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Innovations for a sustainable future: rising to the challenge of nitrogen greenhouse gas management in Latin America

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Latin America encompasses a dizzying array of ecosystems and socioeconomic models, and the region will be highly vulnerable to the projected impacts of climate change in the next century. At the same time, Latin America can significantly contribute to the mitigation of greenhouse gases (GHG) emissions within a sustainable development framework. Land use conversion with associated biomass burning, agriculture with N fertilizers and animal waste are the main anthropogenic sources of nitrous oxide (N_2O) emissions in the region, and have increased markedly in the last decades. Effective sustainable management for the mitigation of N_2O emissions requires the proper evaluation of all sources, many of which are still roughly estimated or unknown, testing alternatives to reduce primary sources, and technological innovation for higher resource-use efficiency within the farm. Current barriers might be overcome through policies that support sustainable practices that reduce negative environmental impacts and simultaneously maintaining ecosystem function and services.

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Introduction

A recent analysis of the challenges for Latin America and the Caribbean (LAC) region related to physical and socioeconomic impacts of climate change concluded that the region is particularly vulnerable to the observed and projected effects of climate change due to its geographic location, population distribution, infrastructure, and reliance on fragile or non-renewable natural resources for economic activities and livelihood [1•]. The conservative projection of yearly economic damages in LAC caused by some of the major physical impacts associated with the projected rise of 2°C in global mean air temperature is approximately 2.2% of the region's 2010 gross domestic product (GDP, $4.6 trillion). Potential losses of this magnitude clearly undermine the region's prospects for improvements in the quality of life by significantly limiting development options and severely restricting access to natural resources and ecosystem services, all with socially damaging consequences for equity and poverty levels [1•].

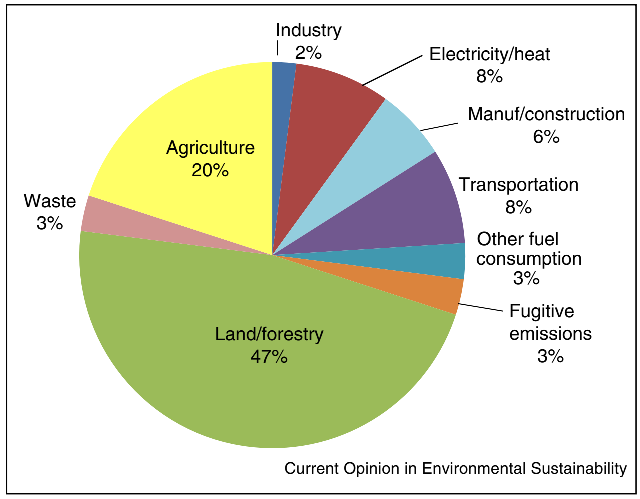
While the region shows genuine vulnerability to the projected impacts of climate change, LAC can also significantly contribute to the mitigation of greenhouse gases (GHGs) emissions within a sustainable development framework. Latin America accounted for 8% of the world's GHG emissions in 2005 [2], which include nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). Although N_2O is naturally present in the atmosphere as part of the Earth's nitrogen cycle, human activities are increasing the amount of atmospheric N_2O, particularly through agricultural activities. Specifically in Latin America, land use change (biomass burning — 50%), agriculture (N-fertilizers — 10%) and animal waste (40%) are the main sources of N_2O anthropogenic emissions [3]. Such increase is of particular concern due to the radiative forcing potential of N_2O (300 times that of CO_2 over a 100-year timescale on a per mole basis) and the strong correlation with increased emissions and agricultural intensification in the region.

Recently, the impacts of changes on the regional N cycle in Latin America were evaluated [4•]. These authors highlighted the lack of detailed information on many aspects of the nitrogen cycle, which is a serious impediment to our ability to evaluate and project how human activity is altering nitrogen pools and turnover at regional scales. Here, we expand this assessment to focus on the main drivers involved in human activities associated with increased GHGs and specifically nitrous oxide (N_2O) emissions in Latin America. In addition, we highlight potential mitigation strategies and projections for research needs and priorities.

