Insights from the Perennial Green Manures project:

An innovative approach to fertilising cropland

Full report

August 2024

Foundation
in partnership with Co-op

Biosffer Dyfi Biosphere
gwerth y byd - world class by nature

ecodyfi

Many thanks to:

The horticultural trialists:
Emma Maxwell and all at Ash and Elm Horticulture
Lucy and all at Dan yr Onnen
Ann and John Owen of Einion's Garden
Petra Weinmann, Jordan Hau and all the growers at the Centre for Alternative Technology
Ruth Kernohan of Enfys Veg
Sue Stickland and Karen Smith

The bioservice area planters:
Rashid Benoy and all at Black Mountains College
Huw Richards of Dan yr Onnen
Emma Maxwell and Dave Ash of Ash and Elm Horticulture
Ruth Kernohan of Enfys Veg
Lisa Sture of Wilder Pentwyn

For PGM processing:
Damon Hammond and all at the Beacon Project, Aberystwyth University

All at Ecodyfi, especially Andy Rowlands and James Cass

All at the Carbon Innovation Fund

Paul Hill and the team at Bangor University

To numerous people who contributed ideas, advice and practical help: Alex Randall, Alistair Meikle, Alys Fowler, Amber Wheeler, Andy Dibben, Arfon Hughes, Ben Porter, Ben Raskin, Bruce Osborne, Catriona Toms, Chris Molyneux, Dave Chadwick, Douglas McMillan, Dylan Owen, Ellie Roxburgh, Emma Maxwell, Frances Gillett, Francis Rayns, Gareth Davies, Gareth Parry, Heledd Wyn, Holly Tomlinson, Ioan Beechey, Jane Morgan, Jerry Alford, Jim Vale, John Mason, Judith Thornton, Julia Cooper, Julie Brominicks, Katharina Dehnen-Schmutz, Ken Giller, Laura Gude, Laura Shewring, Maria Cooper, Peter Watkins, Phil Potter, Rasmus Einarsson, Rebecca Swinn, Rhodri Lloyd-Williams, Sally Westaway, Sian Stacey, Steve Pickup, Tesni Gordon

A summary of this report is available in Cymraeg at:
www.biosfferdyfi.cymru/prosiectgwrtaith-gwyrdd-lluosflwydd

This report and (summary report in English) is available to download at:
www.dyfibiosphere.wales/perennialgreen-manures

The Perennial Green Manures Project was run by Ecodyfi and funded by the Carbon Innovation Fund (CIF), a partnership between the Co-op and the Co-op Foundation.

Ecodyfi is a not-for-profit Development Trust delivering sustainable community regeneration and promoting a growing green economy in the Dyfi Valley, Mid Wales.

Report written by Clo Ward (2024). Edited by Hannah Engelkamp and Phil Sumption. Thanks to Phil Sumption for cover design and help with formatting and to Judith Thornton for scientific advice on the text.

Tilly Gomersall

Tilly Gomersall was the **project manager** for the Perennial Green Manures (PGM) project. Tilly's interest in farming came from a fascination with botany, a concern for the natural world and a desire to find ways of producing food without exploiting nature and people. She has been working in commercial vegetable production since 2020 and has been running her own business, 'Hadau a Phridd', producing fresh vegetables for the Mach Veg Box scheme and other local outlets. She also produces seed for Wales Seed Hub. Tilly has been studying for an MSc in Sustainable Food and Natural Resources at the Centre for Alternative Technology where her focuses are soil health in food production, and adaptive crops for changing climates.

Clo (Chloe) Ward

Clo (Chloe) Ward was the **researcher** for the PGM project. Clo has worked in horticulture for over 30 years, specialising in perennial systems and promoting environmental techniques by display gardening, writing and teaching. Seeking answers to climate questions in agriculture Clo returned to scientific study in 2013, undertaking an MSc in Food Security at Aberystwyth University. This led to a PhD at Bangor University on 'An evaluation of perennial mobile green manures for climate change mitigation in agriculture' which forms the basis for this project.

Insights from the Perennial Green Manures project:

An innovative approach to fertilising cropland

Current methods of fertilising crops are not ideal. They impact on greenhouse gas emissions and the biodiversity and carbon sequestration within the farming landscape. Much of this is due to the supply and management of nitrogen. Nitrogen is an essential nutrient for crop growth, but agriculture's impact on the nitrogen cycle has far-reaching consequences for the environment.

Perennial Green Manures (PGMs) are plant-based fertilisers made from the harvested foliage of perennial plants, including trees and shrubs grown in what we have termed 'bioservice areas' integrated into farmland. This report explores whether PGMs could offer a more sustainable way to fertilise crops. Could combining the benefits of organic nitrogen for soil and crop health with the precision of modern agricultural methods increase nitrogen use efficiency and reduce pollution?

Our PGM project ran from May 2022 to July 2024 in the Dyfi Valley, Mid Wales. We supplied PGMs to five horticultural producers who trialled them alongside their usual methods of fertilising crops. We gathered opinions from growers, farmers, foresters and ecologists on how PGMs could be used for socially, economically and environmentally sustainable agriculture. The project culminated with the planting of five 'bioservice areas', to provide future PGMs to horticultural enterprises.

In this report we outline the environmental issues with supplying nitrogen to crops and the ways in which Perennial Green Manures could address these pitfalls. We summarise the research to date on PGM use, including the five horticultural trials undertaken in mid Wales. We cover the possible implications, obstacles and benefits of growing PGMs at scale, and lay out the further research needed to progress with PGM use for possible benefits to farmers, land managers and the rural environment.

