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# Joint nitrogen and phosphorus management for sustainable development and climate goals

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## Abstract

The United Nations Sustainable Development Goals (SDGs) and the Paris Climate Agreement are possibly the two most important pieces of international environmental policy thus far this century. The SDGs set a number of socioeconomic and environmental targets to be achieved by 2030, and the Paris Climate Agreement provides a framework for the international community to stay below the 2$^{o}$C temperature threshold. Such a range of ambitious goals will require measures that can simultaneously address several issues and produce multiple co-benefits, from improved water quality to reduced food waste. A joint approach to reducing nitrogen and phosphorus pollution is a prime example given their myriad impacts on the environment and human health. This study assesses the national climate plans of fifteen countries for language indicating a target or clear commitment that could involve improved N and P management. These countries represent 75% of both global greenhouse gas emissions and N and P consumption. We find that a joint approach could make important contributions to achieving all the national climate plans analyzed and 7 out of 17 SDGs. Joint abatement measures exist for wastewater, agriculture and consumer behavior. Challenges to a joint approach to nitrogen and phosphorus management include their role as essential nutrients and key differences in their availability and chemistry. Whilst there is currently insufficient integration between science, policies and practice on this issue, near-term policy opportunities exist. Looking forward, how humanity manages its relationship with these essential nutrients over the coming decades will be a key bellwether of whether sustainable development is truly achievable.

Keywords: Nitrogen; Phosphorus; Sustainable Development Goals; Paris Climate Agreement; Environmental Policy

## 1. Introduction

2015 was perhaps the most important year ever for international environmental policy. In September, the United Nations signed on to the Sustainable Development Goals (SDGs), a suite of 17 environmental, social and economic objectives to be achieved by 2030 ranging from marine protection to gender equality. In December, a new international climate treaty – the Paris Climate Agreement – was gaveled into being, a result of decades of diplomacy and the submission of 152 country climate plans, officially referred to as Nationally Determined Contributions (NDCs). It is widely hoped that these two milestones determine the direction of global and national environmental action for the next several decades [1,2]. The NDCs and SDGs together will require significant action from governments on the environment across several fronts – from protecting and restoring water quality and biodiversity, to mitigating climate change and the release of hazardous waste. Given this range of focal points, measures that can achieve multiple objectives simultaneously will be crucial for reducing policy transaction costs and increasing the likelihood that governments' many environmental goals are met [3]. Moreover, the political shift in countries like the United States towards prioritizing national economic interests regardless of the international consequences means that environmental actions that can deliver local benefits that are as great, if not greater, than the benefits achieved internationally will be more likely to generate political support [4].

One important issue where action could help achieve multiple sustainability objectives and deliver local benefits as great as the benefits at larger scales is nutrient management, specifically the improved management of nitrogen (N) and phosphorus (P) flows. The following study provides a preliminary analysis of measures that take a joint approach to N and P management, and discuss how they can aid the implementation of country NDCs and a number of SDGs. And conversely, how the lack of such an approach could impede progress on these two landmark achievements in environmental policy.

### 1.1 Nitrogen and Phosphorus Pollution

How humanity manages N and P flows will be a central determinant of the state of the environment over the course of this century. On the one hand, N and P are essential nutrients and therefore crucial for agricultural productivity. According to one estimate, the Haber- Bosch process – the industrial synthesis of ammonia, the main feedstock for all N fertilizer types – enabled an increase in food production that is now responsible for feeding half of the world's population [5]. Meanwhile, in 2016, 90% of the 28 million tons of P mobilized from finite geological deposits was used to support food production [6].

On the other hand, nutrient pollution is one of the most important environmental threats of our time. It was recently identified as one of only two planetary boundaries that humanity has surpassed – a level of human interference with an environmental issue beyond which damage is expected to increase dramatically, with potentially irreversible consequences [7]. Agriculture is the dominant source of nutrient pollution, as the inefficient management of manure and synthetic fertilizer leads to significant losses of N and P (Figure 1). Over the entire agri-food chain – from fertilizer production to waste management – only 8% of newly mobilized N and 15% of P is consumed by people [8].