Regional GHG emissions by sectors

Brazil contributed half of all regional GHG anthropogenic emissions in 2005 and together with Mexico, Venezuela and Argentina, accounted for nearly 80% of total emissions [2]. The share of total emissions among economic sectors is more critical when considering potential mitigation measures that could be adopted in the region. In 2005, the sectors 'Land use changes and forestry (LUCF)' and 'Agriculture' contributed with largest shares of total anthropogenic GHG emissions across the region, with 47% and 20% respectively (Figure 1). The Venezuelan national inventory, however, showed differences in the relative emissions by sector. The energy sector represented the largest source of GHG (75% of total emissions) followed by agriculture (17%) while LUCF represented a *net sink* of approximately 14 300 Gg CO_2 eq [5] (MARN-Venezuela, 2005). In addition N_2O emissions country-level emissions ranged widely, with 3% (Mexico) to 28% (Argentina) of total anthropogenic GHG emissions for the region (www.unfcc.int/ghg_data_unfcc).

Figure 1



Contributions of total anthropogenic greenhouse gas emissions in Latin America and the Caribbean (LAC) from different sources, 2005. The contributions refer to percentage shares of total anthropogenic GHG emissions from LAC, and not the total fraction of each sector's (i.e. energy) contribution.
Source: Vergara [1•] based on data compiled from World Resources Institute (2012).

GHG emissions from LUCF also showed important changes in other countries. Brazil's share of regional and global GHG emissions from land use changes was particularly significant in 2005, but has declined in the last decade. A recent update of emissions figures [6] indicate that in 2010, Brazil had reduced GHG emissions by nearly half, to 1.25 Pg CO_2 eq, compared to baseline emissions of 2.03 Pg CO_2 eq in 2005, strongly associated with the reduction of deforestation rates in the Amazon basin. In Argentina, between 1990 and 2000 [7], the LUCF sector showed greater relative changes, however, but with an increase in the net carbon sink of nearly 200%. Native vegetation conversion to agriculture and ranching also decreased in Mexico between 1990 and 2010 [8], which probably contributed to decreased GHG emissions in this country as well.

The comparison of N_2O emissions by country (Table 1) indicates that Brazil is by far the largest emitter in the region. In general, agriculture accounts for the largest share of N_2O emissions in the region (up to 96.8%). Globally, N_2O emission from agriculture is equivalent to about 66% of total gross anthropogenic emissions [9]. Agriculture plays a key role in the LAC economies, accounting for approximately 6% of regional gross domestic product (GDP) and 15% of employment in

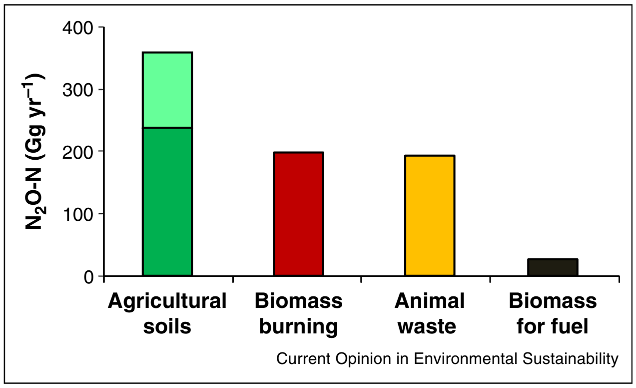
Table 1

Total anthropogenic emissions of greenhouse gases (GHG, Tg CO_2 eq) and N_2O (Tg CO_2 eq) from the largest emitters in Latin America. Data based on National Inventories of GHG submitted to the UNFCCC and prepared according IPCC guidelines

Country	Argentina	Brazil		Mexico		Venezuela
Year	2000	2000	2005	2000	2006	1999
Total GHG	238.70	2087.66	2191.86	563.23	711.65	177.90
Total N_2O (% of total GHG)	67.56 (28.3%)	169.20 (8.1%)	546.00 (24.9%)	12.13 (2.1%)	20.51 (2.9%)	16.15 (9.1%)
N_2O by sectors (% of total N_2O)						
Agriculture	65.39 (96.8%)	121.68 (71.9%)	476.20 (87.2%)	7.46 (61.5%)	6.99 (34.1%)	15.42 (95.5%)
Land use change	0.06	6.45	20.90	0.31	0.17	0.01
Energy	1.01	2.98	12.10	2.50	10.95	0.22
Industry	0.15	6.17	22.80	0.11	0.36	0.08
Waste	0.96	3.84	14.00	1.96	2.05	0.42

Source: www.unfcc.int/ghg_data_unfccc, July 18, 2014.