Words in **purple** appear in glossary

Words in **green** contain links to other sections or external websites

Contents

1. Challenges in sustainable crop production

The landscapes around us are determined by what we eat and how we produce it. Farming methods alter the composition of the soil, the gases in the atmosphere, the biodiversity within farmland and the space left for natural and semi-natural habitats. These in turn determine the stability of our environment and human wellbeing.

The Committee on Climate Change report 'Land use: Policies for a Net Zero UK' 2020[1] highlights a need for better management of soil nutrients to reduce greenhouse gas emissions as well as a need for more trees in farmland for **carbon sequestration** and ecosystem resilience.

Maintaining high crop yields whilst also improving environmental outcomes is challenging however. The Perennial Green Manures project explored the possibility that growing and using perennial green manures could offer a way to increase farm resilience whilst also contributing to biodiversity restoration and climate change mitigation.

Nitrogen in agriculture

Much of the impact of food production is determined by how we supply nutrients to crops, especially nitrogen. The recent Defra 'Report of the Nutrient Management Expert Group'[2] states that "Mitigating and adapting to climate change and protecting environmental quality whilst meeting society's needs for food and other resources is one of the most pressing challenges facing humanity. Nutrient management plays a key role in ameliorating this crisis."

Nitrogen is an essential nutrient for crop growth, and lack of nitrogen is the most common limitation on crop yields. Plant roots mostly take nitrogen up in the forms of ammonium or nitrate. These can be increased in soil by adding manufactured fertilisers or by adding nitrogen-rich organic materials such as manures, composts or green manures.

All plant-available forms of nitrogen – manufactured or organic – have been converted into these forms from nitrogen gas which makes up 78 % of the air. This process is known as 'nitrogen fixing', a chemical reaction which requires a great deal of energy. Biological nitrogen fixing is performed by some species of bacteria which live in the roots of nitrogen-fixing plants. The plants donate sugars made by photosynthesis to the bacteria which use them to fuel the nitrogen fixing, converting nitrogen gas to nitrogen compounds that plants can use. Nitrogen is also fixed industrially, using fossil fuels to provide the energy to make nitrogen fertilisers, in a process known as 'Haber Bosch' after the inventors of the technique.

Biologically fixed nitrogen is traditionally supplied to crops by growing nitrogen-fixing green manures such as clovers and vetches in crop **rotations**. These are grown on cropland which is periodically taken out of production to increase the soil fertility. The nitrogen fixed in the roots becomes concentrated in the leaves where it performs many vital functions. The green manures are then usually incorporated into the soil by cultivation such as ploughing or harrowing. They can also be killed off by other methods, such as using a roller or 'crimper' to crush the stems, which enable them to be left as a **mulch** on the soil surface. As they decompose the soil gains ammonium and nitrate which are used by the next crop grown on that land.

Supplying nitrogen to crops by use of either industrial or biological methods can have environmental problems, as shown in the table below.

Nitrogen and greenhouse gases

Industrial **nitrogen fixing** results in a significant amount of carbon dioxide emissions. Though in future it may be possible to power the process via electrolysis using renewable energy,[3] at present fertiliser production is estimated to take around 2 % of the world's fossil fuel use.[4] In contrast biological nitrogen fixing is powered by sunlight and produces no carbon emissions.

The organic matter provided by green manures is great for soil functioning. It feeds soil fauna and gives soil a spongy structure which helps with water retention and drainage. Adding organic matter can also help mitigate climate change if it becomes incorporated into very stable soil constituents such as **humus** which binds soil particles together. Increasing the amount of carbon in the soil in this way is known as carbon sequestration and reduces carbon dioxide in the atmosphere.

Addition of both biologically and industrially fixed nitrogen to soil affect another greenhouse gas – nitrous oxide (N_2O). Nitrous oxide is produced by microbes as part of natural soil cycles, usually in very small quantities. Under certain conditions however, if the soil is warm and wet and has a high nitrate concentration, nitrous oxide emissions increase. Nitrous oxide is a powerful greenhouse gas, and in the UK accounts for 32 % of emissions

The Nitrogen Problem		
Method of nitrogen fixing	**Traditional green manures** Grown in rotation on cropland. Biological nitrogen fixing using sunlight energy. 	**Manufactured nitrogen fertiliser** Added to soil as a chemical compound. Fixed industrially using fossil fuel energy. 
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 adding carbon to soil	No organic matter provided
Matching of nitrogen supply to the crop's needs	It can be hard to add exactly the right amount of nitrogen at the right time. Too much nitrogen in soil is prone to losses.	Easy to apply exact amounts of nitrogen when and where it is needed by crops
Efficient use of agricultural land	Green manure systems use prime cropland for nitrogen fixing in rotations, so reducing overall yields per unit area.	No extra cropland needed

The nitrogen problem. *A comparison of supplying biologically fixed nitrogen by traditional rotational green manures and industrially fixed nitrogen fertiliser, and their associated environmental issues* from agriculture. Though methane makes up 55 % of the UK's agricultural emissions.[5] there is an option to reduce this by our dietary choices, whereas growing crops is a fundamental necessity.

Fig 1.1 shows the nitrogen cycle in agriculture in which nitrogen moves between nitrogen gas, organic matter and various nitrogen compounds in the soil. In whatever form the nitrogen is added, the nitrogen compounds in soil are easily converted into forms which can be lost as pollutants. If ammonium concentrations are high it can be lost to the air by a process called volatilisation causing ammonia pollution, and nitrates can be **leached** out, polluting watercourses.

