SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

ACHIEVING NATURE-POSITIVE PLANT NUTRITION: FERTILIZERS AND BIODIVERSITY

Issue Brief 02, August 2021

KEY POINTS

Mineral nutrition of agricultural crops and pastures strongly affects food and biodiversity, both of which are essential to the well-being of humanity. Excessive applications of nutrients, particularly nitrogen and phosphorus, have numerous negative impacts on biodiversity in agricultural systems and beyond. However, applying too few nutrients can also negatively affect our natural systems if it results in increased pressures to convert natural ecosystems to production systems. Optimally managing nutrient inputs for biodiversity, food, nutrition and other outcomes must be based on context-specific targets and solutions that enhance biodiversity from farm to land-scape and global scales.

Biodiversity provides critical and often irreplaceable ecosystem services to agriculture, wider society and nature. The relationships among food, biodiversity and nutrients are complex, with many trade-offs to manage and synergies upon which to capitalize. Fertilizers and other agricultural practices affect biodiversity in many ways, from soil bacteria to the broader effects of human-induced climate change on the environment (Figure 1).

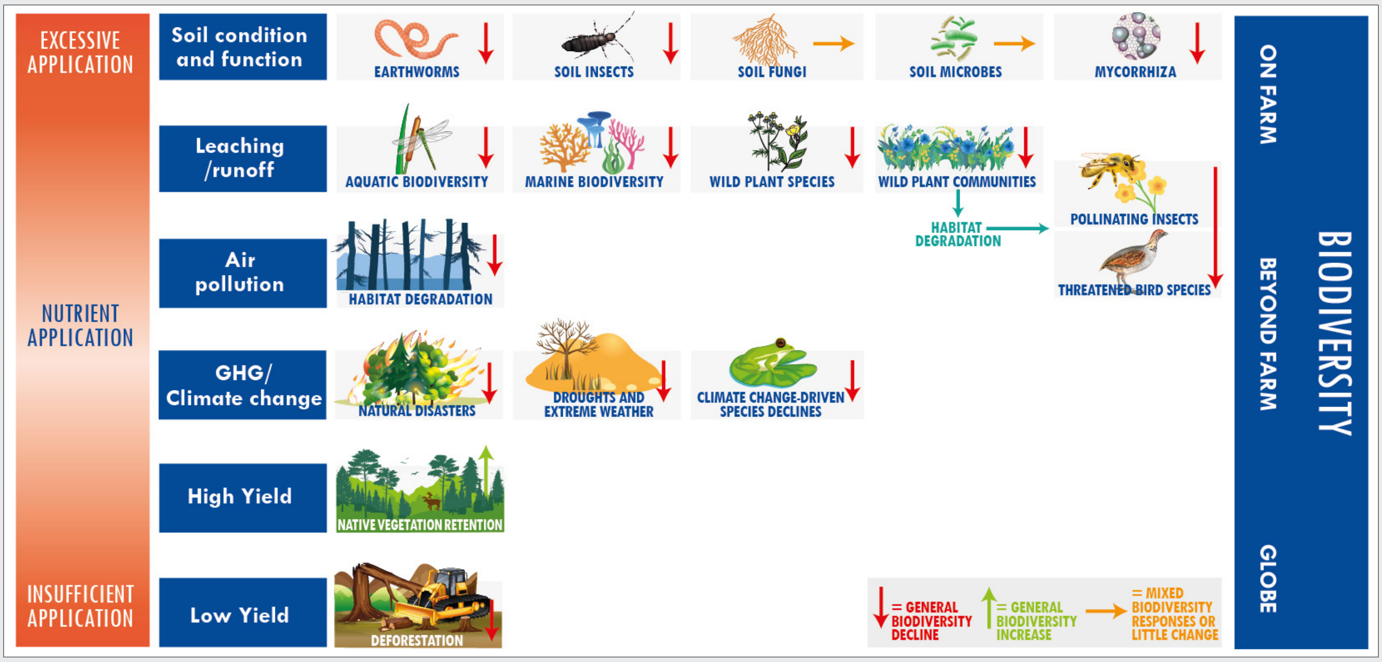

Figure 1. Common responses of biodiversity to nutrient applications in agriculture. Scales of impact range from field to planet. Biodiversity responses can be direct (e.g. effects on plant diversity) or indirect (e.g. plant diversity decline leads to habitat degradation and consequently reduces bird and pollinator diversity). Responses can be biodiversity-positive (green arrows), biodiversity-negative (red arrows), or neutral/ mixed evidence (amber arrows).

Most reports deal with negative effects on biodiversity and other aspects of the environment caused by excessive or inappropriate fertilizer application, including biodiversity impacts through soil changes, offsite pollution or gaseous emissions. While there is abundant research on negative consequences of nitrogen or phosphorus use in agriculture, less is known about positive impacts on biodiversity, or the role of other nutrients, including potassium and micronutrients. Nutrients have raised agricultural yields in many parts of the world, reducing the incentive to clear natural ecosystems for production. By limiting the expansion of agriculture, fertilizers — if applied properly — can also have large positive impacts on biodiversity. Considering the need to raise global food production on existing agricultural land, this impact pathway will be of particular importance in the coming decades.

Whilst there are generalized calls for reduced nutrient inputs, what is really needed are context-specific targets and solutions for the integrated, efficient use of nutrients in agriculture that optimize for multiple objectives, including biodiversity. Excellent opportunities exist for incorporating biodiversity responses into nutrient stewardship approaches. Harnessing them will require greater interaction and collaboration of agriculture- and biodiversity-focused stakeholders.

WHAT IS THE ISSUE?

This brief focusses on how nutrient management in agriculture affects biodiversity, recognizing that this is inter-linked with numerous other dimensions of agricultural development that impact biodiversity (e.g., land clearing, burning, tillage, soil compaction, erosion, agricultural chemicals, monocultures).

The rapid global loss of biodiversity and ecosystem services is one of the most pressing challenges of our time ***(1)***. The rates and extent of biodiversity loss are such that many experts suggest we are in the midst of a sixth mass extinction ***(2)***. This is caused by many threats, including habitat loss, over-harvesting, climate change, invasive species, and pollution of soils, water and air. Agriculture and food systems are the most significant cause of biodiversity loss ***(3)*** and drive many other environmental impacts ***(4)***. Agriculture affects biodiversity in many ways, including the conversion of natural ecosystems to production systems, on- and offsite consequences of agricultural management, and large-scale pollution and contributions to climate change ***(5)***. Since 1985, there have been considerable conversions from natural shrubland and forest to production grassland and cropland ***(Figure 2)***, with much of the conversion in highly biodiverse tropical regions ***(6)***. Despite this, some agricultural systems can also support very high levels of biodiversity and even provide habitat for species of conservation concern ***(7)***. This is particularly the case where farming systems are diverse and contain sizeable, connected habitat elements, and where species are dependent on more 'traditional' farming practices ***(8)***.

