Climate-wise agriculture – how best to fertilise our crops?

Clo Ward explores the tricky issue of nitrogen in agriculture.

Experimental plot at Bangor University's research farm. Showing chambers in which nitrous oxide is collected and measured.

With the urgent need to restore biodiversity and sequester carbon as well as feed the population, our land has many jobs to do. As we seek to reduce emissions from agriculture, the question of how to ensure ongoing soil fertility without fossil-fuel-based fertilisers and with reduced reliance on animal manures becomes ever more pressing. Green manures can offer a solution, but usually require setting aside productive agricultural land for nitrogen "fixing". Recent CAT-partnered research as part of a PhD at Bangor University looked at alternative approaches, with a focus on trees and shrubs as potential sources of soil nutrients, specifically nitrogen.

Impact of nitrogen supply on climate change

Lack of the nutrient nitrogen is the most common limitation on crop yields. Though nitrogen is everywhere – making up 78% of air, within all living things and in organic matter in soil – crops mostly take it up in the form of ammonium or nitrate. The conversion of nitrogen gas to these forms which are available to plants is a process known as nitrogen "fixing", and it requires a large amount of energy.

The ammonium and nitrate in manufactured fertilisers is fixed from atmospheric nitrogen in an industrial process which uses 1 to 2 % of the world's fossil fuels, with resulting carbon dioxide emissions. In organic agriculture, nitrogen is instead fixed by plants, using photosynthetic energy to power nitrogen-fixing bacteria in root nodules of green manure plants, e.g. clovers or vetches. These are then ploughed-in to increase soil fertility for the following crop. Adding the organic material of leafy green manures improves soil health and can increase the amount of carbon in soil, so reducing atmospheric CO_2. The nitrogen within any other organic material has got there by one of these two routes; for example, nitrogen in animal manure has come from the animals' food. That food, whether it was grazed from a hillside or fed from a trough has been grown by use of either manufactured fertiliser or biological nitrogen fixing.

A downside of biological nitrogen fixing is that it takes up space. Land must be taken out of cropping to grow the green manures. If farmers are not buying in nitrogen e.g. as fertilisers or manure, they will typically use a quarter to a third of cropland for this type of fertility-building at any one time, in a system of rotational leys. This reduces the overall yields per hectare from organic systems. With land in demand, another solution – used alongside organic sources of nitrogen in CAT's Zero Carbon Britain scenario – is that of nitrogen

Dried perennial mobile green manure leaves stored for use as organic fertiliser.

fixing powered by hydrogen produced via electrolysis using renewable energy.

The environmental impact of providing the fixed nitrogen is problem number one. Problem number two is how to keep that nitrogen from leaking out of the agricultural system.

Nitrogen use efficiency

After green manures are ploughed into soil, the proteins in the plant tissues are decomposed by soil microbes, releasing ammonium and nitrate. These are the same nitrogen-containing compounds that are added as manufactured fertiliser. They are easily taken up by plants, but also easily lost by leaching of nitrate or as nitrous oxide (N_2O) gas. N_2O is produced in soil by microbial action, and is a powerful greenhouse gas which makes up a third of the climate change impact of UK agriculture. Emissions are higher in warm wet conditions and when there is more ammonium and/or nitrate in the soil than the crop can take up.

To increase nitrogen use efficiency, therefore, fertiliser nitrogen is usually added in several applications over the growing season to match the crop's needs, and methods of precision agriculture are being developed to increase efficiency further. Organic materials, being bulky and variable are not well suited to techniques of precision agriculture, and ploughing-in green manure can result in too much available nitrogen before the crop is ready for it. With N_2O emissions being higher in warm, wet conditions, the increasingly unpredictable weather makes management of organic nitrogen even more tricky.

Can we grow fertiliser on trees?

To manage organic nitrogen more efficiently, some growers use "cut-and-carry" or "mobile" green manures, by harvesting nitrogen-rich leaves grown in a separate field and adding them to cropland as needed, rather than ploughing directly into the soil prior to planting. This allows better timing to match the crop's needs, reducing excesses in the soil.

Traditionally, green manures are non-woody plants as they need to be dug in, but cutting and adding leaf nitrogen opens up possibilities of using leaves of trees and shrubs. Alder (*Alnus glutinosa*), for example, is a UK native nitrogen-fixing tree which thrives in flood-prone soil and is tolerant of repeated cutting. Other species of alder grow on drier ground, as do the native nitrogen-fixing shrubs gorse and broom. So could we grow our nitrogen on trees, and harvest the leaves to fertilise crops, thereby fixing nitrogen and creating woodland on the same bit of land? A fertiliser-producing forest?

