

Global prioritisation of renewable nitrogen for biodiversity conservation and food security

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Abstract: The continuing use of petrochemicals in mineral nitrogen (N) production may be affected by supply or cost issues and climate agreements. Without mineral N, a larger area of cropland is required to produce the same amount of food, impacting biodiversity. Alternative N sources include solar and wind to power the Haber-Bosch process, and the organic options such as green manures, marine algae and aquatic azolla. Solar power was the most land-efficient renewable source of N, with using a tenth as much land as wind energy, and at least 100th as much land as organic sources of N. In this paper, we developed a decision tree to locate these different sources of N at a global scale, or the first time taking into account their spatial footprint and the impact on terrestrial biodiversity while avoiding impact on albedo and cropland, based on global resource and impact datasets. This produced relatively few areas suitable for solar power in the western Americas, central southern Africa, eastern Asia and southern Australia, with areas most suited to wind at more extreme latitudes. Only about 2% of existing solar power stations are in very suitable locations. In regions such as coastal north Africa and central Asia where solar power is less accessible due to lack of farm income, green manures could be used, however, due to their very large spatial footprint only a small area of low productivity and low biodiversity was suitable for this option. Europe in particular faces challenges because it has access to a relatively small area which is suitable for solar or wind power. If we are to make informed decisions about the sourcing of alternative N supplies in the future, and our energy supply more generally, a decision-making mechanism is needed to take global considerations into account in regional land-use planning.

Keywords: concentrated solar; ammonia synthesis; biofixation

1 Introduction

Modern agriculture is highly dependent on petrochemicals, especially for nitrogen (N) fertiliser which is made using natural gas. The use of petrochemicals to produce fertiliser is unsustainable for two main reasons. First, they are non-renewable and consumption is growing faster than the supply due to both growth in human populations and per capita consumption with increased living standards (Kruger, 2006). Second, their use emits greenhouse

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gases and aggressive mitigation measures such as committed to in the Paris Agreement may constrain their use (Thomas *et al.*, 2016). If N use were to be constrained, either through access or through price, then agriculture productivity would fall and more land would be required to maintain food production. This agricultural extensification threatens global biodiversity, since the conversion of native ecosystems to agriculture has long been the major threat to biodiversity.

Nitrogen fertiliser can be produced from other sources (Dunn *et al.*, 2012). These include replacing the existing petrochemical power supply for the Haber-Bosch process with renewable energy supplies from solar or wind power, and using organic sources of nitrogen. However, these sources would all use some additional land, which again would potentially impact biodiversity. An assessment of alternative sources of renewable N suggested that using solar energy to power the existing Haber-Bosch industrial process was the most land-efficient option, with a footprint one tenth that of wind energy and one thousandth that of green manures (Eisner *et al.*, 2016). A cost-effectiveness prioritisation would be unable to differentiate between options because the difference in footprint is so great that this aspect would dominate footprint-to-cost ratios globally, meaning that solar would always be selected over other options, at any land price and any solar resource availability. However, there are factors other than land use which determine the choice of N source. These factors include the resource availability and the affordability to the landholder (Chianu and Tsujii, 2004). There are also factors which influence the desirability of the source of N such as the competition for agricultural land and biodiversity conservation and the impact on radiative forcing (Nemet, 2009; Rosenthal, 2010; Turney and Fthenakis, 2011). The extreme variations in the area of land needed to produce alternative sources of nitrogen make it essential that we understand the implications of renewable N fertilisers for regional land use planning.

This paper aims to prioritise renewable sources of nitrogen with the goal of minimising the impact on biodiversity through agricultural extensification and the competition for arable land, given the distribution of practical resource constraints. The N sources considered include the most land-efficient sources of renewable energy to power the existing Haber-Bosch infrastructure (solar and wind); terrestrial, freshwater and marine organic fertilisers (alfalfa, azolla and seaweed); and the use of crop residues.

2 Methods and data

The steps used to map and prioritise N sources are given in Figure 1. Firstly, given the aims of preserving biodiversity while maintaining food security, data sources of N and thresholds were identified from the literature, where available (Table 1). The data needed to map these factors globally was sourced. An algorithm was developed which mapped the highly suitable regions for each N source (Figure 2). These were then mapped to produce a map of the most suitable regions for each source of N. Areas of major overlap were combined into a col-

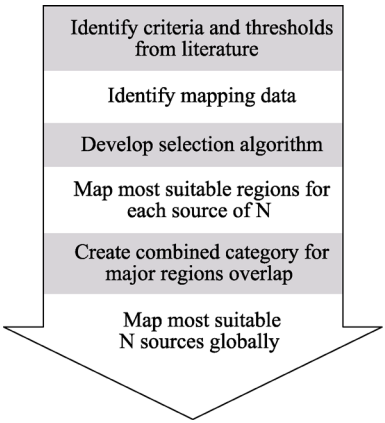


Figure 1 Process for developing maps for selecting sources of N production most suitable at each location

lective category, and a global map of most suitable N sources was created.

Table 1 Data sources used for mapping N source prioritisation.

Variable	Reason for inclusion	Data	Threshold	Reference
Biodiversity	To assess impact	Ecoregional biodiversity indices	0.1064	Kier <i>et al.</i> , 2009
Commercial cropland	Space constraint for N production	Cropland-yield gap	>20%	Monfreda <i>et al.</i> , 2008
Green manure	Farm income to purchase fertilisers. Yield gap > area required to grow N	Yield gap	0.513	Monfreda <i>et al.</i> , 2008
Sun	Most land efficient	DNI for concentrated solar NASA SWERE	4.93	NASA, 2011 Deign, 2012
Wind	Second most land efficient	NASA SSE	5.5 ms ⁻¹	NASA, 2005 Blankenhorn and Resch, 2014
Albedo	Solar power can contribute to global warming at high albedo sites	Albedo (1 month)	Reflectance values lowest 20% (albedo 0.35)	NASA Earth Observations, 2016 Nemet, 2009
Wetland rice	Azolla valuable N source, no land cost		Presence/absence	Salmon <i>et al.</i> , 2015
Aquaculture		Data not found		N.A.
Seaweed	No land cost	Coastal zone	40km	Natural Earth, 2016