Nitrous oxide is produced by microbes from the nitrate in soil solution which has either been added as a fertiliser or produced by the decomposition of organic materials. When adding fertiliser, the nitrogen is immediately available to both crops and N_2O-producing microbes, and so it is important to keep soil nitrate concentrations low by adding it in small quantities where and when needed by the crop. Systems of precision agriculture which can apply fertilisers in specific quantities are becoming increasingly sophisticated to enable this.

Nitrous oxide emission from agricultural soils is a neglected issue in climate change mitigation. It is responsible for 32 % of agricultural emissions in the UK.[5] Nitrous oxide is produced in soil in warm, wet conditions when there is more available nitrogen than the crops can use.

When adding organic nitrogen such as green manures, it is also important to prevent soil nitrate concentrations becoming high. A difficulty with

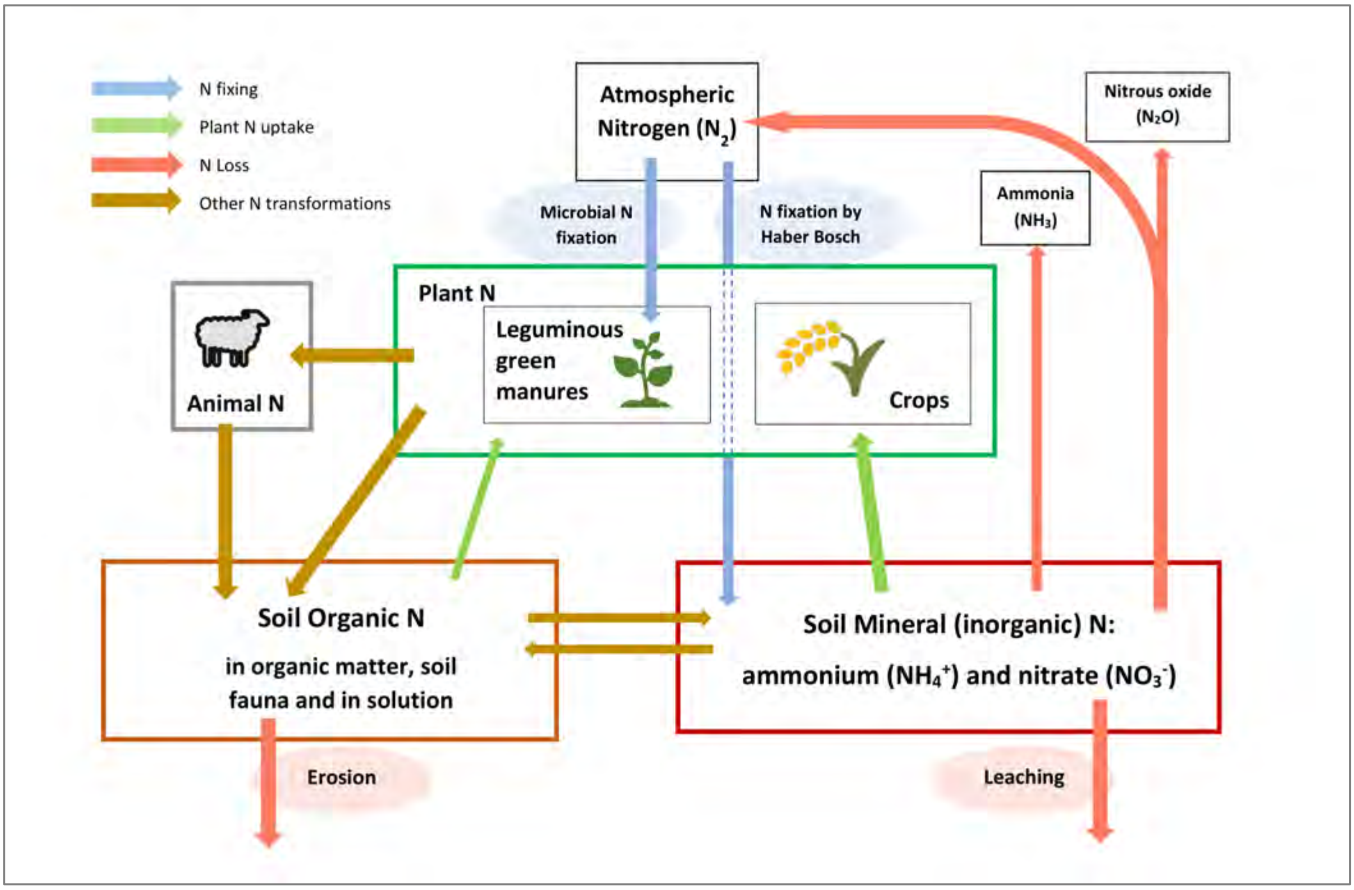


Fig 1.1 The Nitrogen Cycle in Agriculture. *Organic nitrogen, added, for example within green manures, decomposes into inorganic nitrogen compounds (ammonium and nitrate) which are taken up by crops*

adding green manures grown in **rotation** is that these systems don't allow much flexibility to add the right amount of nitrogen at the right time. This can lead to a build-up of more nitrate in the soil than the crops can use, risking high nitrous oxide emissions.[6] With N_2O emissions being higher in warm, wet conditions, the increasingly unpredictable weather makes management of organic nitrogen even more difficult.

Nitrogen and land use

The method by which we provide nitrogen also affects the amount of land needed for crop production. Nitrogen-fixing green manures are commonly included in **cover-crop** mixes over winter, when crops are not being grown, and they can also be grown in and among crops as **living mulches.** These practices have multiple benefits for soil and crop health as well as providing nitrogen. However, to fix enough nitrogen to fertilise crops without using external nitrogen inputs requires a significant amount of land for capturing sunlight energy. Growers using green manures as their main nitrogen source typically have one quarter to one half of the cropping area under green manure **leys** at any time, including during summer months.