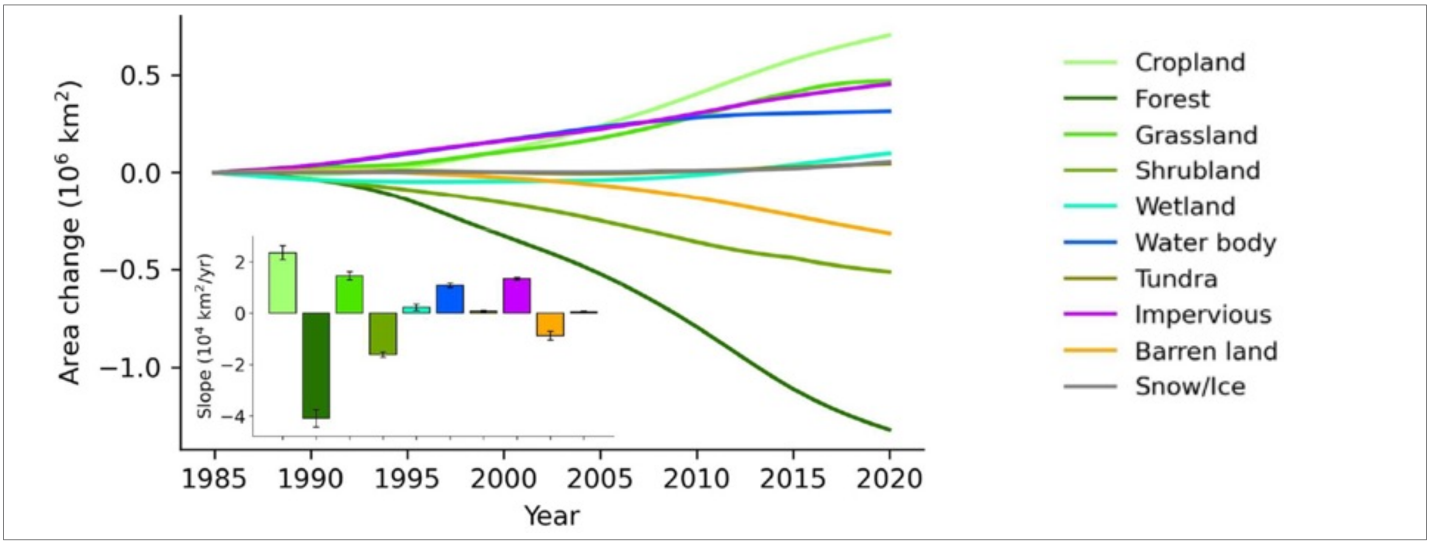

Figure 2. Global changes in major land use categories since 1985 (6). Trends include increases in cropland and grassland, and decreases in forest and shrubland.

Biodiversity is not just 'nice to have'—its loss has serious implications for humanity and nature. This is because biodiversity drives many of the vital ecological processes and planetary life-support systems on which we are dependent for our own survival **(9)**.

As demands for food have grown globally, there have been huge efforts to increase agricultural yields, which has been possible so far through a range of technologies and management interventions, often classified collectively as 'agricultural intensification'. Central to this has been the increased use of nutrients in crop production, mostly through the use of mineral fertilizers, but also through organic fertilizers such as livestock manure, composts, sewage sludge, legumes in crop rotations, or leguminous tree crops. Since 1985, global agricultural production has doubled, fueled by a considerable increase in global fertilizer consumption, from about 130 Mt $N+P_2O_5+K_2O$ in 1985 to 190 Mt at present. Annual nitrogen consumption alone rose from 70 Mt to 105 Mt.[1]

Whilst the increases in food production have been profound, with food security increased for billions of people globally, there have also been considerable on-site and off-site biodiversity losses **(10, 11)** and other negative environmental impacts **(12)** associated with fertilizer use in agriculture. Another issue is that increases in nutrient application have not yet been experienced equally around the world. Considerable productivity inequities, known as 'yield gaps' — the difference between potential and realized crop yields — exist in some regions. For example, achieving food security in sub-Saharan Africa may require 9-to-15-fold increases in nutrient inputs **(13)** in the next 30 years, which could have potentially negative biodiversity consequences as well as considerable greenhouse gas emission implications **(14)**.

Whilst the focus is often firmly on biodiversity losses due to nutrient surpluses, the increased productivity associated with increased nutrient inputs and other genetic or agronomic improvements has contributed to the sparing of natural land from conversion to production land **(15)**. Responsible nutrient management may also have additional benefits such as increased soil organic matter or soil fertility. On a global scale, the precise contributions of agricultural fertilizer inputs to land sparing, or positive as well as negative impacts on soil health, have not been fully quantified. Besides, we cannot rely on closing yield gaps alone to (i) reduce land conversion and associated biodiversity loss, and (ii) free up land for ecological restoration and/or carbon sequestration. Any global drive to optimize nutrient management inputs for biodiversity and other natural resource outcomes must be coupled with improved land use planning, native vegetation clearing legislation and enforcement, and incentives for retaining natural ecosystems **(16)**.

1. International Fertilizer Association. *http://ifadata.fertilizer.org/ucSearch.aspx*

WHAT IS HAPPENING?

How nutrient management affects biodiversity

The responses of biodiversity to nutrient management vary depending on (i) scale at which they occur (e.g., field, landscape), (ii) types of species involved, (iii) type and composition of fertilizer applied (e.g., inorganic, organic, nutrient composition), (iv) land use and landscape context (e.g., monocropping, land use mosaic), and (v) socioeconomic context that influences markets, policy and landholder responses to productivity changes.

There are numerous pathways through which agricultural nutrient application can affect biodiversity, within the vicinity of application, in downstream ecosystems, and even at much larger scales of the landscape and beyond. Following an exhaustive review of the literature, we have categorized nutrient management and biodiversity interactions according to four broad pressure and response categories (Figure 3).

D) INSUFFICIENT NUTRIENTS
Multiple scale biodiversity impacts due to agricultural expansion

- Increased conversion of natural ecosystems due to low crop yields
- Massive biodiversity loss at local to global scales due to uncontrolled habitat destruction, habitat simplification, etc.
- Increased land degradation
- Increased erosion and siltation of waterways and marine ecosystems
- Increased human-animal conflict

A) EXCESS NUTRIENTS
Field to farm biodiversity impacts

- Changed soil organic matter, lowered pH
- Reduced soil fauna, mixed responses of microbes and soil fungi, reduced arbuscular mycorrhizal fungi
- Reduced agrobiodiversity/ local plant diversity
- Negative impacts on other biodiversity through habitat degradation
- Many negative effects on local ecosystem services

EXCESSIVE OR INSUFFICIENT NUTRIENT APPLICATION

C) EXCESS NUTRIENTS
Pollution at local to global scales

- Gaseous nutrient losses from soil, fertilizer, manure (NH_3, N_2O, NO_x)
- GHG emissions contributing to climate change and ozone depletion (CO_2, N_2O, CH_4)
- Air pollution (e.g. NH_3, NO_x, ozone, fine particulate matter, acid rain)

B) EXCESS NUTRIENTS
Offsite and landscape biodiversity impacts

- Nutrient losses due to leaching, runoff, erosion, waste
- Eutrophication of adjacent waterways and groundwater, and enrichment and pollution of marine systems
- Run-off and spray drift into adjacent vegetation leading to biodiversity losses
- Increased OR decreased conversion of natural ecosystems to production systems (socioeconomic context-dependent)

Figure 3. Generalized environmental, biodiversity and land conversion responses to excessive (A–C) and insufficient (D) agricultural nutrient inputs.

A. EXCESS NUTRIENTS, field-to-farm impacts. Biodiversity responses at this scale mostly affect species that are not already well-adapted to, or tolerant of, agricultural systems and their specific management practices. Many of the known effects are those of inorganic fertilizers on soil biodiversity, but what is apparent is that different elements of biodiversity often respond in different ways. Increased nutrient inputs can also result in diminished plant diversity **(17)**. By raising the levels of nutrients (e.g., nitrogen) in a system, a number of impacts can occur, including (i) direct toxicity at application points through raised levels of nitrogen compounds; (ii) accumulation of nitrogen or phosphorus compounds leading to changes in species composition and diversity, favoring species that are N or P tolerant or disadvantaging species adapted to nutrient-poor systems; or (iii) other soil changes (e.g. increase or decrease of soil organic matter, acidification or contamination).