2.1 Data sources

Data sources for resource availability, constraints and suitability thresholds used for mapping N source prioritisation are given in Table 1. See supplementary data for source maps. The reference is provided for the thresholds applicable to the variable and for the datasets used. The data sources were rasterised based on 1 km cropland mapping (Monfreda *et al.*, 2008). The data sources are for the period 2005–2016. They are just to project a hypothetical future scenario, and mostly reflect physical characteristics such as solar and wind resources, albedo and distance to the coast which would be unlikely to change on a decadal time scale. One exception might be yield gaps, which are used for selecting suitability for green manures. This is based on 2008 data (Monfreda *et al.*).

2.2 Decision process for selecting alternative sources of N

Using solar energy to power N production is most land-efficient renewable method and would allow the ‘sparing’ of land for other purposes such as growing food and protecting biodiversity (Scheidel and Sorman, 2012; Eisner *et al.*, 2016). Solar is at least ten times more land efficient than the alternatives for the production of N. But there are other factors which might constrain its use. Not everywhere has sufficient sunshine, but may have wind resources, and in some regions the land would be better used for agriculture or biodiversity conservation. Also, some farming produces insufficient income to purchase N produced using solar power making it less accessible to subsistence farmers (Chianu and Tsujii, 2004). These farmers may choose other options they can access without cost, including green manures, waste recycling and, where located near the coast, marine algae, especially in areas

with high marine N (Cavagnaro, 2015). In biodiverse regions, subsistence farmers impact native ecosystems when they use land for N production, so importing N for these farmers has the potential to limit their impacts (Matthews and De Pinto, 2012). For these reasons, it is necessary to consider how to prioritise the location of each alternative source of N.

Figure 2 shows the logical process for deciding between sources of N for each location which combines a decision matrix and a decision tree. First, in the decision matrix options are selected on the basis of cropland use and the biodiversity level (Figure 2a). Cropland is better used for food production than for N production to maintain food supply, so in those areas N should be imported, as is currently practiced. Very unproductive agricultural land produces insufficient income to purchase N and so farmers need to produce their own organic fertiliser on-farm (Crucefix, 1998). In areas of high biodiversity, the land used for N production competes with biodiversity, so N should be imported, and farm and household residues recycled, where feasible. If there is no cropping currently present and low biodiversity then the land can be used for renewable energy production with low impact. If such land has high biodiversity then the land should be prioritised to preserve this, and not used for renewable energy production.

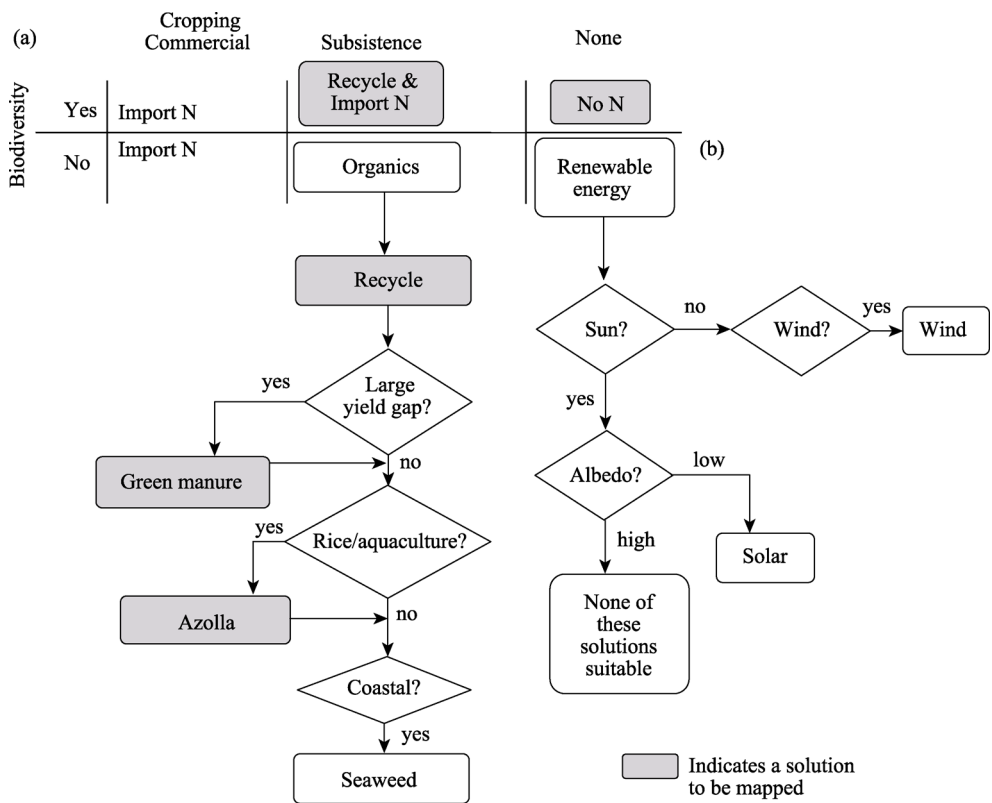


Figure 2 Decision matrix (a) and decision trees (b) for siting N sources

Figure 2b shows a decision tree for selecting organic fertilisers and the renewable energy source for powering N production. Organics are best suited for subsistence farmers in low biodiversity areas due to their affordability but high land requirements. Recycling organic matter is generally beneficial, where feasible. If there is a very large yield gap then green manures can increase overall productivity. Azolla is a significant N source in rice production

and coastal areas have access to seaweed.

Renewable energy systems are best sited in low biodiversity areas unsuitable for cropping. Sites with low insolation and high wind are suitable for wind power. Sites with adequate insolation and low albedo are suitable for solar. Otherwise, none of these options are suitable, but there may be suitable possibilities in the future or solutions not considered here.

