. While previous agricultural systems have more heavily relied on animal manure and N_2-fixing plants as N sources, the high-input systems that developed in the past century in the Global North have promoted nitrifying conditions. Modern fertilizer application is governed by timing, rates, and specific procedures. Often these practices go hand in hand with limitations of human labor and economic cost, reducing the practicability of these measures. While adding nitrogen fertilizer is key to achieving high yields, it also contributes to GHG emissions (through N_2O losses into the atmosphere) and to the eutrophication of water resources (through NO_3^- leaching). A central question is whether we can reduce or optimize the use of nitrogen fertilizers and thus reduce nitrous oxide emissions without sacrificing the yield (the so-called "climate-smart agriculture," FAO, 2013; Dahlin and Rodríguez-Iturbe, 2016).

Besides leading to GHG emissions, intensive farming and its enormous use of nitrogen fertilizers also depletes base cations and, hence, acidifies soil (Anderson et al., 2013; Tian and Niu, 2015), which in turn hampers soil fertility. Soil acidity affects soil processes by altering activities of microorganisms, thus changing organic matter decomposition, nutrient mineralization, and immobilization (Haynes and Swift, 1988; Fageria and Baligar, 2008).

Increased mechanization in agriculture and forestry has resulted in more compacted soils. This negatively affects plant growth and reduces the stability of aggregates and coarse pores, which in turn diminishes water and air permeability, root space for plants, and nutrient transport and drastically restricts the habitat of soil organisms (Frey et al., 2009; Hartmann et al., 2014; Cambi et al., 2015). As the permeability of the upper soil decreases, surface drainage, soil erosion, and nutrient leaching are increased. This can lead to long-term and permanent damage, resulting in yield losses and reduced ecosystem performance.

Intensive monoculture cropping and changing climate may also have strong consequences on pest control, and its implications on soil functioning need to be considered. Agriculture is already suffering from more and more frequent storms and extreme weather events, which endanger the safety of crops and the planning of cultivation.

3. Improving soil structure and fertility and reducing GHG emissions with additives: lime, zeolites biochar, and nitrification inhibitors

To improve soil structure and fertility, several soil additives such as lime, zeolites, biochar (BC), and nitrification inhibitors (NIs) are being used. These were shown to have beneficial effects on soil properties and plant yield, and some may also be useful in reducing GHG emissions. An overview is given in Table 1.

3.1 Lime: regulating soil pH and improving soil permeability

Lime is used as a soil amendment to counteract acidification, to increase permeability, and to modify aggregate stability. Lime causes clay flocculation and thus improvement of soil structure and hydraulic conductivity. It has beneficial effects on earthworm activity and macroporosity. This has consequences for vegetation cover as well as C and N in soils: because of better crop growth, more crop residues could remain in the soil and enhance soil organic carbon (SOC).

Permeability to allow for water and air flows is an important feature of soils. If soil permeability is impaired, crusts are likely to develop at the soil surface, leading to soil capping, hindering water transport, and indirectly favoring erosion. To improve the permeability of the soils, polyvalent ions such as Ca^{2+}, including quicklime/burnt lime (CaO) and finely ground limestone powder ($CaCO_3$), can be supplied as soil additives (Becher, 2001). How effectively liming material acts is largely determined by how fast the respective amendment can be solubilized (Holland et al., 2018). Besides the material's reactivity, its particle size, soil temperature, and moisture are important. Quicklime and hydrated lime ($Ca(OH)_2$) react much faster than limestone because the solubility product is three orders of magnitude larger for CaO and $Ca(OH)_2$ than for $CaCO_3$ (Haynes, 2013). While this is advantageous from the ecological point of view, there is an economic drawback to using quicklime and hydrated lime: both are more expensive additives than limestone powder.

Soil acidification can pose a serious threat for agricultural production. Besides wet and dry deposition, ammonium-based fertilizers, urea, and the presence of elemental sulfur contribute substantially to soil acidification. To a lesser extent, root exudates, legume growth, and the mineralization of organic matter can acidify soils (Goulding et al., 2016). Acidification leads to loss of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+), accumulation of H^+ and Al^{3+}, and dissolution of first Mn and later also Fe minerals. As Al^{3+} concentrations rise, the element's toxicity impairs crop yields. Low pH also hampers phosphorus availability to plants. Lime amendments increase the pH and are widely used to mitigate the effects of soil acidification, diminishing Al^{3+} toxicity and ameliorating phosphorus uptake through increasing mineralization (Holland et al., 2018). Soil structure and organic matter content determine how much of the amendment is needed to mitigate acidification: while soils with high clay content necessitate the application of high amounts of lime, soils with high organic matter content require less lime to counteract acidification. The most common amendments are limestone and dolomite, which not only resupplies Ca^{2+} but also Mg^{2+}; less frequently, quicklime, hydrated lime, and natural shell sands are also being applied (Holland et al., 2018).

