Minimising the land area used by agriculture without petrochemical nitrogen

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Abstract

Biodiversity is threatened in a post-carbon future due to the expansion of agriculture resulting from reduction in the use of petrochemical-based fertilisers. Here we prioritise alternative fertilisers based on their potential to minimise future agricultural expansion. We map the threat to biodiversity globally for the best-case scenario for replacing mineral N. To consider both biofixation and industrial nitrogen fixation, we calculated the footprint for three green manures (azolla, algae and alfalfa), and three options for mineral nitrogen production using renewable energy to power the Haber-Bosch process (wind, photovoltaics and thermal solar). Solar-powered Haber-Bosch would provide the minimum global footprint, with concentrated thermal solar power stations a particularly attractive option since they are best situated in low-rainfall areas where biodiversity is also lower. This approach would also save about 1% of global carbon emissions from the combustion of fossil fuels. Mapping the biodiversity impact of expanding the current solar power station footprint to meet the area required to replace the fossil fuel powered mineral N shows a reduction in biodiversity impact from footprint expansion to less than one ten-thousandth of that which would occur with current management practices in the absence of mineral N. A proactive approach is required in selecting alternatives to mineral N in order to limit the impact of agriculture's post-carbon footprint on biodiversity.

Keywords

Cropland footprint, fossil fuel supply, nitrogen fertiliser, extensification

Introduction

The global financial crisis (GFC) was a period when the global oil supply was unable to keep up with demand (Murray & King 2012), and this was associated with an increase in deforestation, especially in areas of high biodiversity (Eisner et al. 2016). Globally, the spread of agriculture is the primary driver of biodiversity loss (Ferretti-Gallon & Busch 2014; Wood et al. 2000). Commercial agriculture is dependent on fertilisers which require petrochemicals, both for the energy necessary to fix nitrogen from the atmosphere using the Haber-Bosch process, and as the source of hydrogen to create the compounds used in nitrogen fertiliser, such as ammonia (NH_3). As the price of fertilisers changes with the price of oil, farmers make decisions about the relative cost-effectiveness of fertiliser-use and land extensification in a process known as land-fertiliser substitution (Brunelle et al. 2015). Since mineral fertilisers are petrochemical-intensive, and petrochemicals are a finite resource, eventually the world may need to rely on non-mineral sources of N. This poses the question of the potential impact on biodiversity agriculture without petrochemical fertiliser.

Nitrogen is the limiting factor in many agricultural systems (Bhattacharjee et al. 2008), therefore, we would expect more cropland to be required to achieve the same level of production if mineral nitrogen were removed. From the distribution of forest change which happened during the GFC, and because of the productivity-biodiversity relationship at a global scale (Chase & Leibold 2002; Currie & Paquin 1987), we would expect cropland expansion to be concentrated in the tropical and subtropical regions, where biodiversity is also concentrated.

This paper aims to estimate the impact on biodiversity of the land area required to produce the nitrogen for use in agriculture when the alternative with the smallest footprint is substituted for mineral N. We compare the footprint of this most land-efficient alternative to mineral N with the expected area required to compensate for a lack of mineral N using current management practices. We assess the impacts on biodiversity globally.

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Methods
Figure 1a shows the potential sources of nitrogen for use in agriculture. There are two alternatives for fixing N from the atmosphere: the Haber-Bosch process and biological nitrogen fixation. Small quantities of N may be harvested from the soil, for example as animal manure, but this is not a renewable resource at commercial stocking densities. Human wastes contain some nitrogen which could in principle be recycled, but this N is lost to the atmosphere with current aerobic treatment processes. Alternative methods of nitrogen fixation are problematic for a variety of reasons (Figure 1b). They continue to pollute the biosphere with reactive nitrogen, one of the planetary boundaries thought to already be dangerously exceeded (Rockström et al. 2009). Currently the Haber-Bosch process relies on non-renewable and greenhouse polluting energy, but the alternatives use far more land, especially green manures.