3 Results and discussion

First we present global spatial analysis of the sites that were most suitable for each individual way of sourcing N, based on the criteria shown in the decision matrix and trees. These were, for solar, competition with biodiversity, cropping, solar resource and albedo; for wind, locations where solar would be suitable but there is insufficient sun but sufficient wind; for green manure, cropping has a large yield gap; azolla is suitable in wetland rice and seaweed in coastal subsistence farming. Then we combine the individual means of sourcing N into a global map.

3.1 Solar power

Areas were selected as suitable for solar power because they have sufficiently high insolation to efficiently power concentrated solar power stations (Deign, 2012). Solar thermal power is chosen over PVs because they perform best in low rainfall areas and so tend to compete less with biodiversity and cropping without additional policy intervention (Philibert, 2005). Solar thermal also has very much lower embodied energy and fewer material constraints for manufacture, with the silver used in the mirrors as the major material constraint (Pihl *et al.*, 2012). Solar thermal plants are currently also slightly more land efficient. Because of their flexibility of location and scale, there are currently about 30 times the installed capacity in PV compared to concentrated solar.

Sites suitable for solar power are chosen on the basis of not displacing cropping, having low levels of biodiversity, and having sufficiently low albedo so that the increased radiative forcing does not significantly undo the benefits of the reduced greenhouse gas emissions (Nemet, 2009).

Figure 3 shows the 5.7 million km² of land best suited to solar power, taking into account solar resource availability, conflict with biodiversity and cropping and reducing albedo. The most suitable locations are mostly in the Southern Hemisphere, western North America and coastal Far East. The location of solar power stations are also shown.

This area represents over 100 times the area needed to power global N production and more than four times the area needed for the total world energy supply (Scheidel and Sorman, 2012). To supply N requirements of USA would require 30,000 MW (Leighty, 2008), which is about 18 times the installed solar capacity. Transmission losses due to distance from markets would be compensated for by having a 30% efficiency gain compared to efficiency losses of fossil fuel combustion (Jacobson and Delucchi, 2011).

Currently only three solar power stations are in the regions most suited to solar power (Arizona, New South Wales and South Australia), although many could be in more suitable places if they were moved slightly. Several of the locations with the best solar resource and least impacts on biodiversity are remote from major energy markets or large energy grids, as is the case in central southern Africa, in Chile and Argentina and in Western Australia (Li, 2013). Other regions have their power stations better aligned with suitability, such as in

southern Spain and the south-western USA.

3.2 Wind

Figure 4 shows the 8.3 million km² of land best suited to wind power globally, mostly at very low and very high latitudes, and in Bolivia, Central Asia and Japan. These regions are unsuited to solar power, they have very good wind resources, low biodiversity and would not be competing with cropping. Most other global wind mapping only takes into account the wind resource available and not land-use considerations (eg Grassi *et al.*, 2015).

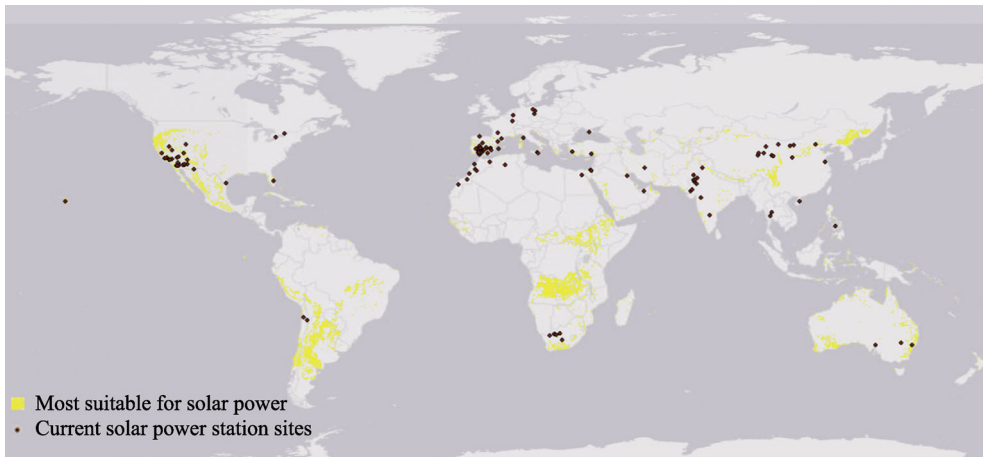


Figure 3 Sites most suitable for solar power, and the location of existing solar power stations



Figure 4 Sites most suitable for wind power. These are mostly at very high and very low latitudes.

3.3 Organic sources of N

The regions selected for organics (Figure 5) tend to be subsistence systems which are not part of the cash economy and lack the income to buy fertiliser. Green manures were selected for the relatively few areas of cropland where the yield gap is so high that their use would still increase their overall land use efficiency (Table 1) and where there is little competition with biodiversity. Marine algae are most suited in low-yield systems within easy transport distance of the ocean (Antoine De Ramon and Iese, 2014; Florentinus *et al.*, 2008). Azolla is

a useful source of N in wetland rice production and aquaculture (Shridhar, 2012), but only wetland rice is included here because terrestrial aquaculture areas are too small for global mapping.

