

The role of arbuscular mycorrhizas in reducing soil nutrient loss

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Substantial amounts of nutrients are lost from soils via leaching and as gaseous emissions. These losses can be environmentally damaging and expensive in terms of lost agricultural production. Plants have evolved many traits to optimize nutrient acquisition, including the formation of arbuscular mycorrhizas (AM), associations of plant roots with fungi that acquire soil nutrients. There is emerging evidence that AM have the ability to reduce nutrient loss from soils by enlarging the nutrient interception zone and preventing nutrient loss after rain-induced leaching events. Until recently, this important ecosystem service of AM had been largely overlooked. Here we review the role of AM in reducing nutrient loss and conclude that this role cannot be ignored if we are to increase global food production in an environmentally sustainable manner.

Nutrient loss from soil

Crops take up approximately only half of the nutrients in applied chemical fertilizers, with the remainder therefore at risk of being lost to production [1]. Nutrients that are mobile in soil, such as nitrate (NO_3^-) and sulfate (SO_4^{2-}), can be readily leached below the root zone of plants. Relatively immobile nutrients, such as phosphorus (P), potassium (K), and zinc (Zn), can also be lost via leaching or erosive processes, when bound to organic matter or colloids, or precipitated with organomineral complexes and chelates (see [2]). Nutrient losses via leaching can be substantial, with up to 160 kg of nitrogen (N) and up to 30 kg of P per hectare lost annually due to leaching and surface run off in some areas [3,4]. Leached nutrients can contaminate ground water and waterways, leading to eutrophication, algal blooms, and the loss of terrestrial and aquatic biodiversity [5]. In addition to losses via leaching, N can also be lost from soil as the potent greenhouse gas nitrous oxide (N_2O) (see Glossary) and as dinitrogen gas (N_2) [6–9] with losses of up to 143 kg of N per hectare [10],

although rates vary among studies [11]. An estimated 150 Tg of N are exported from soil each year, with plant uptake, leaching, soil erosion, and gaseous N losses accounting for 55%, 16%, 15%, and 14% of losses, respectively [12]. Together, these nutrient loss pathways can be expensive in terms of lost potential crop production and environmentally damaging.

Plants have an important role in reducing soil nutrient loss. In addition to direct root uptake of nutrients, most terrestrial plant species can also acquire nutrients by forming associations with arbuscular mycorrhizal fungi (AMF) [13]. Hyphae of AMF can extend beyond the root surface by more than 10 cm [14,15], with common hyphal densities of >10 meters of hyphae per gram of soil [14,16,17]. This extensive absorbing network, which extends beyond the rhizosphere nutrient-depletion zones that form around roots, allows AM to access a larger volume of soil than roots not colonized by AMF. There is clear evidence that AMF can help plants acquire nutrients including P, Zn, ammonium (NH_4^+), nitrate (NO_3^-), copper (Cu), and potassium (K) [18–20]; for example, up to 90% of plant P and 20% of plant N can be provided by AMF, although estimates vary among studies and study systems. Uptake and transfer of nutrients from organic sources to plants has also been reported [21–23].

In addition to improving plant nutrient acquisition, there is emerging evidence that AM have the ability to reduce nutrient loss from soils by enlarging the nutrient interception zone and preventing nutrient loss after rain-induced leaching events. Until recently, this important

Glossary

Arbuscular mycorrhiza (AM): the association formed between the roots of most terrestrial plant species and AMF.

Arbuscular mycorrhizal fungi (AMF): fungi belonging to the Glomeromycota that form AM with the roots of most terrestrial plant species.

Biogeochemical cycling: the chemical, physical, geological, and biological processes and reactions that govern the cycling of nutrients and C in the environment.

Denitrification: the microbial transformation of NO_3^- to N_2O and ultimately N_2 .

Leaching: the drainage of water containing solutes away from soil by the action of percolation.

Nitrification: the microbial transformation of NH_4^+ to NO_3^- .