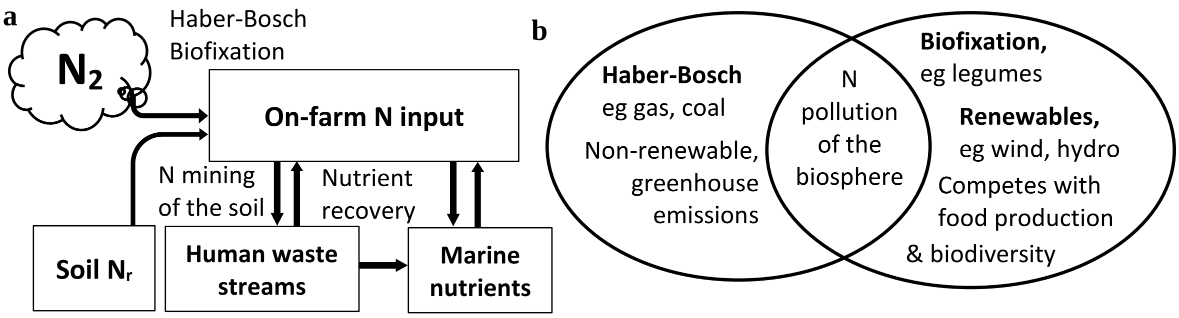

Figure 1(a) Some major potential sources of nitrogen for agricultural production. Effectively unlimited quantities of N can be fixed from the atmosphere using the Haber-Bosch process or biofixation. In the short-term N can be mined from soils through grazing, animal manures or cover crops which also occupy space and are not renewable. A proportion of N could be recycled, either directly from waste, or via the oceans. (b) The major problems with the alternative methods of nitrogen fixation. The conventionally powered Haber-Bosch process is dependent on non-renewable energy and responsible for substantial greenhouse gas emissions. The alternatives are agricultural land-intensive, particularly biofixation. All these approaches continue to pollute the biosphere with reactive nitrogen, to different degrees.

The literature was searched for renewable sources of nitrogen which were prioritised by their nitrogen content and land-use area. A footprint was calculated for the most promising options, based on current global nitrogen usage and the N yield of the option. These were used to map potential future impact on biodiversity of the most effective option in terms of meeting future requirements for nitrogen with the lowest use of additional land. The biodiversity impact of this was compared with meeting the shortfall through cropland extensification based on no mineral N.

Results and discussion

The yields for the alternative sources of nitrogen are given in figure 3. The option with the minimum footprint of 14,400-32,000 km^2 uses concentrated solar power. There is little difference between this and using photovoltaics (PVs) but solar is an order of magnitude more land-efficient than wind power and three to four orders of magnitude more efficient than green manures. These results are similar to those of Smil (2004) who calculated similar land-efficiencies for energy supply (power densities), and whose figures we used where available. This result is to be expected since energy production is the only land-use component which changes when the Haber-Bosch process is powered by renewables.

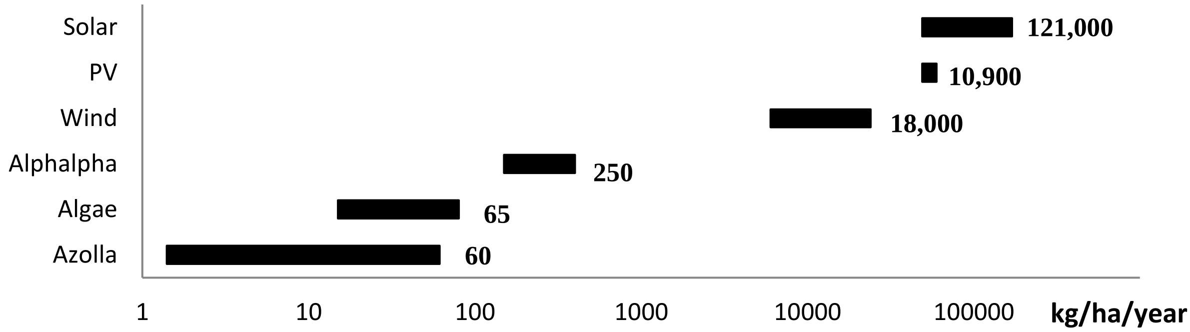

Figure 2 N fixation rates in Kg/ha/year of some alternatives to fossil fuel powered Haber-Bosch. Powering the Haber-Bosch process using renewable energy produces N using at least two orders of magnitude less land area than N-fixing green manures. Of these energy sources, concentrated solar has the potential to be over three OMs more land-efficient in the right locations, which would also compete less with agriculture and biodiversity.

Figure 4 shows the expected biodiversity impact of using solar energy to power future N production. Even without sites being selected for the purpose of minimising the impact on biodiversity, the effect is tens of thousands of times lower than allowing cropland expansion to make up the shortfall in production without petrochemical powered N fixation. This is largely because of much smaller area requirements, but also because solar power works best in areas with the most sun and least rain which tend to have little biodiversity. However, we found that current solar power stations are not necessarily in the best locations for either biodiversity conservation or power generation and performance could be improved on both these measures by purposefully selecting their location. The selection process would need to avoid arable land since this would reduce the land available for agriculture, which in turn would need to expand, further impacting on biodiversity. Solar thermal plants are attractive from a biodiversity conservation perspective because meeting technical and economic requirements tends to be more congruent with conservation objectives. However, concentrated solar thermal plants cannot share land with agriculture. PV power plants tend to occupy more farmland than concentrated solar thermal plants because PVs are more rain tolerant and the technology is scalable, with many more small plants. PVs can occupy rooftops and other shared space where it is not in competition with food production or biodiversity. There is also the attractive option of ‘solar sharing’ between farmland and PV by using spacing or Wavelength Selective Photovoltaic technology whose use of the solar resource is complementary with crop requirements, reducing light saturation of the crop and potentially also improving production (Kikuchi & Koshimizu 2014).