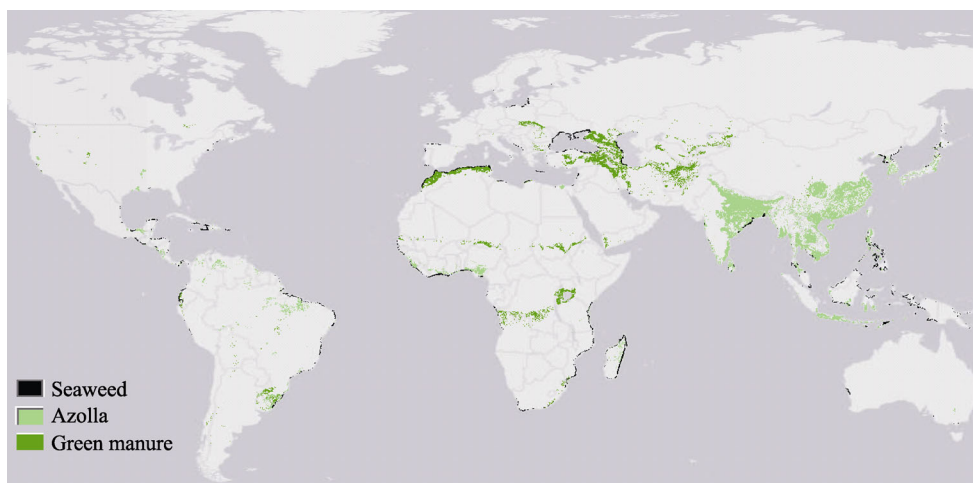


Figure 5 Locations suitable for organic nitrogen sources: green manures, seaweed and azolla

The regions which are most suitable for organic N sources, comprise 2.2 million km² for green manure in the areas with the lowest yields, 0.85 million km² of coastal subsistence farming suited to marine algae use, and azolla in 6.0 million km² of wetland rice production. Yields would be able to be at least maintained with N supplied in this way, although some of these regions would additionally benefit from importing N (Figure 6).

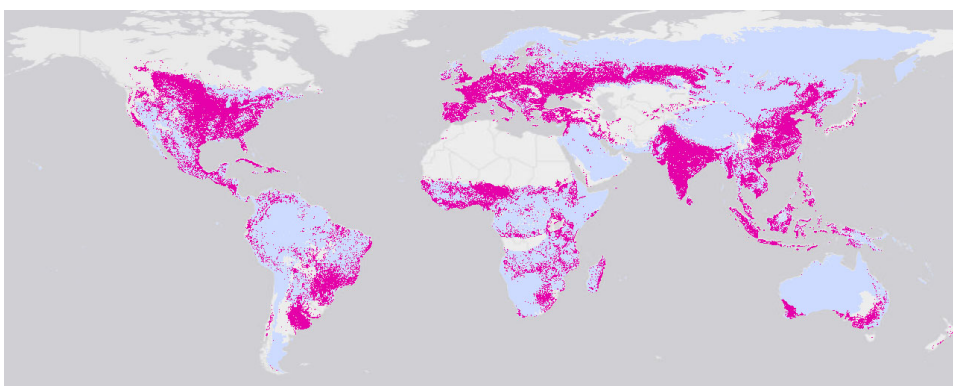


Figure 6 Regions where it is preferable to import N rather than compete with crops or biodiversity, or where high biodiversity makes N production unsuitable

The N-efficiency of green manures assumes that the land is used solely for manure production. There are management practices, such as zero-till seed drilling (Fischer *et al.*, 2012), which produce some N without consuming additional land, but these practices have not been included here.

3.4 Cropland and high biodiversity regions

Figure 6 shows regions where competition with biodiversity or cropping makes N production undesirable. For cropland in high biodiversity regions (29.8 million km² globally), N

would best be brought in from other regions to reduce cropland expansion into biodiverse areas, and it is preferable to retain natural ecosystems than to convert the land to N production. Assistance would be needed to supply subsistence areas with N, at suitable levels to reduce encroachment, since their income is insufficient to purchase N for themselves. Recycling agricultural residues makes sense in all agricultural systems, and recycling household wastes would be beneficial in subsistence systems, where feasible. If there is no cropland, high biodiversity areas should have no N production or importation (Do nothing) to retain their conservation values.

Both cropland and biodiversity regions are based on existing locations which might change under future climates.

3.5 Regions with no suitable options

Some areas, including northern Canada, North Africa, large parts of Central Asia and inland eastern Australia are unsuitable for any of these sources due to a combination of factors including lack of solar or wind resource or high albedo (Figure 7). None of the options in this study are suitable in these areas, however, alternatives which do not adversely interact with albedo (eg geothermal) may be suitable in some places. The use of recently developed white PV panels, produced to increase albedo, may result in a net increase radiative forcing in desert regions and a reduction of the urban heat island effect, although at an efficiency cost (Heinstein *et al.*, 2015).

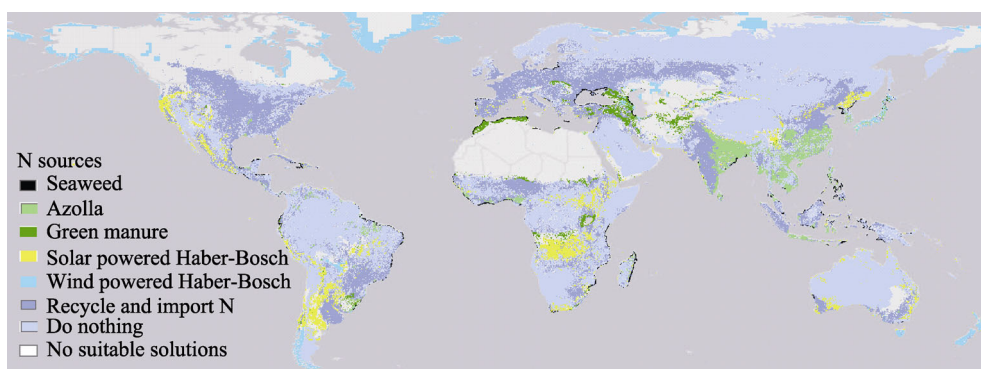


Figure 7 Sources of N for cropping prioritised for biodiversity and cropland conservation. Solar is the most land-efficient option, but is highly suitable in relatively few regions due to competition with biodiversity or cropping or reducing the albedo of the site, contributing to global warming. Organics are very land inefficient for N production so are only suited for use on land with low productivity and low biodiversity.