B. EXCESS NUTRIENTS, 'beyond-farm' and 'landscape' effects. Non-agricultural ecosystems within or near to agricultural landscapes are vulnerable to external threats such as agrochemical drift and run-off **(18)**. This can occur where intensively managed, high external input production systems abut natural ecosystems. The responses associated with fertilizer drift into adjacent natural ecosystems include increased exotic plant invasion, reduced plant diversity, reduced diversity of fauna with high dependency on native plant species, and groundwater pollution. A second and more significant pathway relates to nutrient enrichment of water bodies as a major threat to freshwater ecosystems and their biodiversity. This often occurs through eutrophication, leading to excessive algal growth and subsequent adverse effects on fish, amphibians, and invertebrates **(19, 20)**. Diffuse nutrient pollution can have influences over considerable distances in coastal systems and marine waters, such as coral reefs. An example of land-based agricultural pollution affecting an area of globally significant environmental value, is that of the Great Barrier Reef **(21)**. A range of industrial and agricultural pollutants impact the reef, with fertilizers for sugar cane being prominent **(22)**.

C. EXCESS NUTRIENTS AND POLLUTION, impacts at landscape to global scales. One of the most prevalent and growing threats to biodiversity globally is climate change, with the food system accounting for 34% of anthropogenic greenhouse gas emissions **(23)**. Whilst land-use change and methane from livestock make up the bulk of these emissions, greenhouse gas emissions originating from fertilizer production and field application of fertilizers and manure play a significant role too. Losses of gaseous forms of N from fertilizer applications (inorganic and organic) also contribute to air pollution **(24)**, atmospheric deposition of nitrogen **(25)**, depletion of ozone layer in the stratosphere and build-up in tropospheric ozone **(26)**, all of which negatively affect biodiversity globally as well as locally.

D. INSUFFICIENT NUTRIENTS, local to global impacts. Insufficient nutrient applications cause soil nutrient depletion and reduce the opportunity for higher crop yields, which in turn may encourage the cultivation of more land. Due to the need for increased food production, agricultural expansion has often proceeded at the expense of natural ecosystems, resulting in massive and often irreversible biodiversity losses and other environmental consequences. This has led to a popular but still controversial conservation paradigm that argues that closing yield gaps through sustainable agricultural intensification can reduce the need to convert land **(27)**. A basic premise of such 'land sparing' is that if yields are increased on existing agricultural land, then this frees up land for biodiversity conservation. Conversely, there may also be a 'rebound effect', where increased yields, efficiencies and profits attract more producers to a particular product, thus leading to increased risk of land conversion **(28)**.

There are other processes that are not fully captured in Figure 3, but which may also impact biodiversity in various ways. For example, large amounts of nutrients may be transferred locally (e.g., moving organic materials) or across regions (e.g., trade of agricultural products), leading to varying biodiversity responses due to nutrient surpluses or deficits.

There is a widespread perception that excessive fertilizer application has a negative effect on biodiversity. Overall, the science supports this perspective, but the literature is also dominated by reports that focus on negative impacts of few elements (e.g., nitrogen, phosphorus). Many of the direct and indirect biodiversity impacts of managing mineral elements as a whole are still little understood. A more balanced view is that biodiversity responses are variable, depending on the nutrient, application rates, cropping system, species, scale at which biodiversity occurs, climate and other context-dependent elements. For example:

- A review of the impacts of nitrogen fertilizer application on soil biodiversity found a highly variable response across different groups of organisms **(10)**. For instance, bacteria showed a 3% increase in diversity and fungi a 13% increase in diversity in systems subjected to additions of nitrogen fertilizer. The functional diversity of microbes was also consistently greater with nitrogen fertilizer applications. Meanwhile, arbuscular mycorrhizal fungi displayed a 10% decrease in diversity across studies, with declines larger with greater applications of inorganic fertilizer. Similar declines were observed for soil fauna (e.g. earthworms, beetles, springtails), but were only evident for inorganic and not organic (e.g., manure) fertilizers.

- A recent meta-analysis of 1679 cases from 207 studies concluded that nitrogen and phosphorus additions decreased invertebrate abundance in terrestrial and aquatic ecosystems, with stronger impacts under combined nitrogen and phosphorus additions, and on the abundance of tropical than temperate invertebrates **(29)**. However, nutrient additions had weaker or inconclusive effects on invertebrate biomass and richness.

- Plant responses to land use and nutrient management often point towards a negative influence of fertilizers on plant diversity **(17)**. However, this differs by nutrient and there are also many exceptions. The addition of nitrogen to low nutrient, botanically rich grasslands, e.g., from fertilizer or atmospheric deposition, has a substantial negative influence on species richness, but that effect can also be reversible **(30)**. On the other hand, severely impoverished grasslands may have low plant biodiversity due to lack of nutrients such as phosphorus, which increases rapidly towards a plateau as soil phosphorus accumulates to more optimal levels **(31)**.

- In many regions, agricultural intensification has a negative overall impact on many bird species. Inorganic fertilizer per se does not directly affect farmland specialist bird species in croplands **(32)**, but it may indirectly contribute to declines due to habitat degradation and reducing the invertebrates birds feed on (Figure 1).

How is this affecting essential ecosystem services?

Biodiversity drives a huge array of ecological functions **(33)**, which deliver ecosystem services that humanity derives for free from nature. The relationship between biodiversity and ecosystem services can be complex. There are many instances where greater diversity leads to an increase in ecosystem service generation and delivery. For instance, introducing strips of grassland or flowering plants into cropping systems increases the numbers of pollinators and birds, and delivers benefits around water runoff and soil and nutrient retention **(34)**. Sometimes, however, increased species numbers may not necessarily translate into increased function or services. In some soil communities for instance, the community composition may be more important for services than species numbers **(35)**.

Biodiversity-driven ecosystem services are particularly prevalent in agricultural systems, where benefits include pollination, pest and disease control, soil aeration, flood control, and nutrient cycling. This is especially pertinent for millions of poor farmers in parts of the developing world, where dependencies on ecosystem services are often high **(36)**.

The major services provided by ecosystems vary across different spatial scales. At the field to farm scale, the main service is food production along with other services including pest control, and soil formation. At beyond-farm scale, services include habitat for wild biodiversity, air and water quality, and pollination. At the largest of scales, services include the regulation (or destabilization) of climate. Where biodiversity declines have negative connotations for ecosystem services that are critical to human well-being, then developing and deploying appropriate policies and interventions to address these becomes paramount **(37)**.

How are these issues presently being addressed?

Addressing nutrient management and its biodiversity implications needs to be seen in the context of a much broader set of strategies for addressing biodiversity loss due to the entire food system. Optimizing nutrient management is vital, but is only part of a much larger picture of the impacts of food production on biodiversity and mitigation options.

These issues are expressed in very high-level global commitments such as the UN Sustainable Development Goals (SDGs)[2]. The

2. *https://sdgs.un.org/goals*

food-biodiversity nexus is often portrayed as a conflict between SDG 2 ('Zero Hunger') and SDGs 14 ('Life below Water') and 15 ('Life on Land'). However, the reality of nutrient management in agriculture is more of a multi-directional interaction between several SDG targets, where some potential win-wins do appear feasible (e.g., SDG Target 2.4). There are numerous global and institutional initiatives (e.g. UN Food Systems Summit, EAT Forum/Lancet[3], FOLU[4] or WWF's Planet-Based Diet[5]) seeking to inform and engage policy-makers, the consuming public, and producers around how food systems can become more sustainable, lead to better human nutrition and health outcomes, and reverse biodiversity loss ***(38)***.