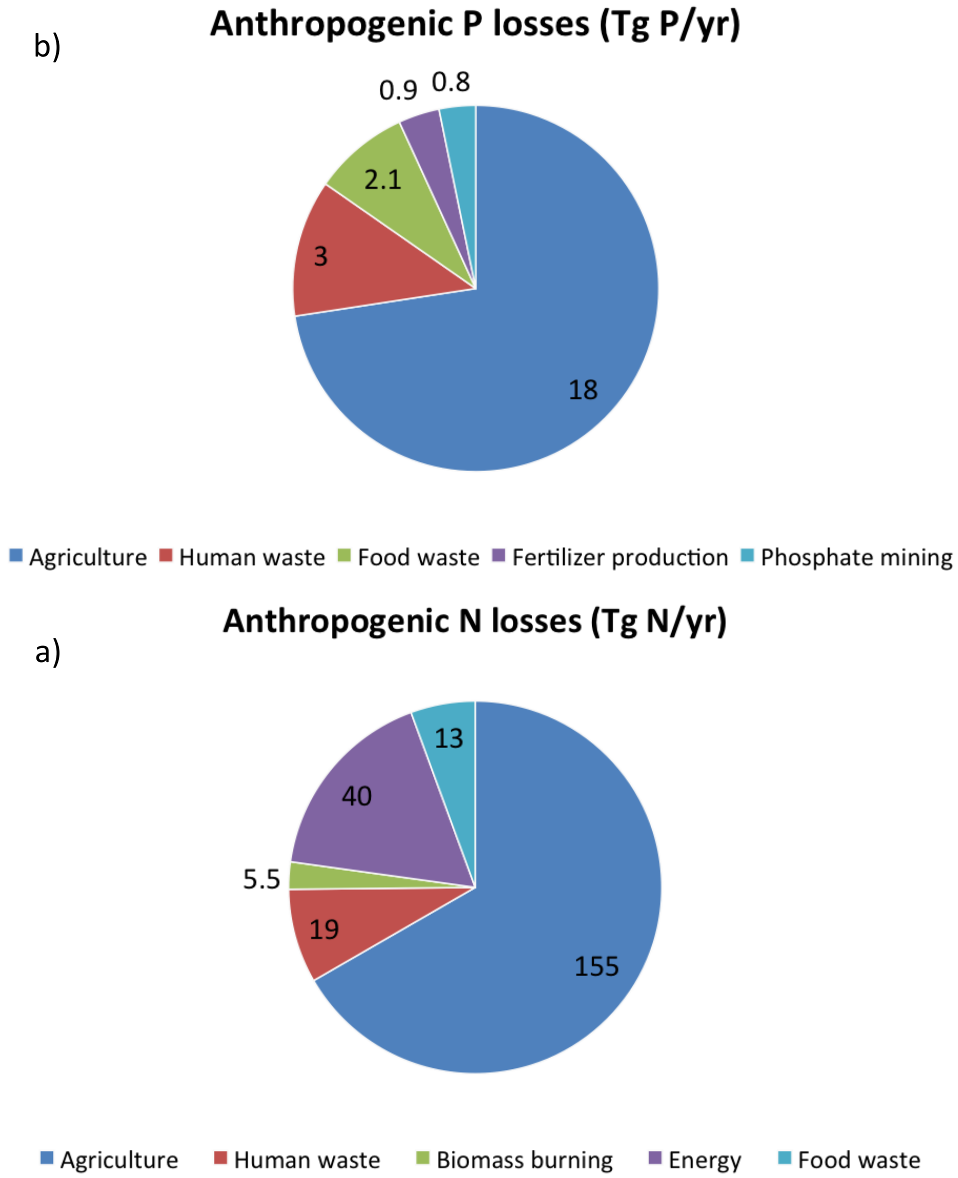


**Figure 1** Annual anthropogenic nitrogen and phosphorus losses by sector [8,9].

These losses have a considerable economic impact on society. One study estimates the global annual social cost of N pollution to be $200-$2000 billion USD, approximately 0.3-3% of global gross domestic product (GDP)[8]. And a recent study of P losses estimates that to avoid 5.0-9.0 Mt of anthropogenic P from entering freshwaters would cost $250-$450 billion USD annually, approximately 0.4%-0.7% of global GDP [10]. This does not include the restoration costs for already degraded water resources, which are estimated to cost the US alone $2 billion per year [11].

The unique chemistry of N and P means that these losses exacerbate a range of environmental and human health problems. Once an N atom is in "reactive" form (any form other than atmospheric dinitrogen, $N_2$) it can convert readily among multiple chemical forms, each with a specific impact on the environment and human health. This phenomenon is referred to as the N cascade [12], and it increases the risk of exceeding other planetary boundaries such as climate change and biodiversity loss, while also putting efforts to reach a number of SDGs at risk.