3.6 Prioritisation of N sources

Figure 7 shows the preferred N source at each location across the globe. Mostly options do not overlap because the decision tree prioritises the best option for a given location. The main exception to this is recycling which is combined with and importing N which are combined in Figure 7. Recycling wastes that are produced on-site uses no additional land area and improves soil condition so is desirable wherever it is feasible. For household waste this may only be the case for small-holders, because of transport costs. Although Figure 7 presents organics and mineral N as alternatives, it may be optimal to combine organics with mineral N (compare with Figure 6). Importing N from production sites that are highly cost-

and land-efficient may benefit many areas suitable for organics by increasing the productivity of organic systems. The use of organic fertilizers could reduce overall N-use and the resulting pollution of the biosphere and increase soil health, soil water-holding capacity and drought tolerance in conventional commercial systems (Ali *et al.*, 2011).

There are risks with supplying N to subsistence farmers in biodiverse regions. There is the risk of becoming dependent on a finite resource, which would result in food insecurity if the supply discontinued. This is particularly the case if supplying N were to increase the carrying capacity in the short-term to levels which could not be supported without it. Also the increased efficiency of agriculture using mineral N can tend to make production more profitable, increasing areas under production. Complementary planning measures are needed to reduce this risk (Phalan *et al.*, 2016). N pollution of the most sensitive regions is also a risk, unless the N is managed carefully.

With most area in the prioritised map (Figure 7) selected for non-production of N (ie, either ‘Do nothing’, ‘Import N or ‘No suitable solutions’), there is relatively little area highly suitable for any of these options. However, there are sufficient highly suitable areas to meet all N needs using the best option available, and even sufficient area selected for solar energy to meet total energy needs.

Prioritisation based on cost effectiveness is often suggested to optimally allocate resources (eg Wilson *et al.*, 2006). The prioritisation used in this paper did not include costs for a number of reasons. First, perhaps half of the world’s people and about a third of the agricultural land is under management systems outside the economic system, so a cost-effectiveness prioritisation is unhelpful in these systems. In order to include these systems, the prioritisation needed to target factors accessible to those making the decisions. Second, the overall aim of the research was to minimise pressure on biodiversity and food insecurity. Finally, price was the most volatile factor in these systems, rapidly changing with markets and management practices, and so results based on price are not very reliable.

3.7 Regions of interest

Three regions can draw on the full range of N sources without high negative impacts (Figure 8). The Caucasian region between the Black Sea and The Caspian Sea has much cropland which is of such low productivity that yields could be improved with green manures, and high wind speeds suited to wind power south of the Greater Caucasus Mountains between the Black Sea and the Caspian Sea. Much of the coastal areas could be suitable for algae use. The Nile delta could usefully use Azolla in rice production with Cyprus and eastern Caspian coastal areas suitable for solar. Azerbaijan alone has the potential of about 800–1500 MW of economically feasible wind power, the main barriers being regulatory (Safarov, 2015). The first wind farm in Georgia, rated at 20.7 MW, began operations in 2016 (Caspian Energy Newspaper, 2016).

In the Far East, Japan has good wind resources and, together with South Korea and China south of Shanghai, has opportunities to use azolla in rice production, which is often practiced in China (Biswas *et al.*, 2005). North Korea has very good solar resources, some of which has already been exploited with international assistance (Yi *et al.*, 2011). Its coastal regions suit algae use, which they harvest (Chennubhotla *et al.*, 2013). North Korea has 2.8% of the world’s aquaculture but chronic food and energy insecurity. The region produces

over 10 million tonnes a year of marine algae, mostly for food, with its main use as fertiliser in India.

Although much of Uruguay has no suitable N sources, its bordering regions are rich in resources. There is abundant solar north western Argentina. Its border region with Brazil to the north would benefit from azolla in wetland production and green manures and in the coastal area seaweed could be used, with the southern coastal zone also suiting wind.