The UK's land area is approximately 24 million hectares, of which about 17.5 million hectares is used for agriculture. Of this, 5 million hectares are used to grow crops, half of which grow fodder crops for animals and half for direct human consumption. The rest is grassland to feed animals.[7] There are 5 million hectares under commercial forestry, woodlands and other habitats.

At present, the proportion of growers providing most of their nitrogen by green manures in rotation is small. However, if this were to become a common method to supply nitrogen to the UK's 5 million hectares of cropland, the area under cropland would have to dramatically increase to allow space for the required leys. Land is in high demand with the need to increase forests and other habitats for carbon sequestration and ecosystem stability. Though the leys are often very biodiverse with a wide variety of plants providing food and habitat for beneficial insects, the habitat provision and carbon sequestration potential is unlikely to provide as many ecological services as a permanent area of woodland or other semi-natural habitat.

Why not just use manure or composts?

Many growers use bulky soil treatments such as composts and manures which are great for soil health, and wastes such as food scraps need to be recycled to retain resources and prevent pollution. However, there wouldn't be a enough of these to fertilise all our crops this way. It's also important to remember that the nitrogen within composts and manures has originally been fixed by either industrial methods or by nitrogen-fixing plants, with their associated environmental impacts. For example, the nitrogen within animal manure has come from the animals' food. The nitrogen in this food may have been fixed by **leguminous** plants, in grazed grasslands or within organic systems producing fodder. Alternatively it could have been produced by industrial processes supplying fertiliser nitrogen to grasslands or fodder crops. When nitrogen is removed from a system, for example within manure from a livestock farm, it must be replaced with more nitrogen brought into that farm, with the associated environmental consequences of that.

Influence of crop and soil health on nitrogen use efficiency

It is not just the form of the nitrogen or the time and place it is added which affects the efficiency of its use. Crops which are not growing to their full potential because of, for example, disease or water stress will not be able to take up available nitrogen. The biology of the soil also affects the efficiency of nitrogen use. Among growers and farmers there is currently a much-needed focus on soil health. Nitrogen cycling in soil is determined by the mix of soil organisms and the interactions between them. It is a hugely complex system, much of which is still unknown, but it is generally thought that a high diversity and activity of soil microbes is good for efficient use of nutrients. Some organisms have specific beneficial roles, for example **mycorrhizal fungi** live in association with plant roots and aid the uptake of nitrogen and other nutrients by plants. Some growers, such as practitioners of Shumei agriculture believe that the right soil life can negate the need for inputs at all.[8] However, the vast majority of growers do add nitrogen to soil in some form, and this report assumes that nitrogen additions, whether of nitrogen fixed within the cropland or brought in from elsewhere, is needed for productive systems.

References

1. Committee on Climate Change (2020) 'Land use: Policies for a Net Zero UK' https://www.theccc.org.uk/wp-content/uploads/2020/01/Land-use-Policies-for-a-Net-Zero-UK.pdf

2. Defra (2024) 'Improving policy and practice for agricultural nutrient use and management' https://tinyurl.com/na3ck398

3. Rouwenhorst, K. H., Travis, A. S., & Lefferts, L. (2022). '1921–2021: A Century of renewable ammonia synthesis' *Sustainable Chemistry*, *3*(2), 149-171. https://www.mdpi.com/2673-4079/3/2/11

4. Einarson, R, (2024) 'Nitrogen in the Food System' https://tabledebates.org/building-blocks/nitrogen-food-system

5. Department for Business, Energy and Industrial Strategy (2022) '2020 UK Greenhouse Gas Emissions, Final Figures' https://tinyurl.com/mrxjrfuy

6. Chen HH, Li XC, Hu F, Shi W (2013) 'Soil nitrous oxide emissions following crop residue addition: a meta-analysis' Glob Change Biol 19(10):2956–2964. https:// doi. org/ 10.1111/ gcb. 12274

Hansen, S., R. B. Froseth, M. Stenberg, J. Stalenga, J. E. Olesen, M. Krauss, P. Radzikowski, J. Doltra, S. Nadeem, T. Torp, V. Pappa, and C. A. Watson. (2019). 'Reviews and syntheses: Review of causes and sources of N_2O emissions and NO_3 leaching from organic arable crop rotations' *Biogeosciences* 16 (14):2795-2819. https://doi.org/10.5194/bg-16-2795-2019

Crews TE, Peoples MB (2004) 'Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs' Agric Ecosyst Environ 102(3):279–297. https://doi.org/10.1016/j.agee.2003.09.018

7. Centre for Alternative Technology, (2019). 'Zero Carbon Britain Rising to the Climate Emergency' https://cat.org.uk/info-resources/zero-carbon-britain/research-reports/zero-carbon-britain-rising-to-the-climate-emergency/

8. 'Sumei Natural Agriculture' https://shumei-international.org/what-we-do/natural-agriculture/ Accessed 15/08/2024

2. What are PGMs and how could they help?

Perennial Green Manures (PGMs) are fertilisers made from the harvested foliage of perennial plants, including nitrogen-fixing species, grown in what we have termed bioservice areas. Bioservice areas are permanent areas of land where plants are grown to produce PGMs, and also provide other biological services to nearby agricultural crops, such as shelter, erosion control and habitat for beneficial insects. For maximum benefit a mix of plants including trees and shrubs are grown. Nitrogen, originally fixed within the roots of nitrogen-fixing species, builds up in the leaves of all of these plants, which are then harvested and added to cropland to fertilise the soil.