Table 1. Combining global challenges and impacts on the soil ecosystem. By adding soil amendments (biochar, BC; zeolite, Z; lime, L), soil physical/chemical characteristics are improved to mitigate the challenges and improve the soil functions.
Tabelle 1. Kombination von globalen Herausforderungen und deren Auswirkungen auf das Ökosystem Boden. Durch den Einsatz von Bodenzusätzen (Biokohle, BC; Zeolith, Z; Kalk, L) werden die physikalischen/chemischen Bodeneigenschaften verbessert, um die Herausforderungen zu mildern und die Bodenfunktionen zu verbessern.

Challenges	Impacts	Functions	Soil characteristics	Amendments
Scarcity of fertile land	Degraded soils Compacted soil	Soil aggregation (+) Soil aeration (+) Infiltration rates (+) pH of acidic soils (+) C-sequestration (+) Soil erosion (–)	High specific surface area High porosity Liming of acidic soils CEC Flocculation Polymerization	BC, Z BC, Z BC, L BC, Z L L
Water increasingly scarce	Degraded soils Desertification of soil Reduced crop yield	Stress resilience against desiccation (+) Improve water-holding capacity and capillarity (+)	High specific surface area High porosity CEC	BC, Z BC, Z BC, Z BC, Z
Inefficiency of fertilizer use	Degraded soils Overfertilization	Reduce leaching (sorption) (+) Improve nutrient supply to plants (+) crop yield per resource (+)	High specific surface area High porosity CEC Buffer capacity	BC, Z BC, Z BC, Z L
Reduce greenhouse gas emissions	Compacted soil	Nutrient immobilization Increased nutrient use efficiency (+) Improve soil aeration (+)	High specific surface area High porosity CEC Molecular sieve Flocculation	BC, Z BC, Z BC, Z Z L
Contaminated land	Contaminated soils	Detoxification (+) Sorption (+) Immobilization (+)	High specific surface area High porosity CEC Molecular sieve Buffer capacity Declined solubility of metals in soil solution	BC, Z BC, Z BC, Z Z L L

The short-term effect of liming is suggested to increase soil biological activity, and hence labile C forms, that can be used by microbes (Biasi et al., 2008), or indirectly by changing the community structure (through pH), to groups with lower carbon use efficiency. These respire more CO_2 per unit carbon that they take up (Keiblinger et al., 2010), resulting in higher CO_2 emission rates (Fornara et al., 2011). However, regarding higher soil biological activity upon lime application, it should be noted that especially quicklime can also be used for disinfection because of the rapid pH increase that it induces. This practice is commonly applied, for example, in the treatment of wastewater and biosolids (Smith et al., 1998).

In order to investigate the short- and medium-term effects of lime additives, a greenhouse pot experiment was carried out. While application of 2,000 kg/ha of CaO significantly and instantaneously increased soil aggregate stability, the addition of $CaCO_3$ failed to affect soil aggregates (Keiblinger et al., 2016). This effect of quicklime was more efficient for soils with high clay content and cation exchange capacity (CEC), making quicklime application a valid option to improve the aggregate stability of fine-textured agricultural soils (Keiblinger et al., 2016). The effects of lime on physical characteristics of soil such as soil aggregate stability, clay dispersion, infiltration rates, water retention, and hydraulic conductivity are discussed controversially in literature. Reported detrimental effects seem to be related to application rates and time: while low application rates initially affected these parameters adversely within the first months after application, positive effects on soil physical properties were observed after half a year (Andry et al., 2009). High application rates were more effective in improving soil physical properties, without initial negative effects (Andry et al., 2009).