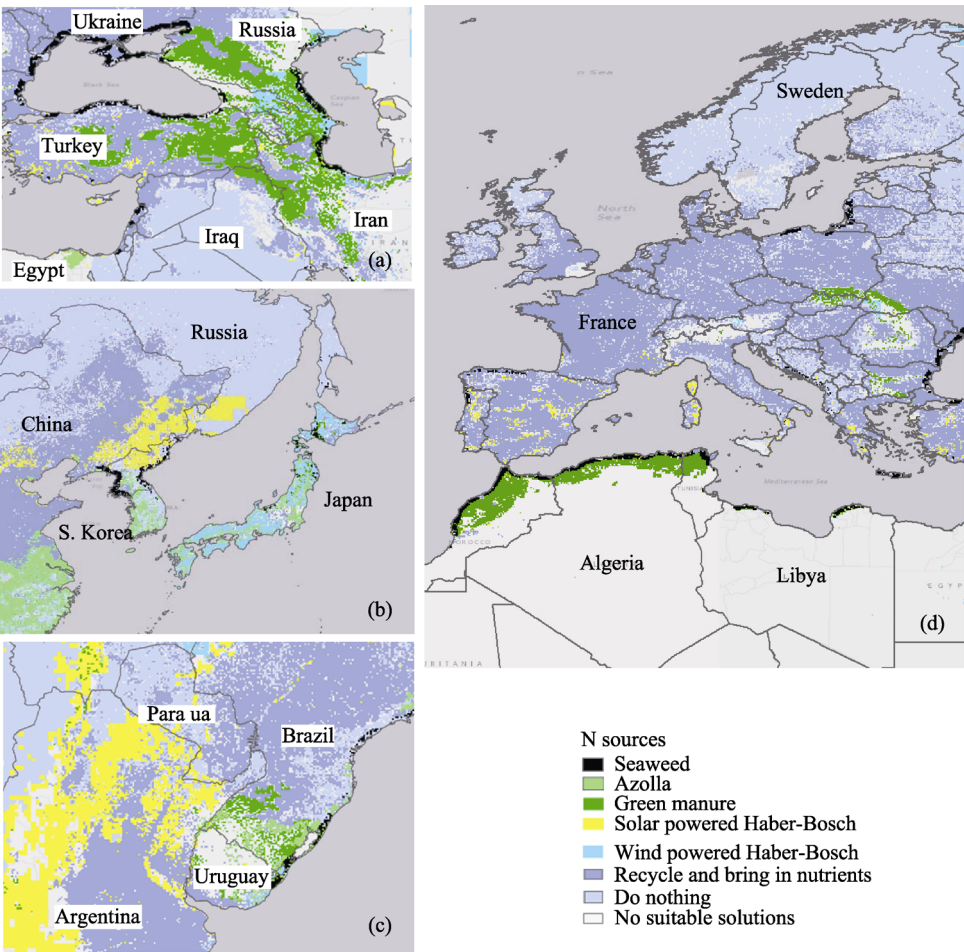


Figure 8 Three regions with a wide range of options for sourcing N, a) Caucasia and surrounding region, b) Japan, China, Korea and c) Uruguay region. In contrast, Europe (d) has a paucity of options. Europe has little area highly suitable for solar or wind because of competing land use and biodiversity and lack of solar resource. The Sahara desert is not selected for solar power because the decrease in albedo would contribute to global warming.

By contrast, the European region has relatively poor access to renewable N sources. Algae may be viable along the coast of the Black Sea, parts of the Iberian Peninsula, coastal Poland, parts of the Baltic states and North Africa, which is also suitable for green manure because of its low productivity. Small areas of the Mediterranean in Corsica and Sardinia, southern Italy, Greece and Turkey and in Portugal and Spain have solar resources, which in Spain are largely exploited. Coastal northern Russia and Norway may suit wind but many otherwise suitable areas are excluded because of conflicts with wildlife or cropping. Plans such as Desertec which aim to provide Europe with power using solar panels based in the Sahara is

problematic due to the warming effect of decreased albedo (Backhaus *et al.*, 2015; Nemet 2009). The benefits from reduced GHGs by using solar power are about 30 times the heating caused by solar panels when well placed, but the heating can increase more than three-fold by placing solar collectors in the Sahara Desert.

3.8 Significance, contribution and limitations

Renewable nitrogen fertiliser has not been spatially prioritised before. This is important in order to be able to maintain food security and biodiversity as we move away from fossil fuels. The 2008 US Farm Bill allocation US\$1 million per year in 2008–2009 for a study of the feasibility of producing N from renewable energy (Capehart and Stubbs, 2007). Leighty and Holbrook (2008) conducted a comparison of H₂ and NH₃ as potential storage for wind power, noting that NH₃ can also be used for fertiliser. Leighty (2010) also investigated the possibility of transmission of both fuels via pipeline and concluded both the fuel and pipeline technology would accelerate conversion to renewables. It has also been found that the efficiency of NH₃ production could be increased by using humidified carbon monoxide as a feedstock instead of hydrogen (Jiang and Aulich, 2008). There is also a Swedish study which compared a variety of technologies for producing renewable N and found that wind powered N costs about 2.4 times the current price. The cheapest renewable technology, thermochemical gasification of biomass is not yet commercially available. They also found that renewable N reduced the GHG emissions incurred by perhaps a factor of ten (Tallaksen *et al.*, 2015).

This study has been conducted at a global scale and the maps are not at sufficiently high resolution to be used locally, especially the biodiversity index. Rather, the presented method could be applied locally using local datasets and with the incorporation additional, locally important criteria.

This paper used a threshold approach to determine suitability of areas for each source of N. It would be beneficial to develop a suitability scale for each so that maps of relative suitability could be produced. It would also be useful to consider industrialised sources of N such as waste from intensive animal industries and municipal waste streams, and mechanisms of treating waste so that the N content can be reused.

4 Conclusion

This chapter has spatially prioritised methods for producing nitrogen for crop production with the goal of minimising impact on biodiversity and reducing competition with cropping, taking into account solar and wind resource constraints. Although solar power is the most land-efficient way to power N production, there are relatively few areas which are very suitable for solar power stations, and some of these are far from energy markets and grids. Siting ammonia production in such locations could contribute *de facto* energy storage into the system. Alternative ways of producing N are also suitable in relatively small areas with many regions continuing to benefit from bringing in N from those more suitable to its production, as they do currently. Biodiversity would benefit if low yield farms were supplied with N, to reduce encroachment onto natural ecosystems, although care is needed to prevent unwanted side-effects.

Acknowledgements

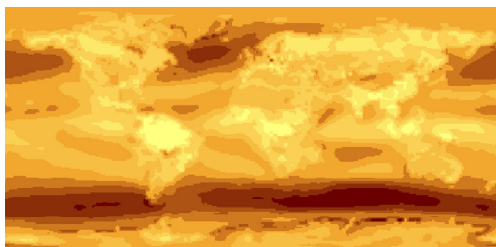
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References