Current methods of using pre-harvested green manures

As far as we know using PGMs grown in bioservice areas in this way is not yet practiced in temperate horticulture or agriculture. However gardeners have long used similar techniques, such as growing comfrey and nettle patches used to supply nutrients, usually by making a liquid feed from the leaves. The practice of 'crop and drop' is also becoming popular, in which plant prunings are dropped from where they are cut onto the soil surface as a mulch. There are now various plant-based fertiliser pellets available to buy which are made from comfrey, hops or mixtures of other plants or plant-waste material. These tend to be fairly expensive and aimed at hobby gardeners, but some growers are using alfalfa pellets which are sold as animal feed and are a cheaper option.[1]

Farmers are innovating solutions to increase nutrient use efficiency on a field scale. Some mow fields of green manures and add them to other areas of cropland as 'transfer mulch', 'mobile', or 'cut and carry' green manures.[2] This allows them to match the amount of nitrogen added to the crop's requirements, so reducing excess nitrate building up in soil. They can be stored, for example as silage, for adding where and when needed. Pioneering grower Helen Atthowe and her late husband Carl Rosato developed a system on their farm in Oregon where crops are fertilised by grass, clover and other plant clippings which are 'mown and blown' onto the cropland using leaf-blowers.[3] Johannes Storch of Bio-Gemüsehof Dickendorf in Germany has innovated a no-til system using mulches in field-scale organic vegetable production. He uses thick transfer mulches on top of closely mown **cover crops** which are then planted through using specially designed machinery.[4]

Could the growing and application of PGMs offer an elegant way to address the nitrogen problem?

Transfer mulches used in temperate agriculture are usually non-woody, traditional green manures, but in tropical agriculture smallholders cut and add the green foliage of nitrogen-fixing trees and shrubs to fertilise soil.[5] In the UK the use of fresh or composted woodchip or ramial chipped wood as a soil conditioner is becoming increasingly popular. Ramial chipped wood is made from thin tree branches (< 7 cm) and is added to soil to provide nutrients and improve soil functioning. There is now a growing trend in ecological horticulture to plant shelterbelts for ramial wood production, similar to our idea of bioservice areas of nitrogen-producing plants.[6]

Potential advantages of PGM systems

Perennial green manures have the same advantages as traditional green manures grown in rotation, in that nitrogen fixing via PGMs does not cause carbon dioxide emissions, and they supply organic matter to soil, so enabling **carbon sequestration**. Like transfer mulches or mobile green manures they can be added when and where needed by the crop, so allowing the matching of nitrogen supply to the crops' needs, increasing nutrient efficiency, and reducing the chances of causing damaging nitrous oxide emissions.

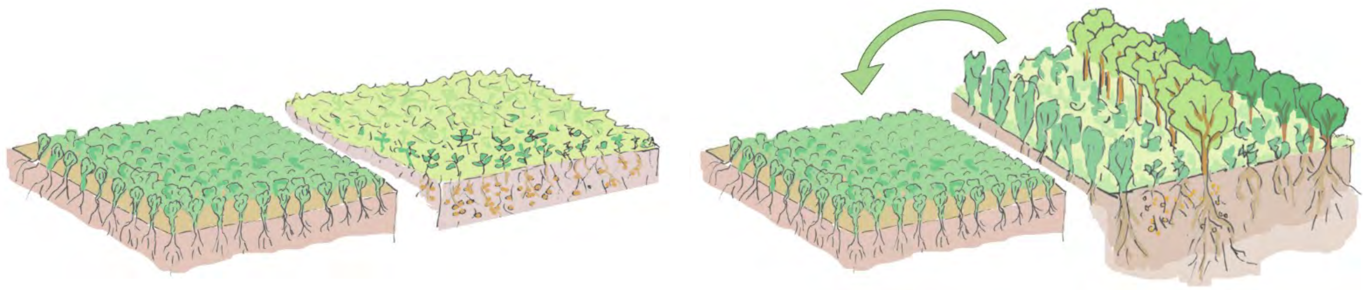


Fig 2.1 *Crops grown in rotation with green manure leys (left) Crops fertilised with PGMs harvested from permanent bioservice areas (right)*

Unlike green manure in rotations, however, PGMs are grown in separate bioservice areas which can be largely left undisturbed, so providing a long-term wildlife habitat (Fig 2.1). For example, a bioservice area could be made up of a mix of **coppiced** trees, shrubs and ground-covering plants. Carbon stores can build up in the uncultivated soil and roots within the bioservice areas to help mitigate climate change. If well designed, the permanent bioservice areas could be more ecologically valuable than temporary nitrogen-fixing leys. They could also be designed to provide other benefits to crops, for example to double up as windbreaks and reduce run-off and water erosion, as well as providing food for pollinating insects and predators of crop pests.

Bioservice areas can be situated on land which is not suitable for crops such as flood-prone areas or steep slopes, without sacrificing prime cropland. The species grown in bioservice areas need to be carefully chosen to suit their environment; for example in a boggy area alder could be grown together with lower growing plants such as comfrey, grasses and clovers which tolerate wet ground. On a dry slope a mix of gorse, broom and drought-tolerant grasses could be grown. Not all land would be suitable for planting as bioservice areas, however. Land which is already ecologically rich and well-managed needs to be preserved as it is.

Skilled design would be needed to maximise the various possible benefits as shown in Fig 2.2 For example, on lower ground next to watercourses it would be important to include deep-rooting plants to uptake any **leached** nutrients, which would be returned to the cropland within the PGM foliage. In fact much of our environment is already too rich in nitrogen, to the detriment of many sensitive habitats. A function of bioservice areas in some places could be, rather than fixing more nitrogen, to mop up excess nitrogen from where it is not needed and add it to farmland where it can be of benefit.