Nitrous oxide (N_2O): a potent greenhouse gas.

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ecosystem service of AM had been largely overlooked. Here we review recent evidence on the role of AM in reducing soil nutrient loss. We discuss the mechanisms and present a conceptual framework showing under which conditions the reduction of nutrient loss by AM is expected to be most prevalent.

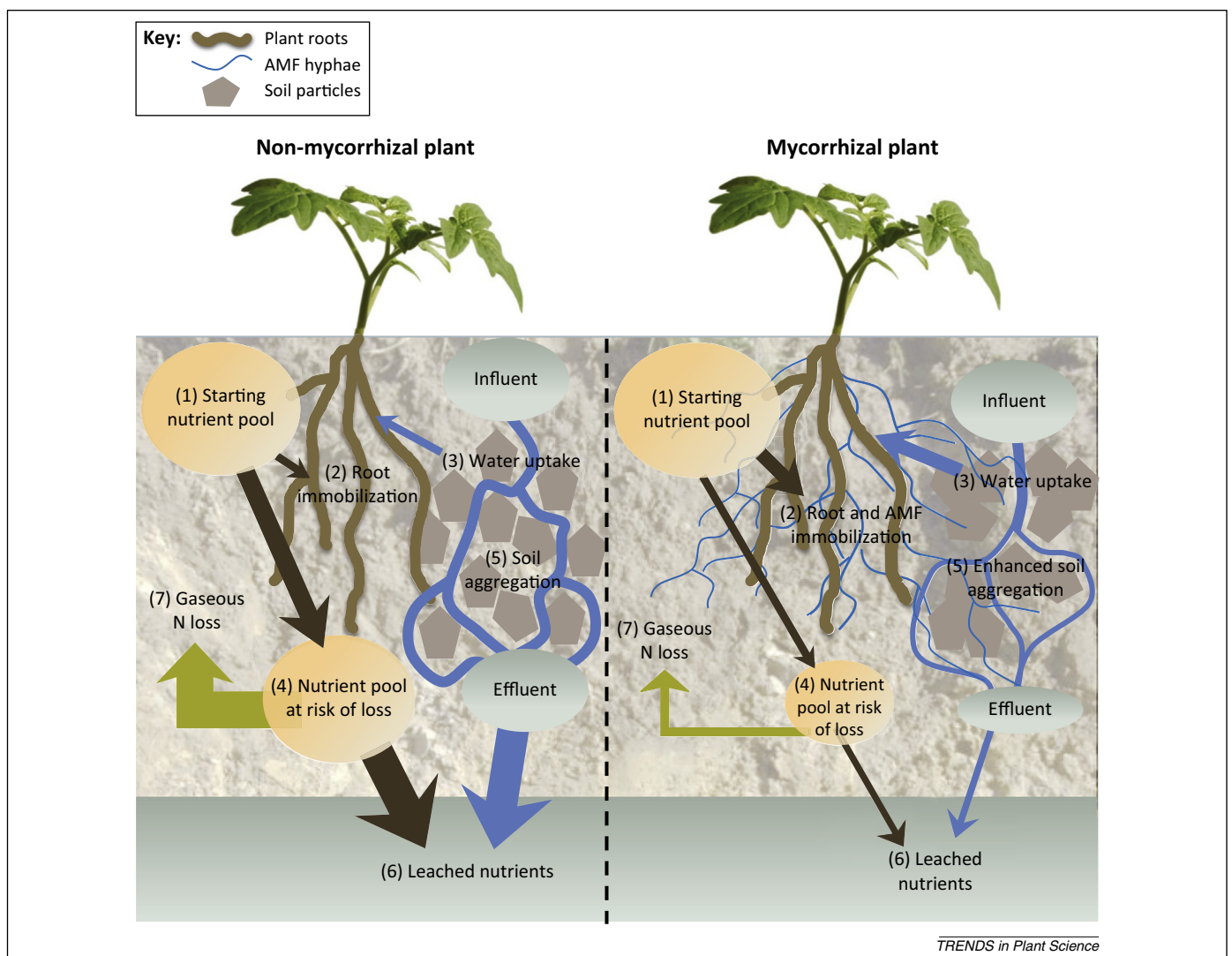
The premise of this review is that AM can reduce the risk of nutrient loss by enhanced nutrient immobilization (compared with non-mycorrhizal plants) or by altering soil nutrient and water cycling processes in ways that favor the retention of nutrients in the soil (Figure 1). We focus on inorganic and organic N and P compounds. Specifically, we review the role of AM in reducing: (i) N loss via leaching of inorganic and organic N-containing compounds and as the potent greenhouse gas N_2O ; and (ii) P loss via leaching of inorganic and organic P-containing compounds.