Figure 2



A general overview of different sources of N_2O-N emissions (Gg yr^{-1}) in the LAC region. Bars indicate total emissions per year calculated for the years of reference. The different colors for agricultural soils indicate the range of estimates for emissions from this sector. Data for agricultural soils (croplands with N fertilizer and application of manure) from [25,26]; biomass burning associated to deforestation [11]; animal waste [11] and biomass burning for fuels [16,18,19].

2010 [4•]. Agriculture also represents a key factor in regional food security. In the beginning of the 1960s, arable land in LAC was responsible for 7% of the global arable land area; 50 years later this proportion has increased to 11% [10•]. More than 50% of the global cultivation of sugarcane and coffee occur in Latin America, while soybean occupies more than 40% of the total global area [10•]. The use of N-fertilizer has grown from only 5 kg ha^{-1} to approximately 50 kg ha^{-1} over the last fifty years [10•].

Biomass burning (from landscape fires, household cooking and heating) represents about 11% of total gross anthropogenic global N_2O emissions [9]. In particular, Latin America alone emitted nearly 40% of the global N_2O emissions due to biomass burning in 1990, a disproportional contribution considering that Latin America corresponds to only about 13% of global land surface [11].

The following sections provide a more detailed perspective on the regional emissions of N_2O related to biomass burning and agriculture with a synthesis of available data from different sources (Figure 2). Despite the differences in source years and data sources, we attempted to assess the overall global relevance of these activities in the region and the potential to mitigate N_2O emissions. Clearly, the relative importance of agricultural activity is highlighted here, but additionally, the underappreciated role of biomass burning for contributing to N_2O emissions is approaching agriculture in terms of its relative contribution to overall emissions.

N_2O emissions from land use change and biomass burning

The clearing of natural vegetation, burning, fertilization of agricultural lands, intensive cattle ranching and increasing dominance by legume species in areas under secondary succession, have been identified as causes of increasing N_2O and NO emissions in tropical regions (see [12] for a review). However, large uncertainties remain for regional estimates of trace gas fluxes in Latin American ecosystems due to the scarcity of data with adequate spatial distribution and a combination of social and ecological factors that may affect the fluxes at local scale [4•].

Deforestation and biomass burning are important sources of N_2O emissions, but vary substantially among the major biomes in LAC. More than 80% of deforestation occurs in humid and dry forest, and savannas/shrublands [13•], and these conversions are most often accompanied by burning of extant vegetation or debris. It is estimated that from 15 to 30 million ha are burned per year in LAC [14,15]. The N_2O emissions caused by biomass burning associated with deforestation in 1990 were estimated to be near 200 Gg of N-N_2O in the region [11]. Subtropical regions in South America are also indirectly affected by biomass burning in tropical areas due to the long-range transport of smoke from Amazonia to the southern and southeastern part of the South American continent [17]. Fuel use for cooking and home heating is an additional source of burning, and it is estimated that 350 million tons of wood are burned per year in LAC, with half this amount in Brazil alone [16]. Assuming that 6.4 g N-N_2O is produced per Giga Joule (GJ) of fuel-wood burned [18] and that 1 ton of fire-wood produces 13 GJ of energy [19], we estimate that 350 million tons of wood burned would emit approximately 30 Gg of N-N_2O, which is currently not incorporated into any estimate of emissions from the region.

Following deforestation, most areas are converted to agriculture and grazing (pasture) lands [20]. The majority of natural vegetation areas that are burned are related to the opening of new grazing and agriculture areas. For example, Argentina experienced unprecedented deforestation in dry forests between 1977 and 2008 as a consequence of agricultural expansion [21], particularly for soybean production [22,23]. Paruelo *et al.* [21] estimated that the burning of 8.7 million tons of biomass yr^{-1} due to deforestation fires in Argentina produced emissions of 0.2 Gg of N_2O. Between 1994 and 2000, GHG emissions, mostly due to the burning of sugar cane residues, ranged between 187 and 208 Gg CO_2 eq (20% was from N_2O) [7]. Biomass burning has also increased in Mexico during the past 40 years although there is substantial inter-annual variability [24]; burning of agricultural residues is common in rural landscapes. Current numbers, based mainly on sugar cane cropping, account for only 9 Gg CO_2 eq [7] emissions per year, which is likely to be a serious underestimate of this source. In Venezuela [5], burning of agricultural residues and savanna areas emitted 0.1% and 0.4% of total N_2O emissions. On the basis of satellite measurements, it is likely that emissions from savanna burning are underestimated considering the dramatic increase in burned area in recent years in LAC [14]. As well, these authors have suggested an enhanced relative importance of small fires from savannas and grasslands to the global GHG emissions, all of which are currently undocumented.