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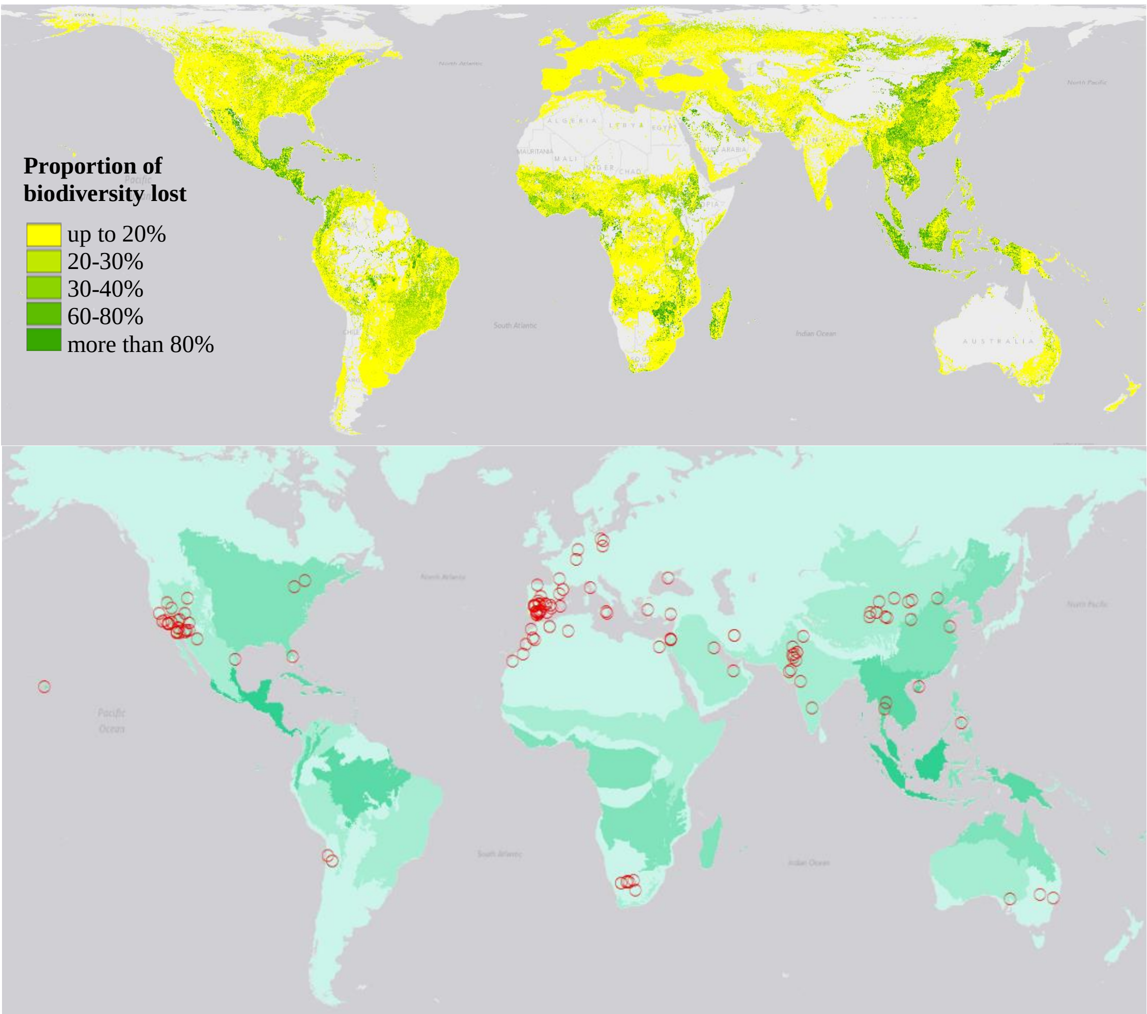

Figure 3 Comparison of (a) the biodiversity impact of the business-as-usual option of current agricultural practices allowing extensification to make up the shortfall in production with (b) using solar power to replace mineral N. The locations of solar power stations are shown in (b) buffered to be visible on a global map, with the biodiversity of the ecoregions they are in. The actual area occupied by agricultural expansion is thousands of times greater than that of the solar power stations required to power the N production process.

Although organic fertilisers have a large footprint and in some cases are not renewable, these remain the best options for subsistence farmers where most produce is used on-site enabling the recycling of wastes, since subsistence farmers lack the means to purchase external inputs. These methods have the benefit of increasing soil organic matter which improves water-holding capacity and drought resilience and may contribute to increased soil carbon sequestration (Erickson 2016). Both renewable and organic fertilisers have the potential to reduce greenhouse gas emissions by reducing combustion of fossil fuels by about 1%.

Conclusion

Of the means of obtaining renewable nitrogen, solar power is the most land-efficient and provides an extremely large gain over the alternative of land extensification in terms of impact on biodiversity. Solar thermal plants in particular tend to be sited in locations where their impact on biodiversity is low compared to cropland expansion, but these impacts could be improved with careful site selection. Solar sharing has the potential to be a win-win-win for energy, agriculture and biodiversity, but needs development of both crop photo-response profiles and corresponding Wavelength Selective Photovoltaics. Traditional fertilisation may remain the preferred option for subsistence producers and further research is needed to spatially prioritise these alternatives.

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