The pH increase upon lime application affects soil N transformation rates. In general, liming promotes N fixation by the soil microbial community (Holland et al., 2018). The effects on N mineralization are less clear-cut. N mineralization has been reported to increase, decrease, or remain unchanged (Bailey et al 1995; Kemmitt et al., 2006; Wachendorf et al., 2015) but probably ameliorates with repeated lime applications (Holland et al., 2018); however, if augmented, also availability for plant uptake increases and crop yields can benefit correspondingly, but N losses via nitrate leaching into groundwater can be spurred, especially in the absence of corresponding plant uptake and upon excessive rainfall (Holland et al., 2018). Liming was shown to reduce N_2O emissions, but increased NH_3 and CO_2 emissions counteract this positive effect and render liming questionable as a GHG emission reduction strategy (Sommer and Ersbøll, 1996; Kunhikrishnan et al., 2016; Holland et al., 2018). Lime application can also induce nitrification and thus reduce lime's buffering effect (Meiwes, 1995); as a consequence, soil nitrate concentrations increase with lime application rates and time (Fuentes et al., 2006). For an overview of the effect of lime amendment to soils, refer to Table 1.

3.2 Zeolites: reducing GHG emissions and increasing N fertilizer efficiency

Zeolites chemically belong to the group of alumosilicates and are of natural volcanic origin. They belong to the most common minerals in sedimentary rocks and have a microporous structure. Their internal surface can span several hundred square meters per gram of zeolite (Ramesh and Reddy, 2011). The micropores of zeolites function as a molecular sieve—it can retain molecules that are small enough to enter the pores—and zeolites can act as cation exchangers (Table 1). Zeolites are widely used to purify water, as catalysts and sorbents in the chemical industry, and as soil amendments in agriculture.

The major building blocks of zeolites are crystalline tetrahedrons of $[SiO_4]^{5-}$ and $[AlO_4]^{4-}$ (Jha and Singh, 2016). The ratio of Al/Si and the resulting charge imbalance in the structure of the respective zeolite determine the ion-exchange capacity and potential acidic sites (Ramesh and Reddy, 2011). Zeolites are classified according to morphological characteristics, chemical composition, crystal structure, effective pore diameter, or natural occurrence. Natural zeolites are often contaminated by other minerals, metals, or quartz, which limits their use to applications that tolerate reduced purity, for example, agricultural use. While synthetic zeolites are of higher purity than natural ones, their elevated price can render their use economically challenging for farmers. Currently, one research focus lies on developing cost-effective and ecologically friendly amendments that can increase crop yield at the same time as reduce nutrient leaching.

Both natural as well as synthetic zeolites are used as soil amendments and can improve soil quality immensely (Jakkular and Wani 2018). The high CEC of zeolites is particularly useful for improving nutrient supply to plants: crop yields should respond positively and nutrient efficiency should be promoted. In addition, zeolites can be used to adsorb toxic metals or pesticides (Eroglu et al., 2017). Zeolites show a two- to threefold higher CEC than other soil minerals. The high CEC of zeolites is crucial for potential reduction of N losses from agricultural fields, because one of the principal N-containing molecules formed after fertilizer hydrolysis in the soil is the positively charged ammonium ion (NH_4^+). Retarding or preventing the biotical or abiotical transformation of NH_4^+ into more mobile anionic molecules such as NO_2^- and NO_3^- or into harmful gaseous species (NH_3, NO_x, and N_2O) is essential for reducing N losses and increasing fertilizer N-use efficiency (Ferretti et al., 2017). The mitigation potential of zeolites for soil NH_3 emissions is known to be very high because NH_3 volatilization is a physical process that can be reduced if NH_4^+ ions are "physically protected" (e.g., within a mineral lattice). Natural clinoptilolite zeolite as amendment to soils has been described to reduce respiratory activity probably because of the adsorption capacity of zeolites for CO_2 (Muhlbachova and Simon, 2003).