N_2O emissions from agriculture

N_2O emissions from agriculture include direct emissions from agricultural soils, principally due to the application of animal manure and mineral N-fertilizers, and manure production in pastures. They also include indirect emissions resulting from the subsequent leaching of nitrate to ground water and surface waters, and from ammonia deposition that had volatilized as a result of agricultural activities. Estimates of ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching for Latin America in comparison to world values for the period between 1970 and 2030 are presented in Table 2. There is a consistent increase in both NH_3 volatilization and nitrate (NO_3^-) in the region in absolute and relative values, which is associated with increased agricultural intensity in both the crop and livestock sector. These trends suggest that indirect emissions of N_2O also will increase in the future.

For South and Central America, it was estimated that agricultural soils in 2005 emitted approximately 240 Gg of N-N_2O [25] up to approximately 360 Gg of N-N_2O [26] (Figure 2) due to the use of mineral N-fertilizers, to crop residues and animal manure [25]. This is equivalent to almost 10% of the global emissions, while arable land in LA is equivalent to 15% of the global estimate.

Table 2

Comparison of total ammonia (NH_3) volatilization (includes NH_3-N emissions from fertilizer and animal manure application, grazing, and from animal housing and manure storage systems). N_2O and NO emissions are based on fertilizer and animal manure application (excluding emissions from fallow land), and nitrate leaching for intensive agricultural systems (NO_3-N, Tg yr^{-1})[a] for Latin America. Percent values indicate the share of Latin America contribution to the world values

Region	Total NH_3-N	N_2O-N	NO-N	NO_3-N
1970				
Latin America	1.6	0.2	0.1	1.0
World	18.1	2.0	1.1	18.2
(%)	(8.8)	(10.0)	(9.1)	(5.5)
1995				
Latin America	3.7	0.3	0.1	2.9
World	34.2	2.7	1.5	28.5
(%)	(10.8)	(11.1)	(6.7)	(10.2)
2030				
Latin America	5.6	0.5	0.2	4.4
World	44.0	3.5	2.0	35.3
(%)	(12.7)	(14.3)	(10.0)	(12.5)

Data from Bowman *et al.* [49].

[a] Intensive agricultural systems include total arable land and grassland in mixed/industrial livestock production systems; pastoral systems are excluded.

The use of nitrogen fertilizers and other agronomic inputs in agriculture is imbalanced in the Latin American region, due to socio-economic factors that limit access to these inputs for many small landholders, combined with ecological factors, including baseline natural fertility of agricultural systems [4•]. For example, Argentina consumes 60% of the fertilizer in the Southern Cone countries (Argentina, Chile, Paraguay, and Uruguay) while in Brazil, three crops (maize, soybean and sugar cane) are responsible for 56% of the N, 71% of the P_2O_5 and 75% of the K_2O fertilizer application. Most of the emissions of GHGs in the agricultural sector in Brazil are associated with the domestic livestock and the cultivation of soybean, maize, sugar cane and rice, which together occupy more than 70% of the country's cultivated area. Emissions in this agricultural sector increased 37% from 1990 to 2005, considering primarily CH_4 and N_2O. In this period, crop productivity increased well above the extension of land area used for agricultural production [27•]. In contrast to Brazil, CH_4 and N_2O emissions in Mexico have remained stable during the period 1990–2010, with CH_4 representing 43% and N_2O 57% of emissions [28]. In 2010, N_2O emissions from soil management (~150 Gg N_2O) represented the largest contributor to GHG emissions from the agricultural sector in Mexico, likely attributed to the use of mineral N-fertilizers resulting from production. In Argentina, GHG emissions in the agricultural and cattle sector during the year 2000 represented 43% of total GHGs; 21% was associated with agricultural practices (primarily N_2O emissions) and 22% with livestock production (mostly CH_4) [29]. Direct N_2O emissions from agricultural lands increased 85% between 1990 and 2000 (from ~63.2 to 117.2 Gg N yr^{-1}), in line with the increment of nitrogen incorporated to the soil (from ~3.3 to 5.6 Gg N yr^{-1}), mainly due to cultivation of leguminous species, but also from mineral N-fertilizers [7]. While emission from synthetic nitrogen fertilization was 2% of the total N_2O emission in 1990, this value climbed to 12% by 2000 [29]. In Venezuela, total N_2O emissions from agriculture (48 Gg N_2O) have three major sources: direct emissions from agricultural soils (15 Gg N_2O); soils in grazed pastures (19 Gg N_2O); and indirect emissions from leaching and runoff (12 Gg N_2O) [5]. Recently measured N_2O emission factors (EF) derived from Venezuelan agricultural soils show a large range (0.30–6.1% of the applied N fertilizer), with overall average values of 1.9% higher than IPCC default value (1%) [30].