We use the term ‘non-mycorrhizal’ when referring to plants that have the capacity to form AM but have not done

so. Further, we define nutrient loss as nutrients moving beyond root zones.

The role of AM in reducing N loss from the soil

AMF can take up N as NH_4^+ [24,25], NO_3^- [7], and amino acids [21,22]. There is also evidence to suggest that AMF may be able to acquire nutrients from organic matter patches [26,27], although it is likely that this is due to uptake of inorganic N following organic matter mineralization (see [13] for a recent discussion). While the molecular basis of N uptake by AMF has not been fully elucidated, the identification of fungal glutamine synthase and nitrate reductase genes in AMF [28,29] further supports the role of AMF in assimilating mineral forms of N [30]. AM may also impact soil N transformations and cycling (see below and [30] for a recent review). Although the contribution of AM to plant N acquisition can be variable, with some studies showing little or none (e.g., [31–33]), it is clear that AM can



enhance plant N acquisition in many situations [30], which in turn may help reduce N loss from the soil (see below and Table 1).

AM can reduce N loss via leaching (Table 2), with reductions in leaching of NH_4^+ and/or NO_3^- having been reported (e.g., [34,35]). These reductions in N loss via leaching have been accompanied by enhanced plant N assimilation and sometimes, but not always, a reduction in leachate volume [34–36]. Reductions in N loss via leaching associated with the formation of AM do however vary with plant species; for example, one study found that the formation of AM resulted in an increase in the growth and nutrient uptake of two fast-growing ornamental perennial plants but that there was a reduction in the concentrations of NO_3^- and NH_4^+ with only one of the species [36]. In another study using large outdoor lysimeters, the presence of AM together with other soil biota contributed strongly to increased N and P content of maize, whereas the leaching of total N was strongly reduced by up to a half [37]. In this study a significant reduction (45%) in the leaching of dissolved organic N compounds was also found.

The impact of AM on N leaching can also be influenced by soil type. For example, in a study [6] investigating the effect of AM on nutrient leaching in two different soil types and under NH_4^+ - or NO_3^- -dominated conditions, it was found that, while NH_4^+ leaching was constantly reduced, the leaching of dissolved organic N compounds was reduced in one soil type only. Further, NO_3^- leaching was not affected by AMF in this study. The importance of AM in reducing N loss via leaching has also been explored at larger scales. For example, a large-scale correlative field

study showed that AMF abundance was a strong predictor of total N leached (reduced N loss) in agricultural land-use systems [38]. However, apart from this example, field evidence for the potential for AM to reduce N loss via leaching is scarce. While there are clear examples of AM reducing loss of N via leaching, at least one study showed the opposite effect [39]. Interestingly, in this study red clover was much more abundant in mycorrhizal grassland microcosms and the amount of NO_3^- leaching may be related to the fact that the clover was fixing N (which could subsequently be lost by leaching). Finally, no association was found between the presence of AMF and N leaching in another microcosm-based model grassland system [40].