As well as being harvested and applied directly PGMs could be processed, for example by drying or pelleting, and stored for later use. If processing into a saleable product, PGMs could be grown some distance from where they are applied. There may be scope for PGMs to be widely grown in areas of lower-grade agricultural land, particularly in areas of higher rainfall which are naturally less suited to arable and horticultural production.

Fertilising cropland by green manures grown in rotation uses up extra land for leys. These can be very biodiverse, but would it offer more ecosystem services if instead we had permanent 'bioservice areas' that included trees and shrubs from where green foliage could be harvested and added to cropland?

What plants make good PGMs?

PGMs can be made from the leaves of many different plants. Some of these are the same species long used as **rotational** green manures such as clovers, vetches, trefoils, and various grasses. Trees and shrubs such as alder, willow, broom and gorse can also be used. In fact, any perennial plant that either fixes nitrogen and/or grows fast is a possible PGM. Tree PGMs must be

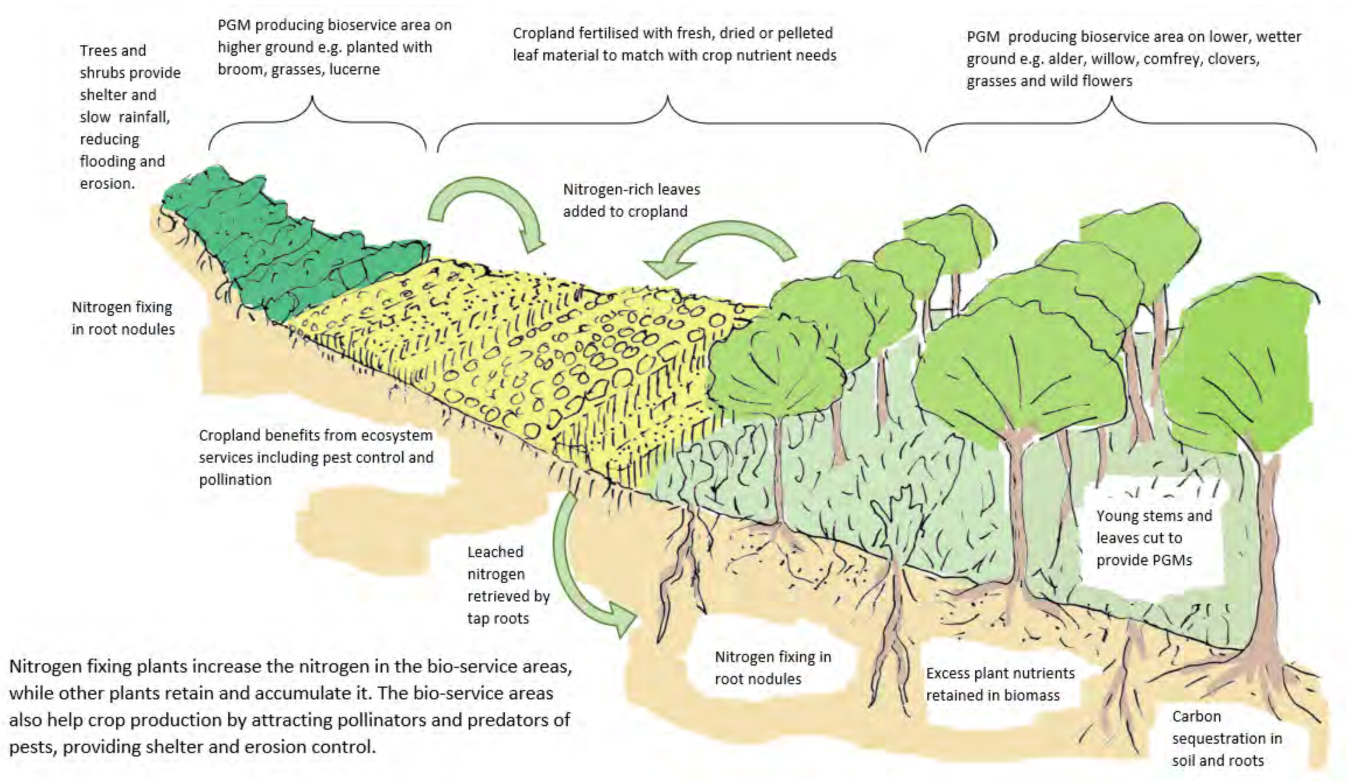


Fig 2.2 *Bioservice areas producing PGMs, integrated into agricultural landscape for maximum ecological and agricultural value*

harvested while the leaves are green for maximum nitrogen content, as during autumn the plant moves valuable nutrients from the leaves to other parts of the plant so that it is not lost within leaf fall.

Different types of plants have different qualities when used as PGMs. As an example, some rot down quickly giving a fast nutrient boost to crops, and some are slow to decompose, releasing nutrients over a longer time. The ratio of carbon to nitrogen (C:N ratio) in plant tissue is a key factor – a high ratio and the nitrogen takes a long time to become available in the soil, a low ratio and nitrogen is usually released quickly. Different plant species which can be used as PGMs also contain varying amounts of other essential nutrients such as phosphorus, potassium or magnesium, which be added appropriately for the crop's needs.