In terms of management interventions, there are calls from scientists at the agriculture-food-environment interface to employ management actions often described as 'sustainable intensification', 'regenerative agriculture' or 'nature-positive farming'. Although definitions and specific solutions vary widely, they generally aim to deliver sufficient food production, on existing land, with reduced environmental impacts ***(39)***. Whilst not restricted to nutrient management, there are many options for including productive, efficient and environmentally-compatible nutrient management interventions under this sustainable intensification umbrella.

What are the obstacles to progress?

In the largest sense, large scale shifts in agricultural management require transformation of the global food system, which in turn requires a wider transformation of global and regional economic systems. This is far beyond the scope of nutrient management, but does need to be acknowledged.

Reconciling nutrient management and biodiversity conservation can frequently be enacted at local scales, but there are challenges with communication and adoption at scales that will have significant and lasting biodiversity benefits. These include the need for training around many 'alternative' management approaches, upfront costs associated with more nature-positive approaches, operational and labor inputs required for agroecological interventions, or lack of government and industry incentives to move to nature-positive management.

A major obstacle lies in the need for policy incentives that address the external effects of nutrient management on biodiversity and making these solutions commercially viable and competitive with existing systems for all actors in the food chain, and farmers in particular. This is a common issue in pursuing nature-positive food systems, and not restricted to nutrient management. However, a significant number of farmers globally appear to already pursue a range of 'sustainable intensification' interventions, with estimates of 163 million farms (29% of global total), on 453 million ha (9% of global agricultural land), undertaking sustainable intensification in some form ***(40)***.

What are the critical knowledge gaps?

Whist we already have a wealth of information relating to sustainable nutrient management and how to better conserve biodiversity, there are also many knowledge gaps, that, if filled would help in accelerating effective changes and implementing innovative management strategies. These include:

- What specific role do fertilizers play in sparing land for conservation in specific regions and landscapes?
- How do different mineral elements managed in agricultural systems affect biodiversity, positively or negatively?
- What are the 'right' levels of soil organic matter and microbial biodiversity for optimal functioning of different agricultural systems, and how can they be achieved and maintained through good nutrient management practices?
- How can biodiversity objectives be included in fertilizer recommendations and nutrient stewardship schemes?
- What are socioecological, economic, and psychological barriers for farmers to adopt biodiversity-friendly nutrient management practices? How can evidence, incentives and new technology help to overcome those?
- What are the specific opportunities for nature-positive and productive nutrient management on the hundreds of millions of smallholder farms worldwide, and what are the implications of farm amalgamation into larger holdings for nutrient use and biodiversity?

WHAT CAN BE DONE?

Optimizing nutrient management to minimize negative effects on biodiversity is an integral component of the new paradigm for responsible plant nutrition, which seeks to achieve a societal optimum through a food systems and circular economy approach ***(41)***. Many of the suggested interventions and approaches for nutrient management will depend to a considerable extent on the scale and speed of food system transformation in different world regions. Such is the variability of farming systems, nutrient management strategies and biodiversity responses, that there are no 'silver bullet' solutions for addressing biodiversity losses; but there are many options that, when integrated, could have positive outcomes, for both biodiversity conservation and food production (Box 1).

3. *https://eatforum.org/eat-lancet-commission/*
4. *https://www.foodandlandusecoalition.org/*
5. *https://planetbaseddiets.panda.org/*

BOX 1. A selection of interventions directly and indirectly related to nutrient management that can be used to mitigate negative impacts, and maintain or improve biodiversity and ecosystem services.

- Better land use planning, avoiding agriculture in areas of especially high biodiversity value and halting any further expansion of the agriculturally used land area
- Closing yield gaps globally to produce enough food and to spare land
- Restoring degraded agricultural land and improving soil health and function through integrated soil fertility management
- Increased agrobiodiversity and integrated approaches to nutrient management (e.g. mineral fertilizers in combination with available organic fertilizers, crop rotations, intercropping, crop-livestock systems with closed nutrient cycles, tree crop and legume integration)
- Avoiding nutrient losses through adopting precision farming approaches for nutrient stewardship at scale, including matching fertilizer type, application rates, timing, and location to land characteristics and crop and producer requirements
- Buffer zones around environmentally sensitive areas such as waterways
- Context-specific targets for nutrient use efficiency and limits on nutrient surpluses, including better monitoring and early warning systems
- Evidence-based policies, financial incentives and outreach to enable producers and supporting businesses to transition to more biodiversity-optimized and sustainable farming approaches, including fertilizers

Incorporating nutrient management into global biodiversity goals and action targets

The complex interactions between food production and biodiversity are an increasingly hot topic, with strong representation in the UN Sustainable Development Goals, and in the forthcoming UN Food Systems Summit. They are also represented in the global biodiversity targets of the UN Convention on Biological Diversity (CBD). Global goals and developmental roadmaps are a way of acknowledging the importance of an issue, summarizing what needs to be achieved, and enshrining it in universally accepted language and protocol, and thus providing a clear mandate for finer scale policy and actions to deliver the goals' intent. It is vital that when developing goals, targets and indicators for nutrient management, a number of issues and nuances are taken into consideration and well represented:

(i) disaggregating the biodiversity impacts of nutrient application from other effects of agricultural intensification and other forms of 'pollution', such as pesticides and plastic waste, as they operate very differently;

(ii) considering that nutrient management brings enormous food and nutrition security benefits and has the potential to reduce agricultural expansion through yield increases;

(iii) recognizing that whilst there may be a need to reduce nutrient inputs in some parts of the world, there is an urgent need to increase use in others: the emphasis should be on optimizing fertilizer use and nutrient use efficiency as a whole;

(iv) setting targets that are context-specific, outcome focused, actionable, feasible and measurable, including taking into account potential indirect implications (e.g., impacts on food security).

In the CBD 2010 Aichi Biodiversity Targets[7], nutrient management was included in Target 8:"By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity". Although this is an outcome-focused target, it lacks many of the other requirements stated above and has not been achieved. In fact, nearly 2/3 of all countries have not even reported on this target, and only a few have claimed to have met it.[8]

The currently discussed post-2020 Global Biodiversity Framework includes 21 targets for urgent action over the decade to 2030[9]. Nutrients are mainly represented by Target 7, proposed as: "Reduce pollution from all sources to levels that are not harmful to biodiversity and ecosystem functions and human health, including by reducing nutrients lost to the environment by at least half, and pesticides by at least two thirds and eliminating the discharge of plastic waste." However, as drafted, the current proposal does not address nutrients and their manifold effects on biodiversity adequately. Likewise, halving the amount of nutrients lost to the environment by 2030 is a very ambitious expectation.[10]

We advocate for a more nuanced and balanced approach to developing goals and targets around nutrient management, focusing on targets that meet the four requirements stated above. Such targets should aim to optimize nutrient use efficiency and minimize nutrient losses to the environment at the locations and scales that most affect biodiversity. One example for this are farming-specific safe target ranges that can be defined for nitrogen use efficiency (NUE), calculated as the ratio of nutrient outputs: nutrient inputs. One example for this is the NUE indicator proposed by the European Nitrogen Expert Panel **(42)**. It guides on-farm nutrient management towards reducing nitrate leaching, runoff, ammonia and N_2O emissions while achieving high levels of productivity and sustaining soil health, thus addressing several key impacts on biodiversity (Figure 3). New Zealand has already enacted such an approach as a collaboration between

6. https://www.un.org/en/food-systems-summit
7. https://www.cbd.int/sp/targets/
8. https://www.cbd.int/aichi-targets/target/8
9. https://www.cbd.int/doc/c/d605/21e2/2110159110d84290e1afca98/wg2020-03-03-en.pdf
10. Assuming that progress can be accelerated through better policies, technologies and practices, a more realistic target could be a 20% increase in cropland NUE in 2030 relative to 2020, with an equivalent reduction in nitrogen surplus and losses. Such increases can be achieved under diverse agricultural conditions.