The cycling of N in soils is rapid and dominated by a series of microbially mediated N transformations [41]. This presents a challenge in the study of the role of AMF in soil N cycling. This is because the establishment of non-mycorrhizal treatments in experiments usually involves sterilization of the soil and back inoculation with bacterial filtrates. While such an approach provides a soil microbial community similar to that of non-sterilized soils (i.e., AM treatments), some time is required for microbial communities to equilibrate [34,35,42]. To overcome this issue, the authors of [43] compared N loss via leaching from cores containing either a mycorrhizal-defective tomato (*Solanum lycopersicum*) mutant or its mycorrhizal wild type progenitor. It was found that mycorrhizal tomato root systems dramatically reduced NO_3^- loss via leaching. This large reduction in N loss may have been due to either an inherently high efficiency of the AM formed by tomato to

Table 1. Soil N and P compounds, their mobility, sources, and transformations, and potential impacts of AM on their loss from soil

Nutrient compound	Soil mobility	Nutrient cycling process		Involvement of AMF
		Source/input	Transformation/loss	
NH_4^+	Low	Organic matter mineralization/ammonification; dissimilatory nitrate reduction; fertilizer addition	Plant and microbial immobilization; bound to soil particles or formation of precipitates/complexes, which may be leached; nitrification yielding NO_3^-	Immobilized by AMF; impact of AMF on soil water relations
NO_3^-	High	Nitrification; fertilizer addition	Plant and microbial immobilization; leaching; denitrification giving rise to gaseous forms of N; dissimilatory nitrate reduction	Immobilized by AMF but less so than NH_4^+ ; impacts of AMF on soil water relations
Dissolved organic N	Variable	Organic matter decomposition; extracellular enzyme production; root exudation, manure application, animal and microbial excretion	Mineralization; plant and microbial immobilization; leaching	AMF may promote mineralization and can immobilize the product (NH_4^+); direct uptake
PO_4^-	Very low	Organic matter mineralization; fertilizer addition; desorption from soil particles; solubilization of phosphate minerals	Plant and microbial immobilization; bound to soil particles or formation of precipitates/complexes, which may be leached	Is often strongly immobilized by AMF; impact of AMF on soil water relations
Dissolved organic P, complex-bound P, sorbed P	Variable	Organic matter decomposition; mineral weathering, extracellular enzyme production; root exudation, manure application, animal and microbial excretion	Mineralization; plant and microbial immobilization; leaching	AMF promote mineralization and can immobilize the product; involvement in solubilization of non-plant-available compounds; impact of AMF on soil water relations

Table 2. Overview of studies investigating the effects of AM on soil N and P loss via leaching

Experimental system	AM effects on N and P loss via leaching	Refs
Clover in microcosms	Experiment 1: approximately 2.7 times reduction in content of P leached with AM under low P conditions. No difference where soil P was high. Experiment 2: approximately 2.4 times reduction in content of P leached with AM under low P conditions. No difference where soil P was high.	[49]
Grassland microcosm	7.5% and 60% reductions in loss of NH_4^+ and inorganic P, respectively, from AM microcosms. No change in NO_3^- with AM.	[35]
Pasture grass microcosm	Approximately 7.5, 3, and 1.4 times reductions in NH_4^+ , NO_3^- , and P concentrations in leachate, respectively.	[34]
Ornamental perennial plants and <i>Rhus integrifolia</i> in pots	Up to 65–80% reduction in NH_4^+ , NO_3^- , and inorganic P content of leachates with mycorrhizal <i>Encelia californica</i> but not <i>R. integrifolia</i> .	[36]
Mycorrhiza-defective and mycorrhizal tomato genotypes	40 times reduction in N loss via leaching of NO_3^- . No change in NH_4^+ loss via leaching with AM.	[43]
Pots with maize	No effects of AM on P leaching when soil inocula from three different agricultural fields were used. 40% to twofold reduction of P leaching when three other soil inocula were used. P leaching negatively correlated with AMF hyphal length in soil.	[65]
Agricultural crop rotation grown in outdoor lysimeters	24.3% reduction in total N leached with AM during two growing seasons. Increase in P leached with AM.	[6]
Grassland microcosms with two different soil types	Reduction by 31% and 24% of total and unreactive P leaching, respectively, with AM. Up to 90% of P leached in unreactive form. NH_4^+ leaching reduced by 69% with AM, reduction of dissolved organic N leaching by 24% with AM in one soil type only. No effect on NO_3^- leaching.	[44]
Grassland microcosm with red clover	40% increase and decrease in NO_3^- and NH_4^+ leaching, respectively, with AM. 20% increase of unreactive P leaching with AM and no effect on dissolved inorganic P.	[39]