Increased biofuel production has been associated with direct and indirect land-use change, changes in land management practices, and increased application of fertilizers and pesticides. In Latin America, bioenergy development is based on two major crops: sugarcane and soybean. In 2008, Cruzten *et al.* [31] established that if the emission factor of N_2O in sugarcane crops surpasses 5% of the quantity of nitrogen in the fertilizers, the environmental damages caused by N_2O emissions would not offset the carbon gain by the biofuel displacement of fossil fuels. Recent studies based on field measurements in Brazil indicated that the emission factor associated with N-fertilizer use was well below 3%. Practices which include the joint application of vinasse and fertilizer, and associated with a large amount of crop straw remaining in the soil, can result in an emission factor of nearly 3% [32]. Sugarcane crop residues from green cane ('non-burning') harvests also increase N_2O emission when soil moisture increases [33].

Soybean cultivation is a very important activity in the agricultural sector of both Argentina and Brazil [34] and the rapid increase in areas devoted to this crop will have important consequences for N cycling in the region. Although emissions from soybean fields are considered low in Brazil [35] and Argentina [36] relative to N-fertilized crops, the large extension of cultivated area (about 25 million hectares in Brazil and 19 million hectares in Argentina, in 2012) with this crop might represent a significant source of N_2O emissions simply due to the very large area currently under cultivation. Very little is known regarding the potential source of N_2O emissions from this important agricultural activity in the region and warrants further research.

Livestock and manure management

The importance of Latin America in the livestock sector is also considerable, since the region hosts approximately 20% of the global cattle population and a similar proportion of poultry [9]. Although this is an underappreciated source of N_2O emissions, estimates for the region's N-N_2O emissions in 1990 from livestock waste were nearly 180 Gg of nitrogen [10•]. This value is equivalent to almost 20% of the global livestock related N-N_2O emissions for the same year. While later estimates did not distinguish emissions derived from mineral N-fertilizers from those derived from animal manure [25,26], it was estimated that approximately 3400 Gg of N as manure were used in LA [26], which is comparable to the 5700 Gg of N applied to croplands as N-fertilizer.

This is particularly relevant for the region as N_2O emissions related to cattle excreta in grazed pastures is considered 33% higher in South America than for the globe on average (23 kg CO_2 eq kg^{-1} vs. 17 kg CO_2 eq kg^{-1}, respectively). This is due to the fact that cattle production in LA is largely pasture-based with open ranges for the animals, and as such, the animals increase in mass more slowly and manure deposited in pasture is more prone to N_2O formation than in feed lots [37]. Nevertheless, a recent field study in central Brazil reported a direct emission factor (EF) for N_2O of 0.007 for the cattle excreta as whole, well below the IPCC EF (0.02) [38].

N_2O emissions from livestock and manure management in Mexico have also remained relatively stable at about 6445 Gg CO_2 eq between 1990 and 2010 due to an overall stable livestock population: cattle rearing has actually decreased, but with a simultaneous increase in poultry production [28]. In Argentina, direct emissions of N_2O from cattle excreta are the second source of GHG emission of livestock sector, being 18 300 Gg CO_2 eq in the year 2000 (21% of the total GHG emission of the sector). Indirect emissions from N volatilization from cattle excreta and urine were 8940 Gg CO_2 eq (10.4% of the total Gg emissions) and relatively stable during the period 1990–2000. Emissions from manure management played a minor role, accounting for 0.2% of the total emissions of the sector in the year 2000 [7].