government and the fertilizer industry, in which national-scale computer modeling of landscape fluxes of nutrients is used to support the development of farm nutrient budgets and fertilizer inputs in terms of right place, right rate and timing.[11]

Particular emphasis should be placed on avoiding ecosystem conversion and eutrophication as perhaps the most important nutrient-biodiversity impacts. Eutrophication of inland and marine waters due to excessive losses of nitrogen and phosphorus represents a particularly complex challenge. It is caused by excess nutrient loads from multiple sources within catchments and coastal zones. Main sources include: (i) fertilizer use in agriculture, (ii) emissions from combustion of fossil fuels, (iii) legume agriculture, (iv) animal husbandry, (v) inadequately treated wastewater, and (vi) aquaculture. Nonpoint (diffuse) source inputs (i-iv above) far exceed point source inputs (v and vi above) and they are mostly associated with farming practices such as cropping systems, soil tillage, and the use of fertilizers and manure (19, 20, 43). Mitigating nutrient loads in large catchments requires consensus, concrete targets, multi-stakeholder interventions and effective monitoring. Good examples already exist in different world regions, which can provide guidance for framing such targets and interventions (Box 2).

BOX 2. The **Great Barrier Reef** in Australia is renowned for its ecological importance, natural beauty, and contribution to Australia's tourism sector and GDP, but it is also under increasing threat from land runoff associated with past and ongoing agricultural inputs, catchment management, coastal development, extreme weather events and climate change impacts such as the recent extensive coral bleaching events. In 2017, a scientific consensus statement[12] provided the common understanding for developing a Reef 2050 Water Quality Improvement Plan. Stakeholders agreed to concrete targets for 2025, i.e., actions required in identified reef catchments, as well as targets for wetland condition and inshore marine health. Through this approach it was possible to define specific targets for nutrient load reductions and make significant progress towards meeting those, e.g.: [13]

- 60% reduction in end-of-catchment dissolved inorganic N loads by 2025; achieved so far: 25.5%
- 20% reduction in end-of-catchment particulate N loads by 2025; achieved so far: 13.4%
- 20% reduction in end-of-catchment particulate P loads by 2025; achieved so far: 16.6%

Improved planning of agricultural development

Another key approach is to more systematically address nutrient-biodiversity interactions in terms of land use, particularly the spatial coincidence of agriculture and areas of high biodiversity. Identifying the areas of spatial overlap will enable concentration of nutrient stewardship and conservation efforts in relation to broadscale agricultural development. There are especially great concerns regarding the potential influence of future projected agricultural expansion and intensification on biodiversity hotspots in Central and South America, sub-Saharan Africa, Madagascar, Eastern Australia, Southeast Asia, India, Indonesia and Papua New Guinea ***(44)***. Effective and well-enforced land planning processes are vital ***(45)*** in such tropical and subtropical regions where conversion of natural ecosystems will have a disproportionately high biodiversity impact because both species richness and endemism are very high.

These hotspots are often areas where there are large yield gaps. There are clear opportunities to use targeted intensification to reduce cropland expansion into critical biodiversity areas ***(46)*** (Figure 4).

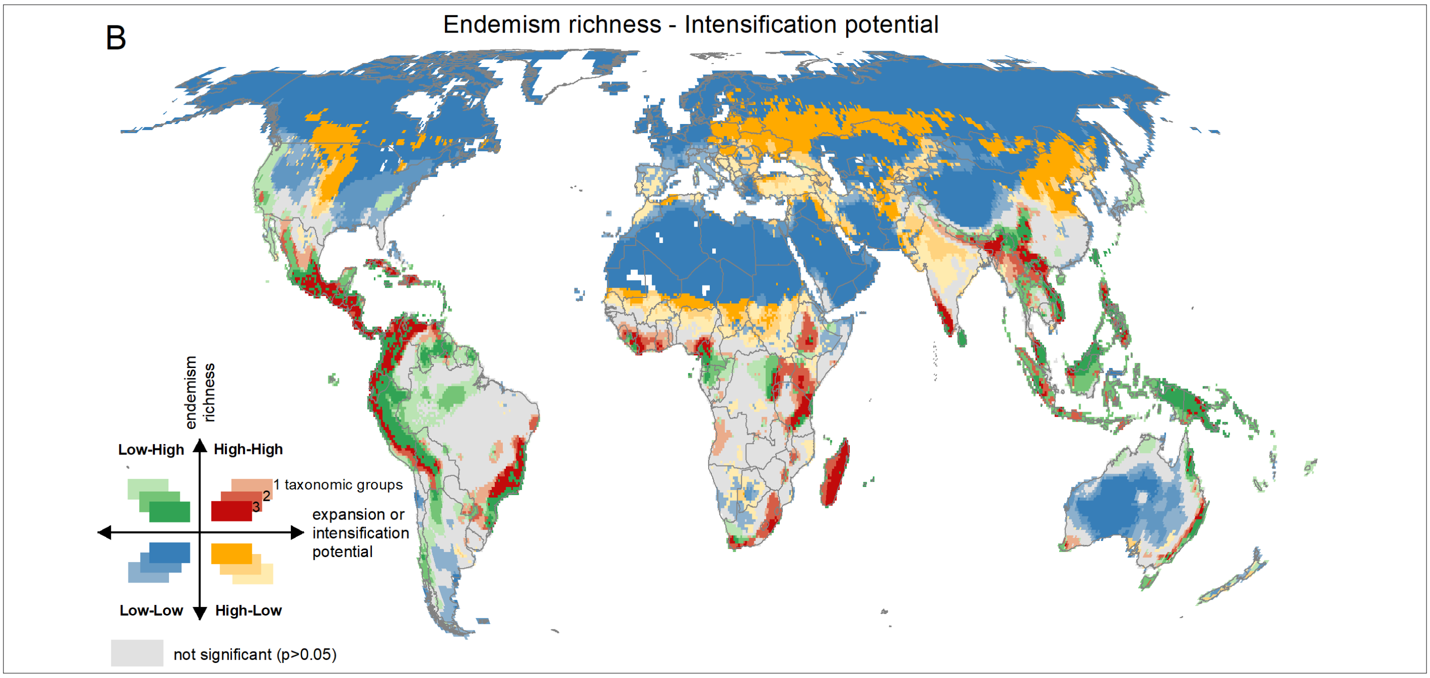

Figure 4. Avoiding the 'red zones': cropland expansion and intensification should be minimal in regions with high endemism richness (44). Areas of high biodiversity and high intensification potential include all of the 'top 10' most biodiverse countries on the planet, Brazil, Colombia, Indonesia, China, Mexico, Peru, Australia, India, Ecuador and Venezuela.

11. https://www.overseer.org.nz/
12. https://www.reefplan.qld.gov.au/science-and-research/the-scientific-consensus-statement
13. https://reportcard.reefplan.qld.gov.au/

Even with greatly improved planning of agricultural development in relation to biodiversity hotspots, intensification will inevitably occur in areas of high biodiversity on a frequent basis, requiring strong environmental legislation and enforcement of nutrient stewardship. Another mechanism for protecting specific areas of ecosystems and habitat from unavoidable localized intensification is to retain or install vegetation buffer zones between agricultural land and natural ecosystems. This can be a very effective way of a) reducing fertilizer (and other agrochemical) drift from arable land, b) intercepting runoff from cropland and grazing land, and c) providing multiple other ecosystem services, such as biodiversity habitat, pollinator resources, natural enemy habitat, connectivity for animal species, flood control, and carbon sequestration ***(47)***. Due to the complexity of influencing factors on buffer effectiveness in any given landscape context, a 'one size fits all' approach to buffers is unlikely to be useful, and context-specific guidelines and tailoring are required, rather than generic approaches.