intercept N or the impact of AMF on soil microbes involved in N cycling. The potential to use mutants in field studies of AM functioning (see also [7,44,45]) is an area that is open to further investigation.

Although N losses from soil due to denitrification can be substantial [11,46,47], only a few studies have investigated AM effects on soil N_2O and/or N_2 emissions and the results are variable. For example, in a field experiment using a mutant-based approach to control for the formation of AM, AM formation enhanced the capacity of plants to immobilize a recently applied pulse of $^{15}\text{NO}_3^-$ but had no impact on soil N_2O emissions [7]. By contrast, in another study comprising two independent greenhouse experiments using either a mutant/wild type pair of tomatoes (different from those used by [7]) or sterilized and re-inoculated soil to manipulate the presence of AMF [44], fluxes of N_2O were 33% and 42% higher where plants had formed a reduced or no association with AMF, in the two experiments respectively. Finally, in a recent glasshouse study using the same tomato genotypes used in [7], AM reduced soil N_2O emissions at high soil moisture [9]. This study suggests that control over N_2O emissions by AM plants is related to higher use of soil water (which will affect rates of denitrification and thence N_2O emissions) rather than increased N uptake. Given the importance of N_2O as a greenhouse gas, this is an area ripe for further investigation.

While it is clear that AM can impact N loss from soils, the underlying mechanisms are less clear. Enhanced rates of N immobilization by AM will reduce the size of the mineral N pools in the soil, thereby reducing the risk of N loss via leaching or the amount of N available to be denitrified (Figure 1). In the case of leaching, the preferential uptake of NH_4^+ by AMF [24] is likely to be especially important as it not only reduces the pool of NH_4^+ that can be leached but also reduces the pool of NH_4^+ available to be transformed into NO_3^- (via nitrification), which is much

more mobile in soil. However, preferential uptake of NH_4^+ over NO_3^- may not always be the case (see [6]) and AM can also assimilate N in organic forms [21,22]. For gaseous N losses, reducing the pool of NO_3^- in the soil will decrease the risk of N loss as N_2O (or N_2) generated via denitrification. Similarly, reducing the soil NH_4^+ pool may also be important as some N_2O is generated in the process of nitrification.

AM can improve soil structure and soil water retention [45,48]. In doing so, AM could help reduce N losses by reducing the volume of soil leachate (Figure 1). Conversely, improvements in soil structure associated with the formation of AM may affect soil moisture dynamics in the root zone, which may promote the N_2O -producing process of denitrification under some circumstances, as rates of denitrification are strongly moisture dependent. Some studies show an AM-mediated reduction in leachate volume [35,49], whereas others do not [34,43]. AM may also affect soil N_2O emissions via enhanced water use by AM plants [9]. AM may also reduce N loss by competing with organisms involved in the soil N cycle (e.g., nitrifiers and denitrifiers) for both NH_4^+ and NO_3^- (see [30]). The abundance of microbes involved in N mineralization may also be impacted by AMF [50,51] and so also needs to be taken into consideration. Finally, whereas carbon (C) exudation from plant roots can be reduced in the presence of AMF [52], AMF exude C from their extraradical hyphae [53]. This C may help to improve soil structure as well as providing an energy source for N-cycling microorganisms, including denitrifiers. This, however, remains to be specifically tested. Finally, the presence of AMF in soil can induce shifts in soil microbial communities, including organisms involved in N-cycling processes (e.g., denitrification [54]), which could also affect N losses from soil through denitrification and leaching.