Zeolites do not only optimize the effective nutrient availability or the reduction of nutrient losses but can also improve water use efficiency (Ferretti et al., 2018) in the soil as well as soil ventilation. Zeolites are being developed as fertilizers to amend N forms such as NH_4^+ or slurry that has previously been incorporated into the zeolite. These fertilizers are suggested to slowly and continuously release N to the plants, thus reducing fertilization costs, with environmental benefits as mentioned above. These charged zeolites have also been reported to decrease soil CO_2 and N_2O emissions but to release more NH_3 and NO_x into the atmosphere than unamended zeolites or soils (Ferretti et al., 2017). If soil was amended with pure zeolite, the emissions of all these gaseous species were reduced. However, considering the N amount applied, there was even a reduction in GHG emissions for the charged zeolite compared to control soil; hence, zeolite can play a valuable role in GHG mitigation and fertilization efficiency (Ferretti et al., 2017). Charged zeolites (that are treated with pig slurry/manure) contain large quantities of N that is readily available to be immobilized into the microbial biomass (Ferretti et al., 2018). In addition, charged-zeolite amended soils show high NO_3^- concentrations after a few days of incubation, which indicates the formation via accelerated nitrification. Eventually, oxidative processes are caused by the increased soil porosity and aeration as well as available substrate foster nitrification (Table 1). However, high NO_3^- concentrations in soils together with high soil moisture conditions caused by heavy rainfall events or intensive irrigation facilitate N losses from the ecosystem. These losses either occur via NO_3^- leaching or as N_2O losses via denitrification under more reductive conditions (Ferretti et al., 2018). In agricultural use, zeolites have been shown to ameliorate water use efficiency as well as water-holding capacity. Infiltration can be improved as the porous structure of zeolites and the resulting capillary suction act as wetting agents. Through decreasing run-off, there is a positive effect on erosion. As water-holding capacity increases, so does the tolerance to desiccation stress (Mumpton, 1985).

The high sorption efficiencies of zeolites also make them potent carriers for herbicides, pesticides, and fungicides (Ramesh and Reddy, 2011). Slow-release synthetic zeolite-bound Zn and Cu fertilizers have been shown to reduce Cd accumulation in crops, highlighting the potential of zeolites to reduce heavy metal contamination (Puschenreiter et al., 2003).

Natural zeolite has been shown to decrease the nitrification due to high sorption of NH_4^+ (Nguyen and Tanner, 1998, Torma et al., 2014); however, a charged zeolite with high loads of NH_4^+ has been shown to increase NO_3^- concentrations (Ferretti et al., 2018), indicating that the desired nitrification slowing effect of zeolites needs to be carefully calibrated in accordance with slow-release fertilization.

3.3 Biochar

Recently, BC has become another organic amendment of increasing interest also for temperate soils (see Table 1). BC is charcoal that has been produced through pyrolysis from biomass but not from other sources such as landfill wastes or other nonbiological materials. In order to be sustainable, BC production needs to focus on wastes or by-products of other processes such as crop residues, wood chips, cooking wastes, and other similar sources. Feedstocks for BC production should be locally available.

A number of field and pot trials have shown that the unique properties of BCs can enhance the productivity of various crops (Asai et al., 2009; Major et al., 2010; Vaccari et al., 2011) by increasing fertility of the soil. However, the benefits of BC regarding fertilization must be differentiated according to climatic and soil chemical conditions: a meta-study by Jeffery and colleagues has found BC to increase crop yields in tropical soils, on an average, by 25%, whereas there was no such effect in soils in temperate climates (Jeffery et al., 2017a). The study suggests to use BC for fertilization purposes in tropical climates, where soil pH and input use are generally lower than in temperate latitudes, and to concentrate on other positive effects of BC, such as GHG emission reduction and optimizing fertilizer cost, in temperate soils with moderate pH and higher fertilizer abundance.

BC enhances soil fertility by raising soil pH, CEC, and buffer capacity (Lehmann et al., 2003). In addition, BC improves soil physical structure (Chan et al., 2007) and increases soil microbial biomass and nutrient availability (Steinbeiss et al., 2009). BC increases water-holding capacity and water availability (Lehmann et al., 2011) and functions as a microbial habitat (Ameloot et al., 2013), which can further add to amelioration of soil upon BC application. The double face of biochar as potential nutrient supplier, on the one hand, and as competitor for nutrient binding at the biochar surface, on the other hand, make its use challenging. It is necessary to find a balance between binding nutrients to reduce leaching and releasing nutrients slowly to ensure constant fertilization. In addition, BC can bind metals at its surface. This is especially interesting if heavy metal contaminants have to be bound for detoxification purposes (Soja et al., 2018).