Integrating biodiversity in nutrient stewardship

4R Nutrient Stewardship ***(48)*** and similar approaches have been developed and promoted in different parts of the world as a set of nutrient management guidelines that seek to be more efficient and site-specific about what form and how, when, where, etc., nutrients are applied. They offer a potential win-win situation of greater agricultural productivity and efficiency combined with decreasing negative environmental responses, through less percolation into ground water, run-off into waterbodies, drift into nearby ecosystems, and so on.

Each of the 4Rs (Right source, Right rate, Right time and Right place) have implications for biodiversity and can have on- and off-site biodiversity elements incorporated into them. Such an approach would be underpinned by two perspectives on biodiversity: (i) inappropriate (and especially excessive) nutrient inputs are likely to have negative effects on biodiversity at both the point of application and off-site (Figure 3); (ii) biodiversity can be harnessed to provide benefits that can work in tandem with nutrient management to increase both productivity and the biodiversity itself.
Examples of how biodiversity responses could be integrated into the existing 4Rs include:

Right source: We need improved understanding of the effects of specific inorganic and organic fertilizer types on various facets of biodiversity (e.g., soil species richness, distribution, community composition), and how this relates to ecosystem service delivery. In particular, a clear understanding of which nutrient sources are less harmful to biodiversity, and the inclusion of this into evidence-based management strategies, would help conserve biodiversity without compromising production. Understanding better the net changes in biodiversity across scales is also fundamental, as there are likely to be trade-offs between field, farm, landscape, and larger scales that need to be accounted for.

Right rate: At present, fertilizer recommendations are mainly geared towards agronomically or economically optimal nutrient amounts. Biodiversity appears to decline more at higher levels of nutrient application. Therefore, a new approach could aim to develop the know-how for determining levels of application that meet the combined needs of crop uptake and biodiversity responses. This would also be vital for setting sensible and mutually beneficial nutrient management thresholds and targets in various agricultural systems.

Right time: Understanding how application timing relates to various aspects of biodiversity in time and space (e.g. life cycles, distribution, food availability, breeding) will help to inform mitigation practices that can be undertaken with regard to how nutrient applications affect various elements of biodiversity at field to landscape scales.

Right place: Avoiding excessive application around the immediate proximity of specific on-farm and in-field habitat features would help to reduce negative impacts, and may not affect crop yields. These could include, botanically diverse field margins, hedgerows, ponds, ditches, rivers/streams/creeks, paddock trees (native species), woody vegetation remnants, or species-rich grasslands.

Developing a systematic list of nutrient management practices that benefit biodiversity would help to design nutrient stewardship roadmaps that reduce excess fertilizer application, improve or maintain productivity and yields, and provide multiple benefits to on-farm biodiversity.

Sustainable intensification of farming systems

Sustainable intensification of farming embodies the general idea that improvements in total factor productivity[14] will simultaneously allow increasing future food production and farmers' income, while limiting the impact of agriculture on the environment. Such an optimum intensification level can be reached using a measure such as green total factor productivity – or total resource productivity – that also accounts for climate, soils and biodiversity ***(49)***.

Beyond 4R and more precise management of mineral and organic fertilizers, proposed actions that could support growth in green TFP often include nitrogen-fixing legumes as part of rotations or intercropping, integration of livestock and their manure into cropping systems, composting with crop residues and food waste, green manures, diversification with grain legumes, conservation agriculture, or planting leguminous trees and shrubs as part of production or natural resource management aspects of the farm system.

For example, leguminous rotations and intercropping can have positive implications on soil nitrogen and yields ***(50)***, and increase soil organic matter. Such management interventions can also have benefits for a range of biodiversity, such as microbes, pollinators such

14. Total factor productivity (TFP) is a measure of all outputs over inputs involved in the agricultural sector or a sub-sector of it. Growth in TFP reflects more efficient use of resources as influenced by knowledge and management.

as bees and other invertebrates such as parasitic wasps, all of which can have positive effects on production through the provision of a range of ecosystem services.

There are already excellent sources of summarized scientific information on potentially effective sustainable agriculture management actions that may have biodiversity benefits ***(51)***. However, depending on the farming context, these vary in their effectiveness, ease of implementation and scalability. Many are likely to be more labor-intensive and dependent on the support provided to farmers for implementation. Other challenges relate to necessary infrastructure and equipment, training for farmers, economic competitiveness, and how to monitor effectiveness across multiple objectives (e.g., yields, input efficiency, on-site and off-site environmental impacts), and adjust management accordingly ***(52)***.

Clearly, sustainable intensification (or regenerative agriculture, or nature-positive agriculture, for that matter), including the optimizing of fertilizer use, can and should occur at different scales:

- The scale of the field and farm—e.g., application when and where needed, in the forms, amounts and frequency required by the crops and conditions, using a 4R-style approach, including measures that both conserve and harness biodiversity and ecosystem services;
- At the landscape scale, production should generally be on the most productive land forms and soil types. However, this needs to be balanced with the importance of conserving a comprehensive and representative set of ecosystems, not just those ecosystems that do not coincide with areas suitable for agriculture or other uses. More effective and nuanced land use planning and policy setting will aid in this endeavor;
- The regional and global rationalization of fertilizer production and use (e.g. reduction in areas where yield gaps are absent or low, increase in regions with high yield gaps), will help address biodiversity responses at multiple scales, including offsite pollution and unchecked agricultural expansion.

WHO NEEDS TO DO WHAT?

The range of influential stakeholders in the food system is vast and likely to vary considerably in terms of sphere of influence and what needs to be done to move towards optimized and nature-positive nutrient management. The main stakeholder groups that can really make a difference in this area and the priority areas of intervention include:

Policy makers need to utilize the best available science, engage in dialogue and elicit expert opinion from agriculturalists, the fertilizer industry and conservation professionals, to develop and deliver improved policy in the areas of a) improved land use planning and regulations, b) incentivization in order to ensure that further land conversion does not occur, especially in areas of high biodiversity, and c) realistic and regionally applicable and feasible nutrient management targets and thresholds that will strike a balance between the dual needs of production and conservation. Also, working with the fertilizer industry and distributors to ensure that inputs are equitably available and appropriately deployed in regions of the world with large yield gaps is going to be essential.

The **global fertilizer industry** should work with conservation scientists to develop and promote fertilizer products that retain their productivity-increasing capabilities, but are more benign on the many facets of biodiversity that are negatively affected by fertilizer application. Industry will also make significant efforts to reduce greenhouse gas emissions in fertilizer production. Investment in nutrient stewardship and precision farming approaches for more sustainable nutrient management and incorporation of biodiversity into corporate sustainability strategies and measures of success are also vital.

Conservation organizations have a very considerable role to play, working with other stakeholders to a) establish where high levels of nutrient use may lead to disproportionate biodiversity impacts, b) inform where yield gap-driven agricultural expansion is a risk, c) provide spatially explicit information on areas of high biodiversity and high vulnerability to other stakeholders, d) work with the industry, farmers and farm advisory bodies to develop improved management options, and e) work with governments and the industry to develop incentives and policy to help farmers to implement optimized and more sustainable nutrient management.