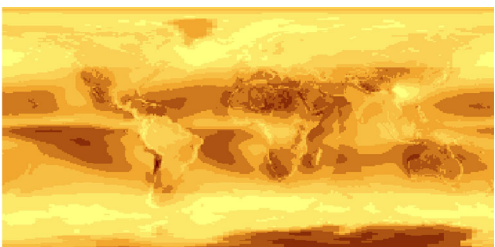
- Ali K, Munsif F, Zubair M *et al.*, 2011. Management of organic and inorganic nitrogen for different maize varieties. *Sarhad J. Agric.*, 27(4): 525–529.
- Antoine De Ramon N Y, Iese V, 2014. Marine plants as a sustainable source of agri-fertilizers for small island developing states (SIDS). *Impacts of Climate Change on Food Security in Small Island Developing States*, 280.
- Backhaus K, Gausling P, Hildebrand L, 2015. Comparing the incomparable: Lessons to be learned from models evaluating the feasibility of Desertec. *Energy*, 82: 905–913.
- Biswas M, Parveen S, Shimozawa H *et al.*, 2005. Effects of *Azolla* species on weed emergence in a rice paddy ecosystem. *Weed Biology and Management*, 5(4): 176–183.
- Blankenhorn V, Resch B, 2014. Determination of suitable areas for the generation of wind energy in germany: Potential areas of the present and future. *ISPRS International Journal of Geo-Information*, 3(3): 942–967.
- Capehart T, Stubbs M, 2007. Renewable energy policy in the 2008 farm bill. In: Caspian Energy Newspaper 2016, *First wind farm launched in Caucasus region* viewed 11/11/2016. <http://caspianenergy.net/en/energy/35967-2016-10-07-09-07-55>.
- Cavagnaro T R, 2015. Chapter five-biologically regulated nutrient supply systems: Compost and Arbuscular Mycorrhizas: A review. *Advances in Agronomy*, 129: 293–321.
- Chennubhotla V, Rao M U, Rao K, 2013. Exploitation of marine algae in Indo-Pacific region. *Seaweed Research and Utilization*, 35(1/2): 1–7.
- Chianu J, Tsujii H, 2004. Determinants of farmers' decision to adopt or not adopt inorganic fertilizer in the savannas of northern Nigeria. *Nutrient Cycling in Agroecosystems*, 70(3): 293–301.
- Crucefix D, 1998. Organic agriculture and sustainable rural livelihoods in developing countries. Report by Natural Resources and Ethical Trade Programme, June.
- Deign J, 2012. *DNI: Measuring bang for your buck*, viewed 19/10/2016. <http://social.csptoday.com/markets/dni-measuring-bang-your-buck>.
- Dunn R, Lovegrove K, Burgess G, 2012. A review of ammonia-based thermochemical energy storage for concentrating solar power. *Proceedings of the IEEE*, 100(2): 391–400.
- Eisner R, Seabrook L, McAlpine C A, 2016. Minimising the land area used by agriculture without petrochemical nitrogen. In: Proceedings of the International Nitrogen Initiative 2016. <http://www.ini2016.com/1234>.
- Fischer R, Byerlee D, Edmeades G, 2012. Crop yields and global food security. Canberra: Australian Center for International Agricultural Research.
- Florentinus A, Hamelinck C, de Lint S *et al.*, 2008. Worldwide potential of aquatic biomass. *Utrecht, Ecofys*.
- Grassi S, Veronesi F, Schenkel R *et al.*, 2015. Mapping of the global wind energy potential using open source GIS data.
- Heinstein P, Perret-Aebi L-E, Escarre Palou J *et al.*, 2015. Energy harvesting and passive cooling: A new BIPV perspective opened by white solar modules. In: Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale, 675–680.
- Jacobson M Z, Delucchi M A, 2011. Providing all global energy with wind, water, and solar power (Part I): Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy*, 39(3): 1154–1169.
- Jiang J, Aulich T, 2008. JV Task-121 electrochemical synthesis of nitrogen fertilizers. University of North Dakota.
- Kier G, Kreft H, Lee T M *et al.*, 2009. A global assessment of endemism and species richness across island and mainland regions. *Proceedings of the National Academy of Sciences*, 106(23): 9322–9327. doi: 10.1073/pnas.0810306106.
- Kruger P, 2006. *Alternative Energy Resources: The Quest for Sustainable Energy*. Wiley New Jersey.

- Leighty B, 2008. Two Farm Bill Research Initiatives Promise New Markets, Transmission, and Firming Storage for Diverse, Large-Scale Renewables as Hydrogen and Ammonia', in The NHA Annual Hydrogen Conference 2008.
- Leighty B, Holbrook J, 2008. Transmission and firming of GW-scale wind energy via hydrogen and ammonia. *Wind Engineering*, 32(1): 45–66.
- Leighty W C, 2010. Transmission and annual-scale firming storage alternatives to electricity: Gaseous hydrogen and anhydrous ammonia via underground pipeline. In: Proceedings of the International Colloquium on Environmentally Preferred Advanced Power Generation, Costa Mesa, California, USA.
- Li D, 2013. Using GIS and remote sensing techniques for solar panel installation site selection [D]: University of Waterloo.
- Matthews R, De Pinto A, 2012. Should REDD+ fund 'sustainable intensification' as a means of reducing tropical deforestation? *Carbon Management*, 3(2): 117–120.
- Monfreda C, Ramankutty N, Foley J A, 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22(1).
- NASA 2005. NASA SSE monthly average wind data at one-degree resolution of the world viewed 19/10/2016, <https://en.openei.org/datasets/dataset/nasa-see-monthly-average-wind-data-at-one-degree-resolution-of-the-world>. — 2011. *NASA solar direct normal* viewed 19/10/2016. <http://en.openei.org/datasets/dataset/nasa-sse-global-monthly-average-solar-dni-data/resource/71ce20f6-240f-47cf-9197-c4f379a56f91>.
- NASA Earth Observations 2016. *Albedo* (1 month), viewed 19/10/2016. http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA&date=2016-08-01.
- Natural Earth 2016. *Coastline*, available online <http://www.naturalearthdata.com/downloads/110m-physical-vectors/110m-coastline/>, (accessed 19 October 2016).
- Nemet G F, 2009. Net radiative forcing from widespread deployment of photovoltaics. *Environmental Science & Technology*, 43(6): 2173–2178.
- Phalan B, Green R E, Dicks L V *et al.*, 2016. How can higher-yield farming help to spare nature? *Science*, 351(6272): 450–451.
- Philibert C, 2005. The present and future use of solar thermal energy as a primary source of energy. International Energy Agency, Paris, France.
- Pihl E, Kushnir D, Sandén B *et al.*, 2012. Material constraints for concentrating solar thermal power. *Energy*, 44(1): 944–954.
- Rosenthal E, 2010. Solar industry learns lessons in Spanish sun. *The New York Times*, March, vol.8.
- Safarov V, 2015. Renewable energy perspectives of oil exporter Azerbaijan. *Renewable Energy*, Apr 16.
- Salmon J M, Friedl M A, Frohking S *et al.*, 2015. Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data. *International Journal of Applied Earth Observation and Geoinformation*, 38: 321–334.
- Scheidel A, Sorman A H, 2012. Energy transitions and the global land rush: Ultimate drivers and persistent consequences, *Global Environmental Change-Human and Policy Dimensions*, 22(3): 588–595. doi: 10.1016/j.gloenvcha.2011.12.005.
- Shridhar B S, 2012. Review: Nitrogen fixing microorganisms. *Int. J. Microbiol. Res.*, 3(1): 46–52.
- Tallaksen J, Bauer F, Hultberg C *et al.*, 2015. Nitrogen fertilizers manufactured using wind power: Greenhouse gas and energy balance of community-scale ammonia production. *Journal of Cleaner Production*, 107: 626–635.
- Thomas R, Graven D H, Hoskins S B *et al.*, 2016. What is meant by 'balancing sources and sinks of greenhouse gases' to limit global temperature rise? *Briefing Note*, (3): 1–5.
- Turney D, Fthenakis V, 2011. Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews*, 15(6): 3261–3270.
- Wilson K A, McBride M F, Bode M *et al.*, 2006. Prioritizing global conservation efforts. *Nature*, 440(7082): 337–340.
- Yi S-K, Sin H-Y, Heo E, 2011. Selecting sustainable renewable energy source for energy assistance to North Korea. *Renewable and Sustainable Energy Reviews*, 15(1): 554–563.