BC can sequester carbon and is, therefore, under consideration to mitigate climate change (Lehmann et al., 2011). In addition, several hypotheses could help to investigate and evaluate the potential of BC to reduce GHGs: (i) BC has a porous structure. On the one hand, this could be beneficial. BC could be mixed with fertilizer to develop slow-release fertilizer mixtures, ensuring constant fertilization with less input. Thus resource use efficiency could be increased and input requirements decreased, which would be beneficial from an agronomic as well as from an ecological point of view. Of course this only holds true if the BC is produced locally, whenever possible as a by-product, for example, of cooking (for an article on BC-producing stoves, see Whitman et al., 2009), and if BC production does not compete with other resource uses. Also nitrogen compounds are able to enter the pore. This can decrease the availability of nitrogen for nitrification and denitrification processes by microbial organisms in soil (Van Zwieten et al., 2014). Yield increases upon BC amendment have been reported to derive from a moderate fertilization effect of BC but especially from a reduction in N immobilization (Jeffery et al., 2017b). In addition, the pores provide a habitat for microbial growth and activity that can immobilize available nutrients; (ii) BC can increase the pH of acidic soils and this allows denitrifying microorganisms (Wang et al., 2013; Harter et al., 2014; Van Zwieten et al., 2014) to promote complete denitrification (Cayuela et al., 2013, 2014). The reduction of N_2O losses with BC application has been attributed to the pathway of total denitrification to N_2 (Cayuela et al., 2013). While complete denitrification to N_2 would reduce N_2O emissions, this reduction is beneficial from an ecological perspective, but the still occurring N_2 loss would be detrimental from the economic perspective. In order to be sustainable, BC amendments and use would have to be optimized to balance these effects.

An increased soil pH might also lead to more ammonia release into the atmosphere, thereby contributing to agricultural air pollution, (iii) depending on soil texture, BC can reduce the soil density and improve its porosity (Quin et al., 2014), reduce the anaerobic microsites for denitrification processes and improve oxidative processes such as microbial CH_4 consumption (Schimmelpfennig et al., 2014). BC can mitigate methane emissions from agricultural activity; however, this effect depends on the management scheme and the pH of the respective soil. While BC application reduces methane emissions of acidic soils and flooded or periodically flooded land such as rice paddies, no such effect could be found for land that exhibits more neutral or alkaline conditions and that is not flooded during crop cultivation (Jeffery et al., 2016). Under these conditions, a reduction in methane oxidation potential was described for arable upland soils. (iv) GHGs such as N_2O and CH_4 were shown to be able to bind to the surface of BCs (Van Zwieten et al., 2015).

3.4 Nitrification inhibitors

While lime, zeolites, and BC influence physical as well as chemical characteristics of soil, the last amendment that shall be discussed in the present article works exclusively on a chemical/enzymatic basis. NIs affect the biological reactions that regulate the conversion of ammonium to nitrate. Several natural and synthetic NIs exist, but only a small number of biological NIs has been identified and characterized in detail. Biological NIs are secreted by plants in the rhizosphere to improve N use efficiency (Subbarao et al., 2015). The best-known synthetic NIs on the market are dicyandiamide (DCD) and 3,4-dimethyl-1H-pyrazole phosphate (DMPP). Nitrapyrin is less common than DCD or DMPP. A major drawback of NIs is that they are biodegradable and thus need to be reapplied in regular intervals. Additionally, their action is limited to the sites of nitrification, further adding to their cost ineffectiveness. However, N losses via nitrification are not only of agronomic value, but they also contribute to environmental pollution. The inhibition of N losses in form of N_2O emissions as well as of NO_3^- leaching is influenced by several parameters, such as soil texture, temperature, and water abundance by precipitation or irrigation (Misslebrooket al., 2014) and this complexity keeps efficient NI use from being straightforward. Limited availability and potential negative effects on beneficial soil microbes further add to complexity in NIs application.

DMPP inhibits the conversion of NH_4^+ to NO_3^- by microbial ammonium monooxygenases by competing with the substrate for binding to the enzymes' active sites (Marsden et al., 2016). DCD, on the other hand, is believed to act as copper chelator of the enzymes active in ammonia oxidation or impairs the uptake or use of ammonia (Chen et al., 2015). Their different modes of action are likely responsible for the discriminate efficiencies of inhibition. DMPP shows a similar or even better inhibitory effect at lower application rates (with about 1/25 to 1/2 the amount compared to DCD, Weiske et al., 2001). While a recent meta-study of both inhibitors shows that DMPP is in some cases not as efficient as DCD, as indicated by higher NH_4^+ leaching, methane emissions, and crop yields (Yang et al., 2016), it is worthwhile to note that DCD as NIs has been withdrawn from the market in New Zealand after traces were found in milk (The Australian Dairy Farmer, 2013). These contaminations may be due to DCDs' high water solubility and mobility in soil and subsequent uptake by plants and propagation within the food chain (Zerulla et al., 2001). While the concentrations that were found were considerably lower than the recommended acceptable daily intake that European regulations allow and can be deemed safe, such findings surely hamper consumer acceptance.