Farmers, farm advisers and service providers need to adopt a role that is more focused on being stewards of natural resources (including, but not limited to biodiversity), and providing a broader range of benefits that moves beyond direct agricultural production. Using the 4R approach, incorporating biodiversity elements into this, conducting biodiversity conservation actions on-farm (e.g., buffer zones, with government and industry support), and broadly adopting sustainable intensification approaches where possible, are prominent examples of the roles to play. This will require considerable support and incentives from governments, assistance from multiple industry bodies, and capacity building from a local and scientifically informed extension network.

Consumers can help by purchasing food that is produced using more sustainable management approaches where such products and labelling information are available and reliable. This needs to be generated and supported by governments, the entire food industry, producers, and conservation organizations. Moves to a 'nature-positive' nutrient management accreditation and labeling scheme, similar to those used by Rainforest Alliance and the platforms on various commodity crops (e.g. palm oil, rice) would be welcomed as long as they are accurately presented and benefits are tangible and measurable.

Researchers in the areas of conservation biology, agronomy, governance, farm technology and numerous other areas can make a great contribution to filling the many knowledge gaps around nutrient management and biodiversity. Social scientists are urgently needed to help with understanding the socioeconomic and behavioral barriers for adopting biodiversity friendly nutrient management practices. In addition, it is critical to ensure that the generated scientific knowledge is utilized by those with the power for enacting positive change, such as governments, the fertilizer industry, conservation organizations, and producers and extensionists.

Above all, there needs to be a balanced approach that accounts for both the necessity of fertilizer management and the great benefits that this brings in terms of food and nutrition security (and potential reduction of ecosystem conversion), and the undoubted environmental damage that inappropriate use can cause. This is why the use of the word 'optimal' is not just semantic, but needs to be operationalized at all scales, through all aspects of production, and by all stakeholders. What is needed initially is a better understanding and appreciation of both the benefits and the issues with fertilizer application by all stakeholders, particular those in the production and the conservation domains. If the conservation sector and the production sector can both begin moving towards a context-specific optimization of nutrient management, then a more enabling environment for positive and enduring change may be created.

WHAT WOULD SUCCESS LOOK LIKE?

What does positive and enduring change look like? In the short term, ensuring that nutrient management is adequately represented in global goals such as the new CBD Targets, is a good first step. Compared to where we are today, priority outcomes that must be achieved within one human generation include:

- Food production meets multiple objectives; nutrient management is optimized to close yield and efficiency gaps, provide better nutrition and meet biodiversity objectives at different scales;
- No further conversion of natural ecosystems is needed; biodiversity hotspots are managed through improved land use planning, including proactive legislation, and incentives;
- Biodiversity requirements are included in nutrient stewardship solutions that are scalable and adaptable to different farming systems;
- Demonstrable improvements in on-farm and off-farm biodiversity and ecosystem services associated with nutrient use in agriculture (e.g., soil health, river health, ocean health);
- Reduced pre-farm and on-farm greenhouse gas emissions associated with fertilizer production and use contribute to mitigating global climate change impacts on biodiversity;
- Critical knowledge gaps are filled through research, and evidence has been incorporated into legislative action that objectively addresses farming and biodiversity objectives.

Increased dialogue between fertilizer manufacturers, and conservation scientists and practitioners, will reveal common ground and points of contention that require resolution. Engaging farming communities, from smallholders to vast agri-business, and all points in between, is critical, as they are the end point users. There needs to be improved policy and legislation in many aspects of nutrient management, as well as incentives to encourage best practice. And of course, there needs to be targeted research that determines what best practice looks like. The fertilizer industry has already committed to a sustainability-driven business approach. This will now also require greater interaction and collaboration with biodiversity-focused stakeholders.

REFERENCES

1. E. S. Brondizio, J. Settele, S. Diaz, H. Ngo, Eds., *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES, Bonn, Germany, 2019).
2. G. Ceballos *et al.*, Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Science advances.* **1**, e1400253 (2015), doi:10.1126/sciadv.1400253.
3. S. L. Maxwell, R. A. Fuller, T. M. Brooks, J. E. M. Watson, Biodiversity: The ravages of guns, nets and bulldozers. Nature. **536**, 143–145 (2016), doi:10.1038/536143a.
4. B. M. Campbell et al., Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society.* **22** (2017), doi:10.5751/ES-09595-220408.
5. WWF, *Living Planet Report 2020 - Bending the curve of biodiversity loss* (World Wildlife Fund, Gland, Switzerland, 2020).
6. H. Liu *et al.*, Production of global daily seamless data cubes and quantification of global land cover change from 1985 to 2020 - iMap World 1.0. Remote Sens. Environ. **258**, 112364 (2021), doi:10.1016/j.rse.2021.112364.
7. H. L. Wright, I. R. Lake, P. M. Dolman, Agriculture-a key element for conservation in the developing world. *Conservation Letters.* **5**, 11–19 (2012), doi:10.1111/j.1755-263X.2011.00208.x.
8. S. J. Attwood *et al.*, Declining birds in Australian agricultural landscapes may benefit from aspects of the European agri-environment model. Biological Conservation. **142**, 1981–1991 (2009), doi:10.1016/j.biocon.2009.04.008.
9. B. J. Cardinale *et al.*, Biodiversity loss and its impact on humanity. Nature. **486,** 59–67 (2012), doi:10.1038/nature11148.
10. M.-A. de Graaff, N. Hornslein, H. L. Throop, P. Kardol, L. T. van Diepen, Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: A meta-analysis. *Adv. Agronomy.* **155**, 1–44, doi:10.1016/bs.agron.2019.01.001.
11. J. Waterhouse, J. Brodie, S. Lewis, A. Mitchell, Quantifying the sources of pollutants in the Great Barrier Reef catchments and the relative risk to reef ecosystems. *Marine Pollution Bulletin.* **65**, 394–406 (2012), doi:10.1016/j.marpolbul.2011.09.031.
12. K. M. Carlson et al., Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Chang.* **7,** 63–68 (2017), doi:10.1038/nclimate3158.
13. H. F. M. ten Berge et al., Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security.* **23**, 9–21 (2019).
14. M. P. van Loon *et al.*, Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Global Change Biol.* **25**, 3720–3730 (2019), doi:10.1111/gcb.14783.
15. J. R. Stevenson, N. Villoria, D. Byerlee, T. Kelley, M. Maredia, Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proc. Natl. Acad. Sci.* **110**, 8363–8368 (2013), doi:10.1073/pnas.1208065110.
16. E. F. Lambin *et al.*, Effectiveness and synergies of policy instruments for land use governance in tropical regions. *Global Environmental Change.* **28,** 129–140 (2014), doi:10.1016/j.gloenvcha.2014.06.007.
17. K. Gerstner, C. F. Dormann, A. Stein, A. M. Manceur, R. Seppelt, Effects of land use on plant diversity - A global meta-analysis. *J Appl Ecol.* **51**, 1690–1700 (2014), doi:10.1111/1365-2664.12329.
18. B. Gove, S. A. Power, G. P. Buckley, J. Ghazoul, Effects of herbicide spray drift and fertilizer overspread on selected species of woodland ground flora: comparison between short-term and long-term impact assessments and field surveys. *J Appl Ecol.* **44,** 374–384 (2007), doi:10.1111/j.1365-2664.2007.01261.x.
19. T. C. Malone, A. Newton, The globalization of cultural eutrophication in the coastal ocean: causes and consequences. *Front. Mar. Sci.* **7** (2020), doi:10.3389/fmars.2020.00670.
20. M. Le Moal et al., Eutrophication: A new wine in an old bottle? Science of *The Total Environment.* **651**, 1–11 (2019), doi:10.1016/j.scitotenv.2018.09.139.
21. F. J. Kroon, P. Thorburn, B. Schaffelke, S. Whitten, Towards protecting the Great Barrier Reef from land-based pollution. *Global Change Biol.* **22**, 1985–2002 (2016), doi:10.1111/gcb.13262.
22. J. E. Brodie *et al.*, Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. *Marine Pollution Bulletin.* **65**, 81–100 (2012), doi:10.1016/j.marpolbul.2011.12.012.
23. M. Crippa *et al.*, Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food.* **2**, 198–209 (2021), doi:10.1038/s43016-021-00225-9.
24. S. E. Bauer, K. Tsigaridis, R. Miller, Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.* **43,** 5394–5400 (2016), doi:10.1002/2016GL068354.
25. G. S. Okin *et al.*, Impacts of atmospheric nutrient deposition on marine productivity: Roles of nitrogen, phosphorus, and iron. *Global Biogeochem. Cycles.* **25**, n/a-n/a (2011), doi:10.1029/2010GB003858.
26. J. Fuhrer *et al.*, Current and future ozone risks to global terrestrial biodiversity and ecosystem processes. *Ecology and Evolution.* **6**, 8785–8799 (2016), doi:10.1002/ece3.2568.
27. F. Baudron, K. E. Giller, Agriculture and nature: Trouble and strife? *Biological Conservation.* **170,** 232–245 (2014), doi:10.1016/j.biocon.2013.12.009.
28. R. M. Ewers, J. Scharlemann, A. Balmford, R. E. Green, Do increases in agricultural yield spare land for nature? *Global Change Biol.* **15**, 1716–1726 (2009), doi:10.1111/j.1365-2486.2009.01849.x.
29. M. P. Nessel, T. Konnovitch, G. Q. Romero, A. L. González, Nitrogen and phosphorus enrichment cause declines in invertebrate populations: a global meta-analysis. *Biological Reviews* (2021), doi:10.1111/brv.12771.
30. J. Storkey *et al.*, Grassland biodiversity bounces back from long-term nitrogen addition. *Nature.* **528**, 401–404 (2015), doi:10.1038/nature16444.
31. K. A. Macintosh *et al.*, Transforming soil phosphorus fertility management strategies to support the delivery of multiple ecosystem services from agricultural systems. *Science of The Total Environment.* **649**, 90–98 (2019), doi:10.1016/j.scitotenv.2018.08.272.
32. A. Kovács-Hostyánszki, P. Batáry, W. J. Peach, A. Báldi, Effects of fertilizer application on summer usage of cereal fields by farmland birds in central Hungary. *Bird Study.* **58,** 330–337 (2011), doi:10.1080/00063657.2011.582853.
33. S. Díaz *et al.*, Assessing nature's contributions to people. *Science.* **359**, 270 (2018), doi:10.1126/science.aap8826.
34. L. A. Schulte *et al.*, Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proc. Natl. Acad. Sci.* **114,** 11247 (2017), doi:10.1073/pnas.1620229114.
35. D. H. Wall, U. N. Nielsen, Biodiversity and ecosystem services: is it the same below ground? *Nature Education Knowledge.* **3**, 8 (2012).
36. W. Yang, T. Dietz, W. Liu, J. Luo, J. Liu, Going beyond the Millennium Ecosystem Assessment: an index system of human dependence on ecosystem services. *PLoS ONE.* **8**, e64581 (2013), doi:10.1371/journal.pone.0064581.
37. D. A. Landis, Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic and Applied Ecology.* **18,** 1–12 (2017), doi:10.1016/j.baae.2016.07.005.
38. D. Leclère *et al.*, Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature.* **585**, 551–556 (2020), doi:10.1038/s41586-020-2705-y.
39. D. Tilman, C. Balzer, J. Hill, B. L. Befort, Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci.* **108**, 20260–20264 (2011), doi:10.1073/pnas.1116437108.