The chemistry of P confines it mainly to aqueous media. Elevated P concentrations in water bodies can stimulate excessive algal growth, leading to eutrophication. The environmental consequences include contamination of drinking water supplies, fisheries and recreational waters with toxin-producing cyanobacteria and the onset of dead-zones in coastal waters with associated fish kills. An estimated 15 Mt P ultimately enters the oceans as a result of human activities every year contributing to the creation of more 400 coastal dead zones globally, including areas of the Baltic Sea, Chesapeake Bay and parts of the Great Barrier Reef [10]. New P flows are supplemented by legacy P stores in river, lake and estuarine sediments as well as agricultural soils, making improved P management an issue that crosses temporal and spatial scales[13].

From a climate standpoint, $N_2O$ is not the only link between nutrient pollution and climate change. First, a central plank of most ambitious GHG mitigation pathways consistent with the $2^{o}$C target is a massive expansion in the amount of land devoted to bioenergy production [14], which could entail a concomitant increase in N and P consumption depending on the crops chosen and the amount of land set aside to grow them [15]. Second, manure management is both a key source of $N_2O$ emissions and P losses as well as methane ($CH_4$), and an uncoordinated mitigation approach could lead to undesirable tradeoffs[16]. Third, according to the IPCC, increasing carbon (C) sequestration in agricultural soils is the mitigation option with the highest mitigation potential in the agricultural sector. However, given fixed C:N:P ratios in soils, humanity's capacity to fulfill the potential of this option will greatly depend on soil N and P availability [4]. Fourth, nitrogen oxides ($NO_x$) and ammonia ($NH_3$) emissions likely have a cooling effect on the climate due to their impacts on atmospheric concentrations of $CH_4$, ozone ($O_3$) and aerosols, partially offsetting the positive radiative forcing from $N_2O$[17]. Finally, recent studies show that changing precipitation rates and patterns as a result of climate change could increase N loading by 5%-33% in the US and P loading up to 30% in the UK, exacerbating eutrophication among other impacts [18,19]. These connections between nutrient pollution and climate change underscore even further the challenges posed by nutrient pollution and the central role that an improved and integrated approach to nutrient management could have in discussions on SDG and NDC implementation.

### 1.2 The importance of a joined up approach

While the chemical differences between N and P put certain areas more at risk of pollution than others (e.g. one study argues that areas with high soil P levels coupled with high erosion and surface runoff potentials should prioritize reducing P losses while areas with high soil N levels and high soil permeability should prioritize N) [20], a more integrated approach to N and P management is essential policy for several reasons. First, agricultural sources of N and P pollution overwhelmingly share the same drivers, namely the inefficient management of synthetic fertilizers and manure. Consequently, several – though not all – of the measures to address one can also reduce losses of the other. For example, if a farmer decides to implement split application, dividing up their nutrient application into smaller doses over the growing season so as to better synchronize nutrient supply and demand, this can reduce overall nutrient application rates and thereby reduce both N and P losses. Second, eutrophication – the central joint impact of N and P pollution – is a complex function of the amount and relative availability of N versus P, as well as C and silica, and so in some cases a narrow focus on either N or P cannot adequately or permanently resolve the problem [21]. This has been recognized by several environmental policies, such as the OSPAR and HELCOM Conventions to reduce marine pollution, which have set joint reduction targets for N and P pollution, though implementation has not always followed suit [22]. Third, a singular focus on N or P can lead to measures that reduce the targeted nutrient while increasing levels of the other, a phenomenon known as pollution swapping [23]. For example, using crop N requirements to determine manure application rates may reduce nitrate ($NO_3^-$) leaching, but simultaneously increase soil P levels and thereby exacerbate P losses [20]. Only a joined-up approach will incentivize policymakers and other stakeholders to prioritize measures that jointly reduce N and P pollution and avoid those that do not. And finally, such a joined-up approach – capitalizing on the synergies and minimizing the potential trade-offs – will be crucial to the successful implementation of two of the most important international environmental commitments that almost all national governments have signed up for: the SDGs and the Paris Climate Agreement.

### 1.3 The Sustainable Development Goals and the Paris Climate Agreement

Together the SDGs and the Paris Climate Agreement embody the international community's top environmental priorities for the coming decades. The SDGs are a set of 17 goals (comprised of a more detailed subset of 169 targets) that aim to increase social, economic and environmental wellbeing by 2030. Successors to the Millennium Development Goals (MDGs), they are global in scope, but with action required from national to local levels, ranging from ending poverty and hunger to increasing access to health services and secondary education. Most of the SDGs are deeply intertwined[3], and unlike the MDGS apply equally to developed and developing countries. For example, Goal 13 calls for "urgent action to target climate change and is impacts", which is central to the success of several SDGs from ending hunger (Goal 2) to protecting marine and terrestrial ecosystems (Goals 14 and 15).