Mitigation options — innovation and sustainable future

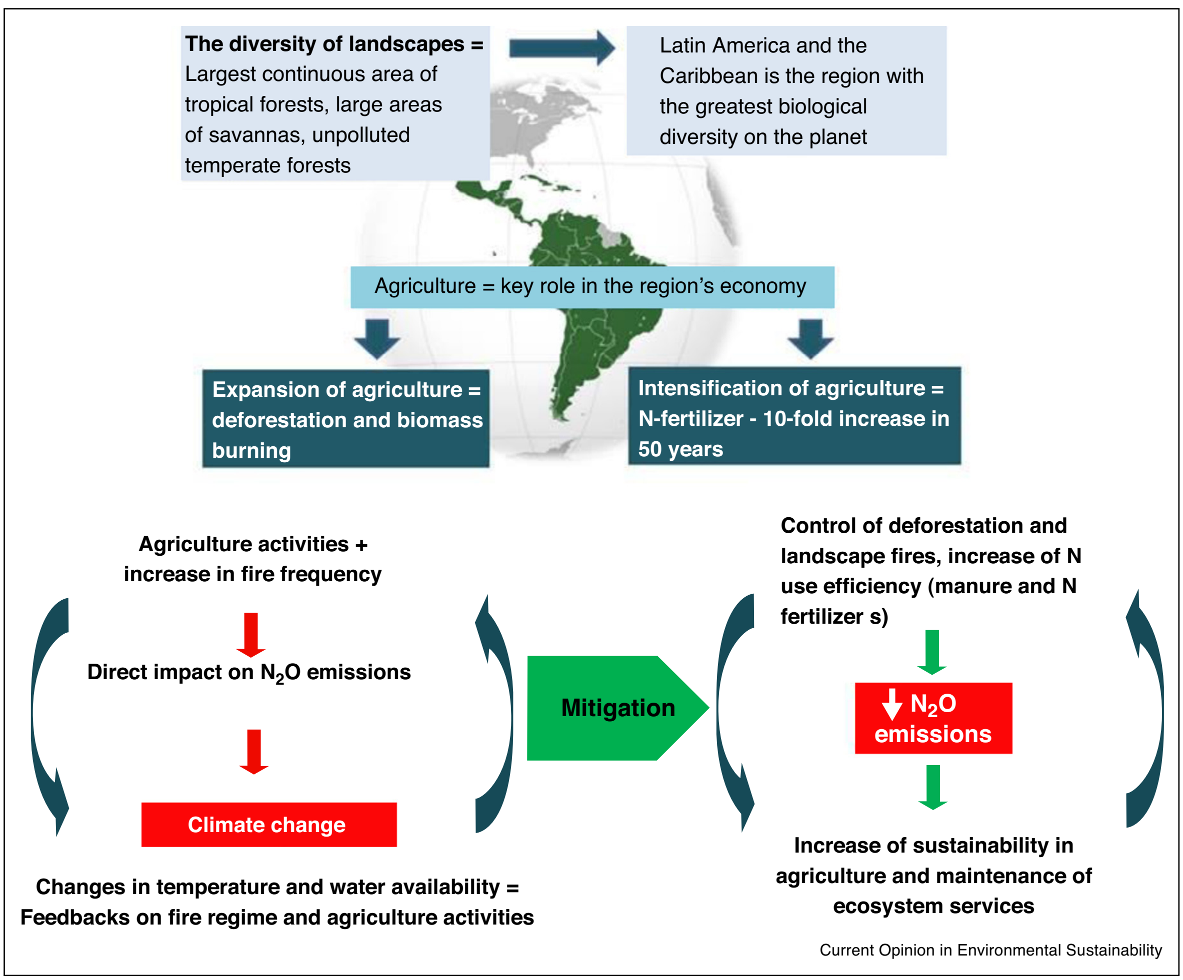
The Global Forest Resources Assessment [39] estimated that Latin America has suffered the largest net loss of forests in the world from 1990 to 2010. South America alone lost approximately 80 million ha of forests in these two decades, which corresponds to a deforestation rate of 4 million ha per year [39]. Forest fragmentation and the use of fire as a land management practice are major drivers of biomass burning and associated N_2O emissions in Latin America. Fire prevention and management (in fire-prone ecosystems such as savannas) is thus a key mitigation action. The need for proactive fire management has been also mentioned in other studies, as a substantial loss of ecosystem services [4•,27•]. Our limited understanding of the science of fire dynamics in the region hampers our assessment of the impacts of landscape fires in the face of global warming and increasing anthropogenic disturbance. In addition, the complexity of deterring deforestation and biomass burning due to the interplay of socio-economic, cultural and political drivers and the undocumented nature of many aspects of these dynamics including the importance of small fires and wood burning in homes makes it a particularly daunting challenge for mitigation options.