References

1. Gatsios, A., Ntatsi, G., Celi, L., Said-Pullicino, D., Tampakaki, A., & Savvas, D. (2021). Legume-based mobile green manure can increase soil nitrogen availability and yield of organic greenhouse tomatoes. *Plants*, *10*(11), 2419. https://doi.org/10.3390/plants10112419

2. Burgt, Geert-Jan HM, Carina Rietema, and Michiel Bus. 2018. 'Planty Organic 5 year: evaluation of soil fertility, nitrogen dynamics and production' https://orgprints.org/id/eprint/32529/

Sorensen JN, Thorup-Kristensen K (2011) Plant-based fertilizers for organic vegetable production. J Plant Nutr Soil Sci174(2):321–332. https://doi.org/10.1002/jpln.200900321

Benke, A. P., A. M. Rieps, I. Wollmann, I. Petrova, S. Zikeli, and K. Moller. 2017. "Fertilizer value and nitrogen transfer efficiencies with clover-grass ley biomass based fertilizers." *Nutrient Cycling in Agroecosystems* 107 (3):395-411. https://link.springer.com/article/10.1007/s10705-017-9844-z

Arlauskiene, A., Jablonskyte-Rasce, D., & Slepetiene, A. (2020). Effect of legume and legume-festulolium mixture and their mulches on cereal yield and soil quality in organic farming. *Archives of Agronomy and Soil Science*, *66*(8), 1058-1073. https://doi.org/10.1080/03650340.2019.1652816

Any fast-growing species which is ecologically beneficial could be investigated for use as a PGM. They can be nitrogen fixing or not and include leafy ground covers such as vetches, trefoils, lupins, grasses, Jerusalem artichokes, *Miscanthus*, and hops, and trees and shrubs including tree lupins, *Laburnum*, *Wisteria*, *Eleagnus, Acacias, Robinia, Paulownia,* hazel, hawthorn, dogwood, *Viburnums*, poplars, privet, aspen, elder and limes.

3. Atthrow, Helen (2023) ‘The Ecological Farm - A Minimalist No-Till, No-Spray, Selective-Weeding, Grow-Your-Own-Fertilizer System for Organic Agriculture’ Chelsea Green Publishing

4. Sumption, Phil (2019) ‘Mulch systems and rotational no till in vegetable farming’ The Organic Grower - No 48 Autumn 2019 https://tinyurl.com/4kwxtvy6

5. Ajayi OC, Place F, Akinnifesi FK, Sileshi GW (2011) Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). Int J Agric Sustain 9(1):129–136. https://tinyurl.com/5duan8jz

Palm CA (1995) Contribution of agroforestry trees to nutrientrequirements of intercropped plants. Agrofor Syst 30(1–2):105–124. https://link.springer.com/article/10.1007/BF00708916

Sileshi GW, Akinnifesi FK, Mafongoya PL, Kuntashula E, Ajayi OC (2020) Potential of gliricidia-based agroforestry systems for resource-limited agroecosystems. In Dagar JC, Gupta SR, Teketay D (eds) Agroforestry for degraded land.scapes: recent advances and emerging challenges, vol 1, Springer, Singapore, pp 255–282. https://doi.org/10.1007/978-981-15-4136-0_9

6. Fontana, M., Johannes, A., Zaccone, C., Weisskopf, P., Guillaume, T., Bragazza, L., ... & Sinaj, S. (2023). Improving crop nutrition, soil carbon storage and soil physical fertility using ramial wood chips. *Environmental Technology & Innovation*, *31*, 103143 https://doi.org/10.1016/j.eti.2023.103143

Westaway S (2020) WOOFS Technical Guides.
1) Ramial Woodchip production and use.
2) Ramial Woodchip in agricultural production.
3) Using ramial woodchip as part of a whole system.
https://tinyurl.com/WOOFS-Ramial

Alder tree leaves and nitrogen fixing nodules on roots

3. The Perennial Green Manures project

The Perennial Green Manures project ran from May 2022 to July 2024 as part of the activities of Ecodyfi, a not-for-profit Development Trust in the Dyfi Valley, Mid Wales. It was funded by a Carbon Innovation Fund grant which support projects contributing to climate change mitigation in food production. The grants are awarded by a partnership between the Co-op and the Co-op Foundation, partly funded by the money raised by carrier bag sales.

PGM processing and the growers' trials

The project aimed to explore the idea of PGMs as a technique to fertilise crops, which could have multiple environmental benefits. As well as practical trials on gathering, processing and using PGMs, we spread the word about PGMs to gather opinions and ideas from a wide range of stakeholders.

The processing of PGMs was undertaken by the Beacon Project, part of Aberystwyth University **(section 6).** We advertised for participant crop-growers by social media and at in-person events, hoping to recruit both organic and conventional growers. However there are few large-scale arable or horticultural growers in Mid Wales and uptake to join the trials was mostly from small-scale growers, and all were using organic methods. Five vegetable growers and one wheat grower began the trials. Unfortunately the wheat crop had poor growth overall due to other factors and so the trial did not run its course. Though we collected data on crop yields and soil characteristics, the trials were just as much about gaining insights from the growers' experiences. We gathered feedback from the growers via surveys and informally at various stages throughout the trials.

Spreading the word and gathering opinions and expert advice

We gave presentations at shows and events to explain the technique of PGMs and gather feedback from growers, farmers, ecologists and other stakeholders. These included the Organic Matters conference (Birmingham, 2022), The Soil Symposium (Centre for Alternative Technology, 2023), The Talybont Agricultural Show (Ceredigion, 2023), The Agroforestry Show

(Wiltshire, 2023), The Wales Real Food and Farming Conference (Ruthin, 2023) and the Oxford Real Farming Conference (2024). Local filmmaker Heledd Wyn was commissioned to make a short film explaining PGMs and our work, which can be viewed **here.** For this we are grateful for funding from the Woodland Trust.