A study conducted in the United Kingdom found only a reduction in N_2O levels, but no yield increase or reduction in NO_3^- leaching (Misslebrook et al., 2014). Corroborating, a review of sites in Germany could not find significantly higher yields with NIs (Hu et al., 2014), except for one site with higher precipitation: here yields rose and nitrate leaching decreased upon NIs application. Similar to other amendments, the action of NIs also appears to depend on environmental conditions. Hu and colleagues further reported that NIs application could help to maintain high yields while reducing fertilizer. In addition, it allows for a larger flexibility of fertilizer application without N losses. This can be especially advantageous as climate change will be accompanied by more frequent droughts and heavy precipitation events (Hu et al., 2014).

There is potential for NIs application in combination with fertilizers and also with other soil amendments such as BC. While BC can bind gases such as N_2O and CH_4, also higher N_2O emissions were found after the application of BC to soils. This is suggested to result from biotic processes of ammonia oxidation and nitrifier denitrification (Sánchez-García et al., 2014). Higher gross nitrification rates in BC-amended agricultural soils (Prommer et al., 2014) as well as higher abundances of ammonia-oxidizing communities support the nitrification-based increase in N_2O emission rates. The liming effect of BC can also provide favorable condition for soil nitrifiers (Prosser and Nicol, 2012). The use of NIs can overcome the problem of elevated N_2O emissions by BC application with the beneficial side effect of reducing NO_3^- leaching potential.

BCs sorption capacity and, hence, the potential efficiency of NIs resulted in greater sorption of DMPP for BC pyrolyzed at lower temperature. This is likely to be related to hydrophobic interactions, as hydrophobicity generally decreases with increasing pyrolysis temperature (Zornoza et al., 2016). The increased sorption of DMPP after BC application may be caused by the hydrophobicity of the BC samples (Keiblinger et al., 2018). Also the organic C (OC) content is influenced by pyrolysis temperature, and sorption and OC were also positively correlated.

Further research is needed to determine economically viable conditions for NIs and compare to alternative strategies for improving fertilizer and water use efficiency. This will allow to minimize costs while maximizing positive effects on food security and reducing detrimental environmental effects.

4. Conclusion

Intensification can be agronomically favorable but ecologically detrimental, or vice versa. In order to work sustainably, a differentiated approach is needed to identify strategies that combine economic viability with ecological soundness. The same applies to soil amendments whose effects need to be considered from an ecological as well as an agronomic perspective.

Here we provided an overview of four soil amendments: lime, zeolites, biochar, and NIs. Lime has been used for considerable time as a soil amendment. It counteracts acidification, increases permeability, and acts on several other soil parameters. Lime amendment exists in several forms, some of which can be procured at relatively low cost, especially compared to other treatments that came into focus more recently. An important feature of lime is the pH-stabilizing effect, N fixation, and promotion of plant uptake and also GHG emissions can be increased. Biochar and zeolites are porous amendments with high CEC. Both improve the nutrient supply to plants and water-holding capacity and contribute to reducing heavy metal contamination in and GHG emission from soils. While BC improves crop yields in tropical, more acidic soils, the primary effect in temperate soils is to reduce GHG emissions and fertilizer cost. BC holds considerable potential for economically viable procurement if it is produced locally, or even as a by-product of other processes. Synthetic zeolites are a more expensive option, which in turn often represent an economically challenging investment. While natural zeolites are of lower purity than synthetic ones, they can be of agronomic value and provide environmental benefits. NIs directly affect a chemical reaction, the oxidation of ammonium to nitrate, and do not act on soil properties. As they are biodegradable, their application has to be repeated several times; in combination with elevated prices for synthetic NIs, this limits their use in many contexts. How well NIs can inhibit N_2O emissions and NO_3^- leaching depends on many factors such as water abundance, soil texture, and temperature.

All amendments act with respect to the conditions under which they are being applied. Rainfall, application rates, and times of application need to be taken into consideration.

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