Increased tree cover on farms provides ecosystem services – environmental benefits to the neighbouring crops – including habitat for pollinators and predators of pests, shelter from wind, and intercepting rain to reduce flood risk. Though rotational leys in organic systems can be biodiverse, also contributing to ecosystem services, replacing some with permanent nitrogen fixing areas could result in increased benefits, especially by providing long-term habitats and carbon sequestration in tree roots and undisturbed soil. To free up more cropland in organic systems to increase overall yields they could also be situated on land which is not suitable for crops, such as flood prone areas or steep slopes. Using these areas for nitrogen fixing on conventional farms could reduce the need for manufactured fertilisers. Leaf nitrogen to be dried or pelleted and supplied to arable farms could perhaps become an alternative income stream for farms without land suitable for crops.

Growing a variety of plants together makes most use of sunlight energy, and also including non-nitrogen fixing plants such as deep-rooted grasses or comfrey helps retain nitrogen in the system. These plants mop up any excess soil nitrogen and store it in their leaves to prevent it leaching away. Species need to be carefully chosen to suit their environment; for example on a boggy area alder could be grown together with comfrey, grasses and clovers which all tolerate wet ground. On a dry slope a mix of gorse, broom and drought-tolerant grasses could be grown. We refer to these permanent nitrogen fixing areas as "bio-service areas" due to their multiple benefits to the neighbouring cropland, as shown in the diagram.

CAT-partnered research

To research whether such a system may be possible, I was lucky enough to receive funding for a CAT-partnered PhD at Bangor University which began in 2016. I tested what I called "perennial mobile green manures" (PMGMs) consisting of leaves harvested in summer from trees, shrubs and perennial nitrogen-fixing plants. These were trialled in pot, field and laboratory experiments in comparison to ammonium nitrate (a commonly used fertiliser), and the