The Paris Climate Agreement is the main global response to Goal 13, the culmination of many years of diplomacy to develop a robust international climate regime. It is underpinned by 152 country climate plans, known as "Nationally Determined Contributions" (NDCs), which cover more than 95% of global greenhouse gas emissions. Instead of the top-down approach that characterized the Kyoto Protocol and drove the Copenhagen negotiations in 2009, the Paris Climate Agreement is a combination of bottom-up and top-down: countries submit their own mitigation and adaptation plans based on what they believe is the right combination of ambition and feasibility. This is supplemented by an international framework under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), which aims to monitor and support countries to implement their submitted plans and increase the ambition of these plans over time [1].

Given the importance of N and P to society, both as essential nutrients and as the source of a multitude of environmental impacts, a joined-up approach to N and P management could make a considerable contribution to country implementation of the SDGs and the Paris Climate Agreement. Indeed, of the 188 draft national climate plans submitted before the Paris conference in December 2015 (referred to as "Intended Nationally Determined Contributions" or INDCs), 43 mentioned fertilizer management and 46 mentioned manure management as specific mitigation measures[24]. And nutrient management is relevant to 16 of the 17 SDGs, though the role of N and P differs depending on the goal [25]. Certain SDGs require more nutrients (e.g. Goal 2 focused on ending hunger), certain require less (e.g. Goals 11-15 focused on reducing environmental impacts), and another set could help improve nutrient management (e.g. Goal 17 focused on increasing knowledge and technology transfer). Consequently, the goal of this study is to provide an initial list of measures that could not only embody a joined-up approach to N and P management, but that could also directly contribute to the implementation of the SDGs and country NDCs.

## 2. Methods

We employ a two-tiered methodology to develop a list of N and P management measures that could contribute to the implementation of NDCs and SDGs. We first did an extensive literature review of peer-reviewed articles and reports that evaluate N and P management measures and their effectiveness. We focused our search on policy areas and measures where both N and P management have shown potential, i.e. we exclude sectors such as transport where only N losses occur, and phosphate mining where only P losses occur. This restriction limits our scope of study to agriculture, wastewater and consumer behavior. The second part of our methodology involved a text analysis of the NDCs submitted to the UNFCCC. We restricted our review to the top ten countries in terms of either greenhouse gas emissions and/or N and P consumption. This gave us a list of 15 countries, including the 28 member states of the European Union as a whole: China, USA, EU-28, India, Russia, Japan, Brazil, Indonesia, Canada, Mexico, Pakistan, Turkey, Australia, Bangladesh and Argentina. Together these countries represent over 75% of both global greenhouse gas emissions and N and P consumption [26,27]. For each policy area of interest, we searched each country NDC for language indicating a target or a clear commitment that could directly or indirectly involve N and P management, following an approach similar to previous text analyses of the NDCs[28-30]. We then sought to link this to the relevant SDG targets via a text analysis of the SDGs, taking into account the multiple environmental and human health impacts that N and P pollution can exacerbate.

## 3. Results and Discussion

### 3.1 Human waste

Human waste – defined here as human feces and urine – is the source of 8% of global N losses and 13% of global P losses [8,9]. At least two overarching and potentially complementary strategies exist to reduce or recover more N and P from this source: wastewater treatment and wastewater reuse in agriculture. For the former, depending on the level of treatment 10%-80% of N and 33%-96% of P can be removed from wastewater flows before reaching the environment [31,32]. One technical option that can reduce and recover both N and P from wastewater is struvite (magnesium ammonium phosphate) precipitation, which can then be reused as a slow-release fertilizer [33,34]. However, struvite removes N and P in a 1:1 molar ratio and the actual N:P ratio in wastewater is typically much higher, meaning that only 16% of N is typically removed via this option compared to 96% of P[32]. Consequently, additional measures are often necessary to further reduce and recover N such as urine source separation [35]. Recent estimates suggest that up to 75% of N can be reused in agriculture via a latrine water recycling system [36,37], while processes such as enhanced biological phosphorus removal can recover up to 50% of P from wastewater for reuse as an agricultural input [9,35].