Given the importance of fire and unregulated biomass burning in affecting N_2O emissions in LA, it would be important to combine the monitoring of land cover with early-warning systems for identification and landscape fire prevention. One of the most efficient approaches is through the use of fire forecasting models. These models aid in identifying the main temporal, spatial and climatic factors that contribute to fire outbreaks and can therefore be employed to minimize impacts. Models to assess smoke-spread can also contribute to prior identification of the areas potentially damaged by fire, thus supporting the decision-making process and possibly reducing the impact of such events.

Another important source of N_2O is the emission from agricultural soils under cultivation, mainly due to the use of synthetic N-fertilizers and organic sources of N in manure. As N_2O is formed principally from N that is not directly utilized by the crop, the basic principle would be to promote agricultural practices that enhance the N-use efficiency by crops, thereby avoiding N losses to the environment [40]. For instance, studies in the region indicated that N_2O emissions vary depending on the nitrogen source and application of N fertilizer [41] and chemical composition of the fertilizer [30]. This reinforces the importance of the definition of specific critical levels of N fertilizer to enhance productivity while at the same time minimizing losses due to N_2O emissions.

More efficient land management and major biological innovations in agriculture have the potential to increase productivity while decreasing environmental impacts. For example, Biological Nitrification Inhibition (BNI) is a process by which certain plants — in particular the tropical pasture grass *Brachiaria humidicola* — naturally inhibit the conversion of reactive N in the soil to forms subject to leaching (NO_3) or gaseous (N_2O) losses. These natural reductions of N losses from the soil under managed pastures have a direct and beneficial environmental effect [42]. Additionally, it has been suggested that the adoption of no-till (NT) agriculture could decrease N_2O emissions when compared with conventional tillage (CT) agriculture [43]. Recently, Van Kessel *et al.* [44] evaluated the effect of tillage on N_2O emissions in a meta-analysis comparing (CT) and NT and reduced tillage (RT) agriculture in humid and dry climatic zones. They concluded that in humid climates, deep placement of fertilizer-N is recommended in conjunction with NT or RT agriculture

Figure 3



Main drivers of N_2O emissions (agriculture and land use changes associated with biomass burning) in Latin America and potential mitigation strategies for these emissions considering feedbacks on climate change and sustainable agriculture.

to minimize N_2O emissions. Additionally, in dry climates, NT/RT practices alone are an effective mitigation strategy for reducing N_2O emissions if sustained for a prolonged time. NT practices have been adopted in several countries of Latin America [10•], and in Brazil alone, there are more than 25 million ha under NT agriculture [45] with the first areas being implemented near the 1970s. In Argentina, while GHGs emissions increased over the last 50 years in those areas where high deforestation and burning occurred, emissions in the Pampas were substantially reduced as a consequence of NT practices [46].

Managing an integrated data synthesis and modeling research network for reducing N_2O emissions from agricultural soils in Latin America is crucial for effective agricultural management practices in the region. A major target is to start from a comprehensive evaluation of all GHG sources (many still roughly estimated or unknown, like compost, organic fertilizers and pesticides), testing of alternatives directed to reduce the identified main GHG sources, and technological innovation for energy production and recycling of both energy and materials at the individual farm scale. Small stakeholder agricultural practices in many regions of LAC are very important for local food production, and the impact of these practices on GHG emissions is almost entirely undocumented. In addition, current practices claiming to be environmentally friendly, including organic production systems, may be quite inefficient in energy use and produce similar or greater GHG emissions as conventional systems [47], in spite of some evidence from a global meta-analysis that suggests that larger soil carbon storage, N_2O emission reductions and larger methane uptake can be achieved [48].

Clearly, increased resource use efficiency is a major goal in Latin American countries that encompasses solutions to the problems highlighted in this review. Some relevant measures to mitigate N_2O emissions in LAC are summarized in Figure 3. Because of the clearing of land for agricultural conversion, the inevitable increase in GHG emissions generate substantial ecological imbalances that need to be restored, but this cannot occur in isolation with a single focus on reduction of GHG emissions. Current barriers might be overcome through policies that support *truly* sustainable practices aimed at reducing multiple negative environmental impacts, including reducing GHG emissions, and increasing the maintenance of ecosystem functions and services [4•].

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- •• of outstanding interest

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