Irrespective of the underlying mechanisms, AM can impact soil N loss. Although the mechanisms that underpin AM impacts on soil N loss are likely to be multifarious and complex, it will be important to understand them if we are to make predictions about AM impacts on N losses, whether in the context of leaching or N₂O (and N₂) emissions.

The role of AM in reducing P loss from the soil

P is relatively immobile in soil compared with N. Usually only a small percentage of soil P is available to plants, while up to 90% of P can be effectively rendered unavailable via precipitation reactions in the soil or sorption to mineral soil particles and/or organic matter [55–57]. Therefore, P fertilizers are often applied in excess and soils are accumulating P [58,59]. Although loss of P via leaching is low compared with that of N, it can be especially important in soils with a low P sorption capacity [60,61]. Furthermore, small amounts of leached P may have a strong environmental impact, with P entering freshwater bodies considered the main cause of eutrophication [62–64].

AM are best known for their capacity to enhance plant P acquisition. The molecular and physiological basis of the role of AM in enhancing plant P acquisition is well understood, with P transporter genes in AMF and genes involved in plant P transport whose expression can be affected by the formation of AM (in several plant species) having been identified (see [13]). Given that P loss can be significant in some soils, and that AMF can acquire large amounts of P, it follows that AM are likely to play a significant role in reducing P loss via leaching in soils susceptible to P leaching. Recent studies are beginning to show that AM have an important role in reducing P loss via leaching (see below and Table 1).

AM can improve plant P acquisition and reduce inorganic P loss via leaching (Table 2) [6,34–36,49]. These effects are generally most pronounced where soil P is low and levels of AM colonization are generally higher [34,35], although this is not always the case [36]. In one study [65] no effects of AM on P leaching in mesocosms were found when soil inocula from three different agricultural fields were used, but there were substantial reductions in P leaching when three other soil inocula were used. Importantly, the amount of P leached was negatively correlated with the amount of fungal hyphae in soil. AMF are capable of reducing not only the leaching of reactive, plant-available P compounds, but also that of unreactive P compounds (e.g., organic P, polyphosphates, P bound to particulate inorganic material) [6].

It is important to note that AM do not always reduce P loss via leaching. For example, in a lysimeter study [37], P losses were slightly higher in an ‘enhanced soil-life treatment’, which included AMF, compared with where AMF were not present. Interestingly, this was despite the fact that colonization of roots by AMF (measured as percentage colonization) was strongly positively related to plant biomass and P content and that the mobilization of soil P resources was strongly increased in the enhanced soil-life treatment. Compared with the strong increase in plant P content, the amount of P leached was very small and the authors concluded that the enhanced loss might be a byproduct of the massively increased mobilization of soil

P by AMF. While total P leaching was higher in the presence of AMF, again leaching of nonreactive P compounds was reduced. This example highlights the importance of considering nutrient losses in different chemical forms, as is also the case for N (see above).

We consider ‘scavenging’ for inorganic P beyond rhizosphere depletion zones to be the primary mechanism by which AM reduce the risk of P loss via leaching [14,66] (Figure 1). AM may also indirectly influence P surface runoff by stimulating plant P acquisition and by reducing soil P availability. While acquisition of P from organic sources and from insoluble inorganic P compounds may explain the reductions in the leaching of unreactive P compounds [6], more needs to be known about the role of AMF in acquiring P from organic and other soil sources before firm conclusions can be drawn. Reduced leaching of organic P compounds could also be due to enhanced uptake of inorganic P by AMF, thereby reducing the amount of P available to be transformed into organic forms by other soil biota. While the effects of AM on the leaching of dissolved organic P and P associated with colloids and other particulate matter are not well understood, their contribution to leaching is captured in measures of leached total P. We also note that the effects of AMF on soil structure and water retention may also be important in reducing soil P loss via leaching, as with N leaching (see above). A reduction in the magnitude of AM effects on P leaching with increasing soil P supply are consistent with studies showing that the formation and functioning (at least in terms of P acquisition) of AM is reduced as soil P is increased.