From a climate perspective, a recycled fertilizer such as struvite has a carbon footprint approximately 25% lower than typical mineral P fertilizer, while avoiding N discharge to surface water via wastewater reuse could reduce total anthropogenic $N_2O$ emissions by 5% [31,38]. Wastewater reuse in agriculture can also reduce methane ($CH_4$) emissions by 60%-80% [39]. Almost all the NDCs analyzed include the waste sector as part of their sectoral coverage, with several countries detailing specific goals. These include improved urban waste management (e.g. Indonesia, Japan, Mexico), and initiatives to increase the reuse and recycling of wastewater (e.g. China, India, Turkey) (Table 1). As for the SDGs, a joint N and P approach could help achieve at least four specific targets (in addition to the aforementioned climate benefits): by 2030 halve untreated wastewater (SDG 6.4), reduce the per environmental impact of cities via improved municipal and waste management (SDG 11.6), environmentally sound management of wastes (SDG 12.4), waste reduction via prevention, reduction, reuse, and recycling (SDG 12.5).

[Insert Table 1 here]

### 3.2 Agriculture

Agricultural soils are the source of over 60% of N and P losses to the environment. While almost all lost P is waterborne, the unique chemistry of the N cascade means that only 60% of N lost globally on average is waterborne, the remainder emitted as $NH_3$ (25%), $NO_x$ (5%) and $N_2O$ (10%) [8,9]. There are at least five measures in this sector that can jointly reduce or recover N and P: crop residue recycling, cover crops, precision agriculture, improved livestock feeding and improved manure management (Table 2).

Crop residues incorporate approximately 30% of the N and P taken up by crops. Complete recycling of these residues could supply approximately 33% of N and 20%-33% of P that would otherwise be provided via synthetic fertilizers[40]. Furthermore, this could substantially reduce crop residue burning, with complementary improvements in air quality and human health outcomes[41]. However, compared to synthetic fertilizers, the N and P in crop residues is not as readily available, as their high cellulose and lignin content hinders rapid degradation [42]. From a climate standpoint, crop residue recycling could also reduce $N_2O$ emissions and increase soil carbon storage by more than 15% [43]. Planting cover crops could reduce N losses by 40%-70% and P losses by approximately 20% [44,45] by capturing nutrients that would otherwise be lost to the environment in the off-season. They could also increase soil carbon storage by 10%-30% [46,47], though the impacts on $N_2O$ emissions are less clear [48]. Precision agriculture encompasses a range of practices and technologies, from GPS technology to fertigation, that better synchronizes nutrient supply and demand in agricultural soils [49]. Depending on the specific practice employed, N losses can be reduced by 20%-40% and P input needs by up to 50% [50,51]. It could also reduce $N_2O$ emissions by 20%-40% and improve soil carbon storage by 1%-10% [43,50]. Improved livestock feeding can include the use of various feed additives and hormones as well as feed processing techniques such as grinding and pelleting to improve digestibility and nutrient uptake. Such measures can reduce N and P excretion rates in manure by 15%-30% and 35%- 60%, respectively [52,53]. In terms of climate benefits, these measures can potentially reduce $N_2O$ emissions by over 50% and methane ($CH_4$) emissions by 1%-10% [31,43]. Finally, improved manure management involves better reuse, recovery and recycling of manure from animal confinements as an N input in crop and grass production. A conversion from solid to liquid manure systems can potentially reduce N losses by 50%, while the mechanical separation of liquid and solid manure (leading to 60% P recovery) can be used to generate an alternative source of P inputs to synthetic fertilizer [50,54]. These measures can also reduce $N_2O$ emissions by 50% and $CH_4$ emissions by over 15% [43,50].

All the NDCs analyzed for this paper include agriculture as one of the sectors covered. Several include specific measures to reduce agricultural GHG emissions, input use or improve nutrient use efficiency. While the focus is on $N_2O$ given its climate-warming properties, the wording of most NDC targets is broad enough to include the possibility of a joint approach with P, which would also help achieve several SDG targets. For example, China has a goal of stabilizing fertilizer consumption by 2020, Mexico is aiming for increased development of agroecosystems, Turkey has pledged to control fertilizer use and implement modern agricultural practices, while Pakistan is pushing to improve manure recycling, reuse and recovery, among others. These initiatives could make progress on at least seven SDG targets across five SDGs – from ensuring sustainable food production systems (SDG 2.4) and halving the proportion of untreated wastewater (SDG 6.4), to conserving marine (SDG 6.6) and terrestrial ecosystems (SDG 15.1).