Appendix Input data layers for N production site selection



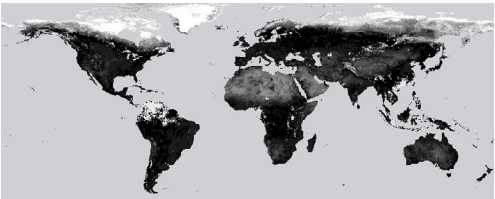
Wind resource available



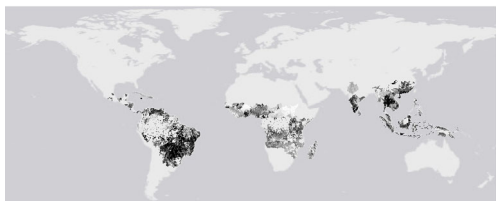
Solar DNI, solar resource for concentrated solar power stations



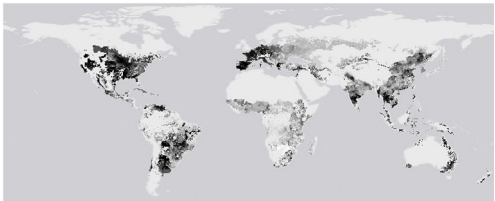
Coastal zone, for marine algae evaluation



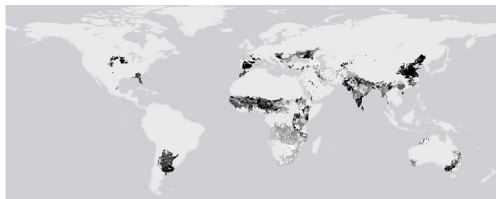
Albedo, for solar site suitability selection



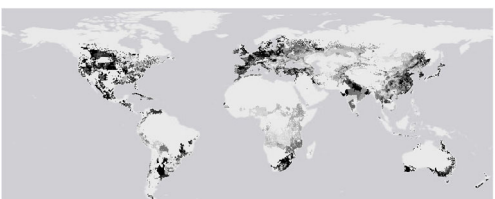
Cassava yield gap



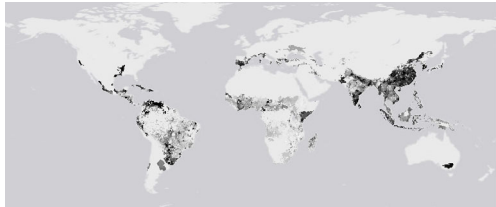
Maize yield gap



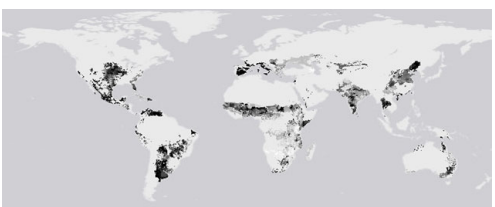
Millet yield gap



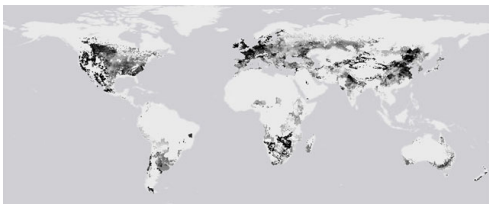
Potato yield gap



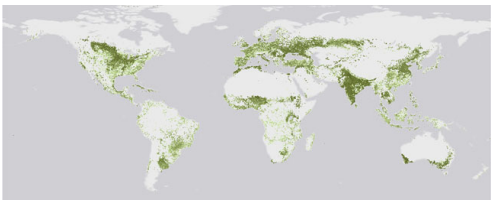
Rice yield gap



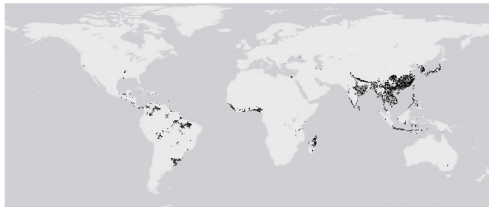
Sorgham yield gap



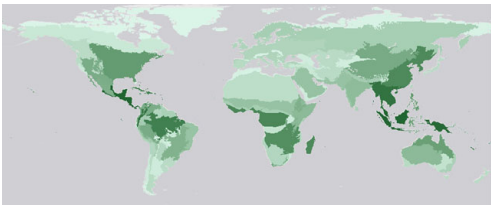
Wheat yield gap



Cropland for selecting area not in competition with crops



Paddy rice for selecting azolla



Biodiversity index by ecoregion for avoiding conflict with biodiversity