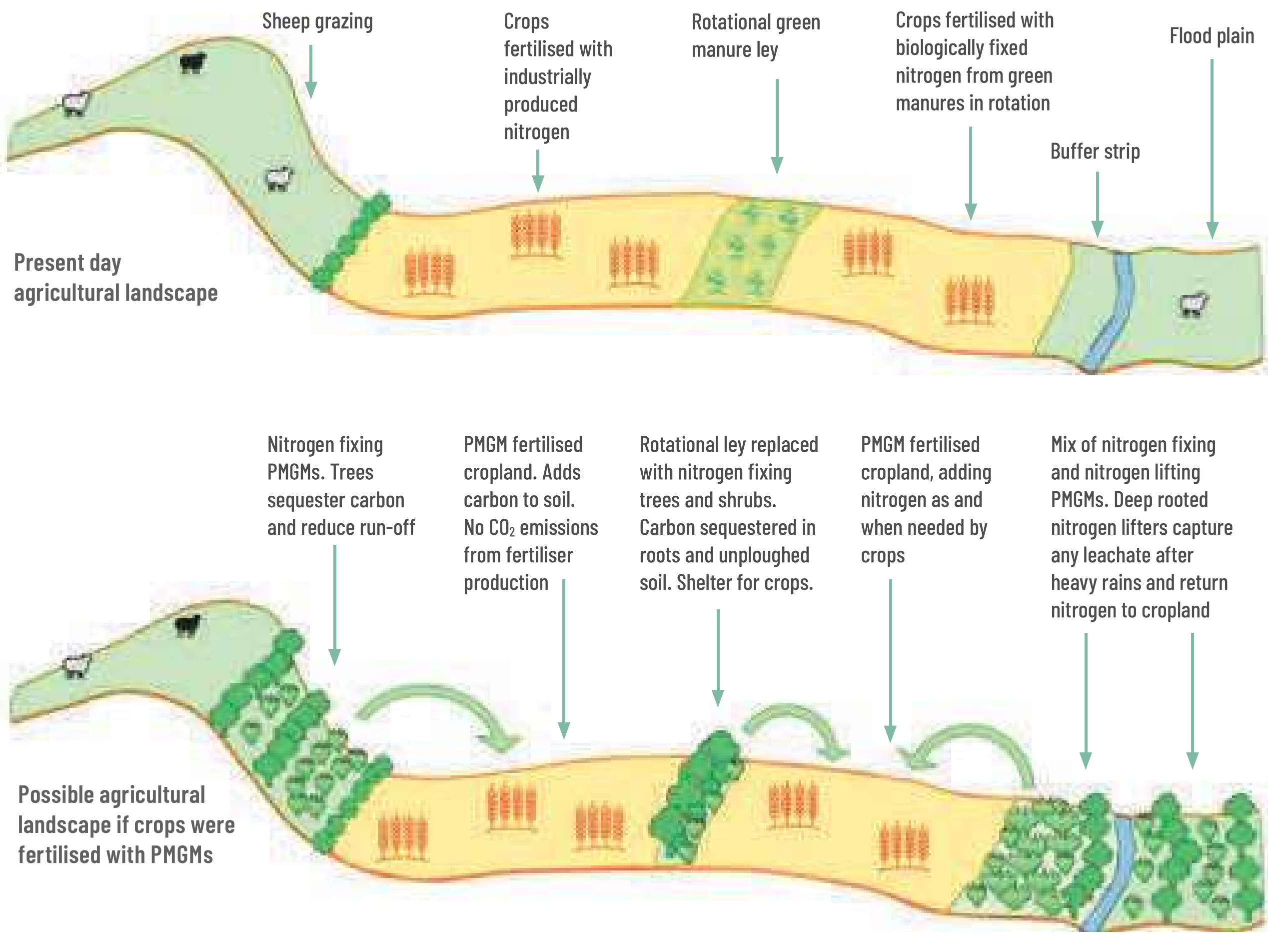
The Nitrogen Problem

Method of nitrogen fixing	Nitrogen fixed by bacteria in the roots of green manure plants, using sunlight energy	Nitrogen fixed industrially, using energy from fossil fuels
CO_2 emissions in production	Carbon neutral ✔	Industrial nitrogen-fixing for fertilisers produces 1 to 2 % of the world's CO_2 emissions ✘
Adding organic matter to soil	Provides organic matter improving soil health and increasing the carbon content of soil ✔	No organic matter provided ✘
Matching of nitrogen supply to the crop's needs	Green manures are usually ploughed in, so it's hard to add exactly the right amount at the right time. Too much nitrogen in soil is prone to losses. ✘	Easy to apply exact amounts of nitrogen at the right times ✔
Use of agricultural land	Green manure systems need to use cropland for nitrogen fixing in rotations, so reducing overall yields per unit area ✘	No extra cropland needed ✔

Crops need to be given nitrogen in a form they can use. This must first be 'fixed' – converted from atmospheric nitrogen into compounds which crop roots can take up. Both industrial and biological methods of nitrogen-fixing have their associated problems.

Present and possible future agricultural landscape using PMGMs to fertilise crops

The amount of arable land remains the same, but the landscape includes more trees and perennials, and less ploughed land.



Amended from a diagram included in a paper currently in review with the journal *Nutrient Cycling in Agroecosystems*.

traditional green manure, red clover. Results showed that the PMGMs could fertilise crops, but released plant-available nitrogen into soil more slowly than clover (when used in the traditional way) or fertiliser, and so had a lower risk of nitrogen leaching and lower nitrous oxide emissions.

The PhD research produced a wealth of data, and my first peer-reviewed paper is due to be published later this year (currently in review). The results showed that such systems may well be feasible and could have many environmental benefits, but as is typical with research it threw up more questions than it answered. For example, I researched the effect of each green manure separately, but combining them together could serve to better match a crop's nitrogen needs. Alder leaves, which supply nitrogen fairly slowly, could be added to soil before crop sowing and then be complemented with a little mulch of dried clover to give quick release nitrogen when needed. Longer term issues to be researched include how best to manage the bio-service areas, such as how and when to cut foliage for least disturbance to wildlife, and whether in the long term the land will need additions of non-nitrogen nutrients such as phosphorous and potassium to replace that removed in vegetation.

The next stage is to try out the technique on real farms, and to this end, the Perennial Green Manures project run by Ecodyfi in Mid Wales has been awarded funding by the Co-op Carbon Innovation Fund to begin trials in spring 2023. In cooperation with farmers and growers we will be looking at practical aspects of the technique - for example: how best to harvest, store and apply the PMGMs; how effective the technique is on specific crops; and which PMGMs or combinations work best. We will also look at the overall environmental impact of the system, for example weighing up the benefits of habitat creation and carbon sequestration against the environmental costs of energy use in harvesting and processing the PMGMs. We hope that by combining agricultural science with farming skills and knowledge we can evolve the technique for the benefit of biodiversity, climate and rural communities.

About the author

Clo (Chloë) Ward has been an organic gardener for 30 years, including a stint as a CAT display gardener from 2007 to 2012. She has a long-term interest in soil health and perennial systems and is now working as a researcher for the Perennial Green Manures project https://www.dyfibiosphere.wales/perennial-green-manures

References available on request. Doctoral thesis available at https://tinyurl.com/4wu9886y