[Insert Table 2 here]

## 3.3 Consumers

Reductions in consumer food waste (responsible for approximately 5% of both N and P losses) and meat consumption are both important N and P loss mitigation measures (Table 3). Their implementation requires a change in human behavior rather than the implementation of new practices or technologies; a more complex endeavor requiring a shift in attitudes, personal and social norms and perceptions of behavioral control in order to achieve lasting change[55]. For example, taxing food products based on their nutrient footprints or creating incentives to increase household composting are not limited by technical constraints, but rather the political feasibility of these measures. Accordingly, the range of possible reductions in N and P losses is large, with reductions in food waste sparking anywhere between 15%-95% reductions and less meat consumption leading to 10%-50% reductions [51]. As to the climate impacts, a recent study suggests that a carbon price of \$52 $tCO_2$ could lead to a 10% decrease in $CO_2$ equivalent emissions from meat and milk consumption by 2020 [56].

There is much less focus on these types of measures in country NDCs, with only China's vague commitment to "enhance education for all citizens on low-carbon way of life and consumption". The SDGs make no mention of meat consumption, with the dietary focus squarely on ending hunger and access to nutritious foods. As for food waste, SDG target 12.3 commits to halving food waste by 2030.

[Insert Table 3 here]

## 4. Policy challenges and opportunities

Despite the number of potential joint measures, there are several challenges to implementation that need to be addressed. Kanter (2018) examines several of them from an N perspective, but this analysis is also relevant to a joint N and P management approach. First, most environmental policies on this topic are not structured in a way that reflect the multitude of environment and health impacts nutrient pollution can cause. This is because much existing environmental policy is organized by impact or by sector. For example, in the EU, $NO_3$ pollution is controlled under the Nitrates Directive, while $NH_3$ and $NO_x$ emissions are regulated by the Gothenburg Protocol under the Convention on Long Range Transboundary Air Pollution. Meanwhile, $N_2O$ reductions can generate credits from the EU Emissions Trading Scheme (the world's largest carbon market), but only from certain industrial sources (and not agriculture). This ecosystem of policy approaches would not necessarily be a problem were it not for the fact that a narrow focus on one form of nutrient pollution can sometimes exacerbate others [4]. Furthermore, policies that do target both N and P, such as the EU Water Framework Directive, do not encourage a joint approach, which can exacerbate the trade-off risks highlighted in Section 1.2 [57].

Second, agriculture is the main source of both N and P losses, which is arguably the most challenging sector for environmental policies to address [58]. This is due to a number of factors: agricultural pollution is typically diffuse, which makes it technically and economically challenging to monitor and enforce environmental measures; farmers are a powerful political force in many countries, making the passage of (often unpopular) environmental measures very difficult; and frequent tensions between food security and environmental protection. This last factor highlights another unique challenge regarding N and P: they are essential nutrients for food production. Feeding 10 billion by 2050 would be impossible without them. This means formulating policies around improving nutrient use efficiency or reducing nutrient surpluses rather than absolute reductions in N and P use [4]. These types of policies are likely to be significantly more effective if farmers and other relevant stakeholders are involved in their design and provided regular updates on their implementation[59].

Finally the distinct chemical natures of N versus P could lead policymakers to push for measures that do not embody a joint approach to N and P. For example, P is a finite resource[51], while N is essentially infinite, the Haber-Bosch process only needing to harness a miniscule fraction of atmospheric $N_2$ every year to satisfy global synthetic fertilizer demand[5]. Food production in nearly every country is reliant on mined phosphate imports from only a few countries. Five countries control approximately 85% of the world's phosphate rock reserves, leaving food systems in most countries dependent on phosphorus imports and vulnerable to fertilizer price fluctuations and geopolitical instabilities in producing countries[60]. By contrast, the Haber-Bosch process can be done anywhere with access to a hydrocarbon feedstock. These differences could persuade policymakers to manage N and P individually, and potentially at different spatial scales. Moreover, most current N and P policies are not set up in a way to encourage joint management: several N pollution measures seek to enhance conditions for complete denitrification (the conversion of $NO_3^-$ to $N_2$) while many P pollution measures focus on enhancing P recovery, recycling and reuse. Consequently, a joint approach to N and P management will require the scientific community to make this a research priority, collaborating across to disciplines to deliver scientific sound, policy-relevant recommendations to policymakers.

The Global Partnership on Nutrient Management (GPNM), a multi-stakeholder partnership mechanism facilitated by the UN Environment provides a platform for dialogue between stakeholders from both N and P communities (www.nutrientchallenge.org/). Publications such as "Our Nutrient World"[8], one of the first collaborations between the N and P scientific communities, highlight overlaps between the management of these nutrients and the advantages of a holistic approach. Despite the clear benefits, there is great potential to improve communication and coordination between both scientific communities. One such area for improvement is at the science-policy interface, where the N community leads the way with the International Nitrogen Management System (INMS) (www.inms.international), a new science policy initiative whose primary goal is to produce the first global N assessment by 2021. The "Our Phosphorus Future" project is attempting to unify the P community in a similar fashion to provide guidance to policy makers via printed and web-based materials on global P management (www.opfglobal.com). Clear links between these distinct N and P initiatives should be established, possibly under the auspices of GPNM, in the form of joint conferences, reports and policy briefings.