40. J. Pretty et al., Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability. **1,** 441–446 (2018).

41. Scientific Panel on Responsible Plant Nutrition, A new paradigm for plant nutrition. Issue Brief 01 (2020) (available at https://www.sprpn.org/issue-briefs).

42. EU Nitrogen Expert Panel, Nitrogen Use Efficiency (NUE). Guidance document for assessing NUE at farm level (Wageningen University, Alterra, Wageningen, NL, 2016).

43. D. J. Conley et al., Ecology. Controlling eutrophication: nitrogen and phosphorus. Science. **323,** 1014–1015 (2009), doi:10.1126/science.1167755.

44. F. Zabel et al., Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nat Commun. **10**, 2844 (2019), doi:10.1038/s41467-019-10775-z.

45. L. Tacconi, R. J. Rodrigues, A. Maryudi, Law enforcement and deforestation: Lessons for Indonesia from Brazil. Forest Policy and Economics. **108**, 101943 (2019), doi:10.1016/j.forpol.2019.05.029.

46. Y. Zhang, M. Pang, B. L. Dickens, D. P. Edwards, L. R. Carrasco, Global hotspots of conversion risk from multiple crop expansion. Biological Conservation. **254,** 108963 (2021), doi:10.1016/j.biocon.2021.108963.

47. L. J. Cole, J. Stockan, R. Helliwell, Managing riparian buffer strips to optimise ecosystem services: A review. Agriculture, Ecosystems & Environment. **296**, 106891 (2020), doi:10.1016/j.agee.2020.106891.

48. International Plant Nutrition Institute, 4R plant nutrition manual: A manual for improving the management of plant nutrition, metric version (IPNI, Norcross, GA, USA, 2016).

49. R. Seppelt, C. Arndt, M. Beckmann, E. A. Martin, T. W. Hertel, Deciphering the Biodiversity-Production Mutualism in the Global Food Security Debate. Trends in Ecology & Evolution. **35**, 1011–1020 (2020), doi:10.1016/j.tree.2020.06.012.

50. F. Stagnari, A. Maggio, A. Galieni, M. Pisante, Multiple benefits of legumes for agriculture sustainability: an overview. Chemical and Biological Technologies in Agriculture. **4**, 2 (2017), doi:10.1186/s40538-016-0085-1.

51. W. J. Sutherland, L. V. Dicks, S. O. Petrovan, R. K. Smith, What works in conservation 2020 (Open Book Publishers, Cambridge, UK, 2020).

52. N. Mahon, I. Crute, M. Di Bonito, E. A. Simmons, M. M. Islam, Towards a broad-based and holistic framework of Sustainable Intensification indicators. Land Use Policy. **77**, 576–597 (2018), doi:10.1016/j.landusepol.2018.06.009.

AUTHORS, CITATION AND CONTACT

Authors: Coordinating lead author: Simon Attwood (Consultant, Biodiversity Conservation and Management, UK)
Contributing authors: All members of the Scientific Panel on Responsible Plant Nutrition.
Tom Bruulsema (Plant Nutrition Canada), Ismail Cakmak (Sabanci University, Turkey), Achim Dobermann (International Fertilizer Association, France), Bruno Gerard (CIMMYT, Mexico), Kaushik Majumdar (African Plant Nutrition Institute, Morocco), Michael McLaughlin (University of Adelaide, Australia), Pytrik Reidsma (Wageningen University & Research, The Netherlands), Bernard Vanlauwe (International Institute of Tropical Agriculture, Kenya), Lini Wollenberg (CGIAR Climate Change, Agriculture & Food Security Program, USA), Fusuo Zhang (China Agricultural University, China), Xin Zhang (University of Maryland Center for Environmental Science, USA)

Citation: Scientific Panel on Responsible Plant Nutrition. 2021. Achieving nature-positive plant nutrition: fertilizers and biodiversity. Issue Brief 02. Available at www.sprpn.org

Further information: Scientific Panel on Responsible Plant Nutrition, c/o IFA, 49, avenue d'Iéna, 75116 Paris, France; info@sprpn.org