Concluding remarks: AM and nutrient loss – the way forward

AM can have a significant role in reducing the loss of N and P from soil. This is an important but largely overlooked ecosystem service provided by AM. We anticipate that these processes could be especially relevant in sandy soils, irrigated farming systems, high-input farming systems, nutrient-rich natural systems, and points in the landscape where water and nutrient fluxes are high (e.g., riparian zones). Maintaining high levels of AMF in soils will be important, especially in agroecosystems where the use of fungicides, fumigants, inclusion of non-mycorrhizal crops such as oilseed rape or sugar beet, prolonged fallow periods, and soil cultivation can reduce the inoculum potential of the soil. Furthermore, excess application of P fertilizers may be especially problematic in this context as, in addition to the higher levels of nutrients being applied, AM colonization of roots is reduced with increased P supply [67–69]. To this end, a reduction in the formation of AM is likely to be one of the reasons for greater levels of P loss from fertilized ecosystems [35]. In Figure 2 the relationships between soil management intensity and nutrient levels, AM abundance, and total nutrient losses are integrated into a conceptual framework to identify the situation where AM-mediated reduction of nutrient loss is maximized. With higher management intensity and nutrient additions, total nutrient loss increases while AM abundance is reduced. We expect the relative contribution of AM to the reduction of nutrient loss to be highest at low nutrient availability, when the effects of AM are expected

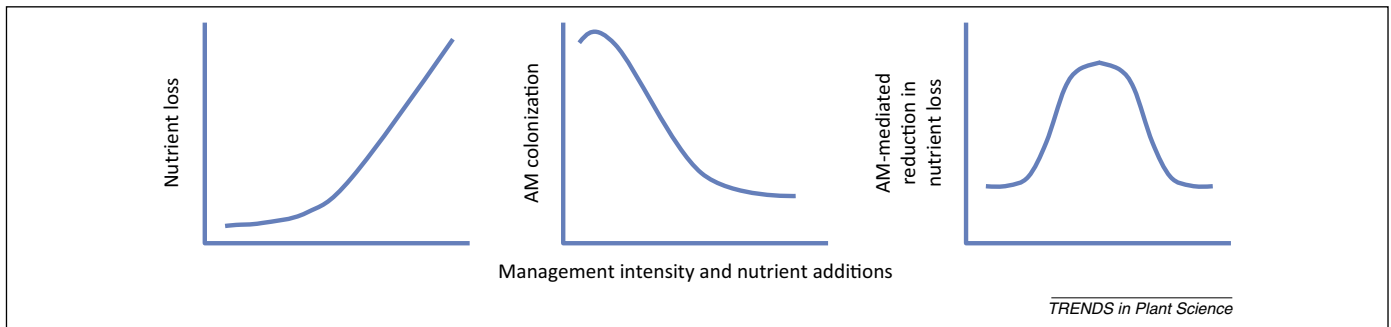


Figure 2. Hypothesized relationship between soil nutrient levels and total nutrient loss, arbuscular mycorrhiza (AM) colonization, and AM-mediated reduction in nutrient loss. The lag in the first panel represents the situation where nutrient-binding sites are unsaturated. In the second panel, the small increase in colonization is consistent with studies suggesting that when soil phosphorus (P) is low, low levels of P supply can stimulate colonization. The third panel suggests that AM-mediated reductions in nutrient loss will be quantitatively greatest at intermediate levels of management intensity and nutrient addition and where levels of AM colonization are not minimized. The relative contribution of AM to reducing nutrient loss is expected to be highest at the low end of soil nutrient availability (not shown).

to be highest. However, in terms of total amounts, the contribution of AM to the reduction of nutrient loss will be highest at intermediate management intensity and soil fertility, where nutrient loss would be expected to occur in significant amounts but AM abundance remains sufficient to reduce it (Figure 2).