Better coordination between the N and P scientific communities and the development of robust links to the policy world, from local to global scales, could provide a foundation for several joint policy actions that contribute towards climate and SDG targets. First, the next round of updated NDCs are scheduled to be submitted under the UNFCCC in 2020 and are meant to build on the ambition of the initial set by adding more stringent mitigation and adaptation actions[61]. Including joint approaches to N and P management in these updated NDCs by implementing a selection of the actions outlined in Section 3 could be an important component of this increased ambition. Countries that already have clear-cut nutrient targets, such as China's commitment to halt the growth in domestic fertilizer consumption by 2020, could lead the way in adopting a joint approach and demonstrate to other countries the important climate and local benefits. Second, several countries have already researched and adopted sectoral plans for the implementation of the SDGs, several of which include explicit measures to address N pollution. For example, in their plan to implement the SDGs in their domestic beef sector, Uruguay has already adopted an N target to reduce N pollution intensity (kg N loss per head of cattle) by 25% by 2030[62]. A target for P could potentially be added given the joint benefits from improved livestock feeding (Section 3.2; Table 2). Nevertheless, the details of such a target will vary from country to country depending on the type of production system that predominates. Furthermore, countries and regions that already have longstanding N policies such as the EU's Nitrates Directive and the Convention on Long-Range Transboundary Air Pollution's protocols on $NO_x$ and $NH_3$, could integrate joint approaches to N and P within their frameworks via, for example, guidance documents on specific mitigation measures or the adoption of conditional subsidies where financial aid from the government is dependent on the adoption of certain management practices[63].

## 5. Conclusion

In spite of the considerable challenges, this study demonstrates that joint approaches to N and P management are key strategies for achieving sustainable development and climate goals. Near-term policy objectives could include specific targets related to nutrient management in the next round of national climate plans; the integration of N and P management strategies within national SDG implementation plans [51]; and the promotion of joint approaches to N and P under existing nutrient management policies. We believe that these environmental aims can be achieved while also significantly increasing nutrient consumption in regions that need to guarantee food security. Looking ahead, future studies need to build on the preliminary roadmap outlined in this paper to develop a more comprehensive, regionally differentiated framework for joint approaches to N and P that can also raise awareness and stimulate input from key stakeholders. More broadly, the many facets of humanity's relationship with N and P – from essential resources to ecosystem threats – reflect the central challenge of sustainable development: improving human wellbeing on a warming and more crowded planet while minimizing the related environmental impacts.

**Table 1** Estimates from the literature of the effectiveness of abatement measures demonstrated to jointly reduce nitrogen and phosphorus pollution from the wastewater sector. Climate impacts are shown, as well as links to country contributions to the Paris Climate Agreement and the Sustainable Development Goals. References for estimates cited in the main text.

| Measure | N impacts | P impacts | Climate impacts | NDC links | SDG links |
|---|---|---|---|---|---|
| *Wastewater reuse in agriculture* | 75% recovery | 20%-50% recovery | 5% $N_2O$ reduction<br><br>25% $CO_2e$ reduction from fertilizer production | China: Commit to improving "waste separation and recycling system"<br>Argentina, Australia, Brazil, Canada, Russia, USA: Covered sectors include waste<br>European Union: Covered sectors include "solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, waste water treatment and discharge"<br>Indonesia: Commit to enhancing "management capacity of urban waste water, reduce land fill waste...and utilization of waste in energy production." | SDG 6.4: By 2030, halve the proportion of untreated wastewater and substantially increase safe reuse and recycling globally<br>SDG 11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention... municipal and other waste management<br>SDG 12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle<br>SDG 12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse |
| *Wastewater treatment* | 10%-80% reduction | 33%-96% reduction | 10%-80% reduction in $N_2O$<br><br>60%-80% reduction in $CH_4$ | India: Encouraging waste to compost conversion to sell as fertilizer; various initiatives to enhance reuse and recycling of wastewater; aims to construct 10.4 million new household toilets and 0.5 million public toilets.<br><br>Japan: "Introduction of electricity-generating waste water processing with microbe catalysis"; "Promote advanced technologies in sewage sludge incineration facilities"; "Reduction of municipal solid waste disposed of by direct landfill"; "Production of semi-aerobic landfill system for final disposal of municipal solid waste."; "Promote advanced technologies in sewage sludge incineration facilities."<br>Mexico: "Guarantee urban and industrial waste water treatment [to be implemented over the period 2020-2030]"<br>Turkey: "Reuse, recycle... to recover secondary raw materials"; "Recovering energy from waste" | |

**Table 2.** Estimates from the literature of the effectiveness of abatement measures demonstrated to jointly reduce nitrogen and phosphorus pollution from the agriculture sector. Climate impacts are shown, as well as links to country contributions to the Paris Climate Agreement and the Sustainable Development Goals. References for estimates cited in the main text.

| Measure | N reduction/recovery | P reduction/recovery | Climate impacts | NDC links | SDG links |
|---|---|---|---|---|---|
| *Crop residue recycling* | 33% reduction in N input needs | 20%-33% reduction in P input needs | >15% increase in soil C storage<br>>15% decrease in $N_2O$ emissions | - Argentina, Australia, Canada European Union, Russia: Covered sectors include agriculture<br>- Bangladesh: "Raise productivity of agricultural land and lower emissions of methane"<br>- Brazil: Restore 15 million hectares of degraded pastureland and enhance 5 million hectares of integrated crop-livestock-forestry systems; enhance cooperation with other developing countries on "low carbon and resilient agriculture."<br>- China: "Zero growth of fertilizer...utilization by 2020"; "Control CH4 and N2O emissions from farmland"; "Comprehensive utilization of straw, reutilization of agricultural and forestry wastes and comprehensive utilization of animal waste"; "Develop water-saving agricultural irrigation and cultivate heat-resistant and drought-resistant crops"; "Develop technologies on biological nitrogen fixation"<br>- India: "To better adapt to climate change by enhancing investments in development programmes in sectors vulnerable to climate change, particularly agriculture"<br>- Indonesia: "Improve agriculture productivity" as part of unconditional reduction target of 26% below BAU trajectory by 2020<br>- Japan: "Reduction of N2O emissions originating from fertilizer application"; "Reduction of CH4 emissions from paddy rice fields"<br>- Mexico: "...Development of agro-ecosystems through the incorporation of climate criteria in agriculture programs."<br>- Pakistan: Improve manure reuse, recovery, recycling and storage; reduce N2O via precision agriculture; crop management practices to reduce N requirements<br>- Turkey: "Controlling the use of fertilizers and implementing modern agricultural practices"<br>- United States: By 2025, 10% reduction in N2O emissions | - SDG 2.3: By 2030, double agricultural productivity<br>- SDG 2.4: By 2030, ensure sustainable food production systems<br>- SDG 3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contimanation<br>- SDG 6.4: By 2030, halve the proportion of untreated wastewater and substantially increase safe reuse and recylcing globally<br>- SDG 6.6: By 2030, protect and restore water-related ecosystems<br>- SDG 14.4: By 2025, prevent and significantly reduce marine pollution fo all kinds, in particular from land-based activities, including marine debris and nutrient pollution<br>- SDG 15.1: By 2020, ensure the conservation, restoration and sustainable use of terrestrial ecosystems |
| *Cover crops* | 40%-70% reduction in N losses | 17% reduction in P losses | 10%-30% increase in soil C storage (r, s) | | |
| *Precision agriculture* | 20%-40% reduction in losses | 50% reduction in P fertilizer needs | 20%-40% reduction in $N_2O$<br>1%-10% increase in soil C | | |
| *Improved livestock feeding* | 15%-30% reduction in manure N content | 35%-60% reduction in manure P content | 56% reduction in $N_2O$<br>1%-10% reduction in $CH_4$ | | |
| *Improved manure management* | 50% reduction in N losses | 60% recovery of P from manure | 50% reduction in $N_2O$ | | |

**Table 3** Estimates from the literature of the effectiveness of abatement measures demonstrated to jointly reduce nitrogen and phosphorus pollution via changes in human behavior. Climate impacts are shown, as well as links to country contributions to the Paris Climate Agreement and the Sustainable Development Goals. References for estimates cited in the main text.

| Measure | N & P recovery/reduction | Climate impacts | NDC links | SDG links |
|---|---|---|---|---|
| *Reduced food waste* | 15%-95% recovery | 10% reduction in $N_2O$ | - China: "Enhance education for all citizens on low-carbon way of life and consumption" | - SDG 12.3: By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses |
| *Reduced meat consumption* | 10%-50% reduction | 10% reduction in $N_2O$ | | |

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