A further increase in management intensity may lead to higher nutrient loss, on the one hand because of excess nutrients in soil and on the other hand because AM abundance is further reduced. Ultimately, the goal should be to ‘push’ the system in such a way that the stimulation of AMF will reduce the total amount of nutrient loss.

It has been proposed that nutrient stoichiometry, especially the N/P ratio, can have a significant impact on AM functioning (see [70] for a review). In these studies the functioning of AM is evaluated by looking at effects on plant growth and nutrition. It is suggested that AM benefits for plant growth and nutrition are highest under P-limiting conditions but with sufficient availability of N. However, the effects of nutrient stoichiometry on nutrient leaching may be more complex and may also, in addition to the effects on plant nutrition, be influenced by the ability of AM to directly or indirectly immobilize nutrients (e.g. in AMF hyphae, through effects on soil microbial communities) and to reduce soil nutrient availability. Nevertheless, it seems reasonable to suggest that improved AM functioning through adequate nutrient stoichiometry could also maximize the effects of AM on nutrient loss from soil; however, this remains to be tested.

Further research efforts should be directed toward the identification of conditions and measures suitable to maximize AM benefits in agroecosystems. It will also be important to consider the impact of other management practices that help to reduce nutrient loss, such as the use of cover crops and optimizing the timing of fertilizer application. In addition to focusing on the fate of inorganic N and P loss in mineral N forms, it is clear that there is also a need to consider loss in organic forms. The processes underlying the involvement of AM in the reduction of loss of organic nutrients require further investigation as little is known about the utilization of organic compounds by AM and whether these effects are direct or indirect via associated microorganisms.

At several points in this review we have noted the paucity of field-based studies of the role of AM in reducing

nutrient loss. Field-based studies, however, present numerous challenges. For example, for measurement of nutrient loss via leaching in the field it will be necessary to use techniques that allow the collection of leachate with minimal disturbance to the soil, such as anion- and cation-exchange resins, lysimeters, or soil water samplers. Establishing non-mycorrhizal treatments in the field is also a challenge, although it can be overcome using a genotypic approach to controlling for the formation of AM [42,45]. Further, we suggest that all of these experimental approaches will be particularly valuable when used in conjunction with isotope labeling techniques (e.g., [7]). Although not considered here, temporal asynchrony may be an important factor in field-based studies. For example, in deciduous systems most nutrient loss occurs in autumn, when plant and mycorrhizal activity is low. However, if AM efficiently scavenge soil nutrients in times of high activity, this should enhance the nutrient uptake capacity of soils as more nutrient exchange sites are available. Hence, effects of AM on nutrient loss in times of low mycorrhizal and plant activity could still be expected through indirect mechanisms. Moreover, there is compelling evidence that AM interact with a wide range of other soil organisms involved in nutrient cycling processes. Due to the reductionist nature of many experiments studying AM effects on nutrient cycling (e.g., using sterilized soils), there is a strong need to further investigate the interactions of AMF with other soil biota and test how they jointly influence nutrient loss from soil. We consider the potential for AM to reduce nutrient loss from soils to be an important ecosystem service that is ripe for further detailed mechanistic investigation.

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Plant Science Conferences in 2015

Frontiers of Plant Biology: Epigenetics & Development

8–12 June, 2015

Suzhou, China

<http://www.csh-asia.org/2015meetings/Plant.html>

EMBO Workshop:

Mechanisms of plant speciation

9–13 June, 2015

Norrköping, Sweden

<http://events.embo.org/15-plant/>

Rhizosphere4

21–24 June, 2015

Maastricht, The Netherlands

<http://www.rhizo4.org/>

International Plant and Algal Phenomics Meeting (IPAP)

27–30 June, 2015

Prague, Czech Republic

<http://www.psi.cz/ipap2015/#programme>

Plant Abiotic Stress Tolerance III

June 29–July 1, 2015

Vienna, Austria

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