We held a focus group with specially invited land-use experts including farmers and foresters, in the Dyfi Valley, to gather opinions on the potential benefits and possible drawbacks of producing and using PGMs. We also sought expert advice on the specific topic of the risk of spreading tree diseases by growing and transporting plant material. Tree pathology consultant Alistair Yeomans of FloraSec, was commissioned to write a **report** which assessed these risks and advised on strategies for mitigation.

Taking the PGM idea forward after the project

The PGM project culminated with the planting of five bioservice areas, to provide future PGMs to horticultural enterprises (Chapter 7). The idea of PGMs also captured the interest of a group of farmers who have come together to experiment further as part of the **Innovative Farmers** network. To help with this, we presented at a webinar (**available to watch here**). The participants will be trialling the application of alder leaves and grass cuttings on **brassica** crops and monitoring crops' yields and soil health.

We took PGMs on the road, including experimenting with methods of chopping foliage, and gathering views from farmers at the Talybont agricultural show

4. Previous research on PGMs

The idea of using the leaves of nitrogen-fixing trees, shrubs and other perennials in temperate agriculture, in the way we envisage, was first investigated at Bangor University as a PhD carried out by Clo Ward, in association with the Centre for Alternative Technology and funded by KESS (Knowledge Economy Skills Scholarships).[1] The research aimed to tackle the **nitrogen problem** by building on previous work on 'mobile' or 'cut and carry' green manures**.** Cutting green manure foliage and adding it to cropland in another area opens up the possibility of utilising a wider range of nitrogen-fixing species including trees and shrubs, so Clo's PhD investigated 'perennial mobile green manures' (which we now just call Perennial Green Manures).

The PhD investigated using foliage of three nitrogen-fixing species: the tree alder (*Alnus glutinosa*), the spikey bush gorse (*Ulex europaeus*), and the herbaceous perennial *Gunnera*. The three PGMs were used in a one-year pot experiment and a two-year field experiment, and their effects were compared with the traditional green manure red clover, ammonium nitrate fertiliser, and a control with no addition. In each experiment, replicate treatments of the different PGM leaves, clover leaves, and ammonium nitrate were added to soil, along with control replicates with no addition. A crop was sown and measurements taken of crop yields, emissions of nitrous oxide (N_2O) from soil and the concentration of various compounds in soil solution, including nitrate and dissolved organic carbon.

Crop yield results

In the pot experiment the PGM-treated plants had the same or higher yields than the fertiliser or clover-treated plants. Nitrogen from the PGMs became available more slowly than from fertiliser or clover, resulting in a more sustained supply of nitrogen and lower nitrate concentrations in soil, so less risk of pollution. In the field experiment PGMs produced lower yields than from fertiliser nitrogen, probably because the growing seasons were short (under four months) which didn't allow enough time for the slower nitrogen release. However, the second year of the field experiment indicated that adding the same treatments of alder and gunnera to the same plots over two years may have had an increasing effect. This suggests that PGMs could become increasingly effective over time if used repeatedly.

Of the three PGM species used, gorse was deemed to be the least suitable, as results from the pot experiment and year one of the field experiment indicated that crop growth was lower than expected for the available nitrogen in the soil solution, and so only alder and gunnera were carried on into year two of the field experiment. This could be because of an **allelopathic** effect of chemicals within gorse tissue which restricts the growth of other plants. However, it has been shown showed that the allelopathic effect of gorse may depend on the plant species growing and therefore in specific circumstances it is possible that gorse could be used as a PGM, supressing weed growth, but leaving crops unaffected.[2]

Another result from the pot experiment was that the gunnera-treated plants had higher root growth than those treated with fertiliser, clover, alder or no treatment. Influencing root growth by choice of PGM could be a useful tool in increasing crop resilience to drought.

Field experiment on perennial (mobile) green manures, at Bangor University

Nitrous oxide emissions

Nitrous oxide emissions were low in the field experiments from all treatments, which is likely to be due to the unusually dry weather that occurred at the time. In the pot experiment conditions were warm and the pots regularly watered to allow maximum crop growth, but also to test for a worst-case scenario for nitrous oxide emissions. Nitrous oxide emissions were high from both the clover and ammonium nitrate treatments. Figure 4.1 shows the fluxes of nitrous oxide over the first 100 days of the experiment (after which emissions decrease to negligible amounts). Fig 4.2 shows the emission factors, a measure of the percentage of nitrogen supplied which has been converted to and emitted as nitrous oxide.

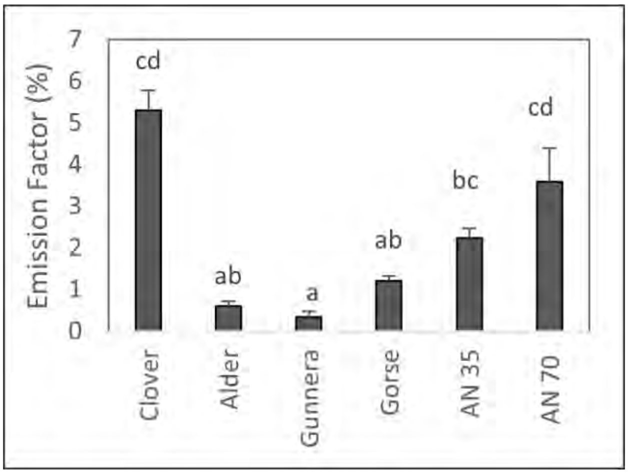


***Fig 4.2** Emission Factor (EF) of the total cumulative N_2O emissions resulting from different treatment in the pot experiment Means ± SEM (n = 5). Letters denote significant differences between treatment at $P < 0.05$) AN 35/70 = 35/70 kg/ha of ammonium nitrate.*

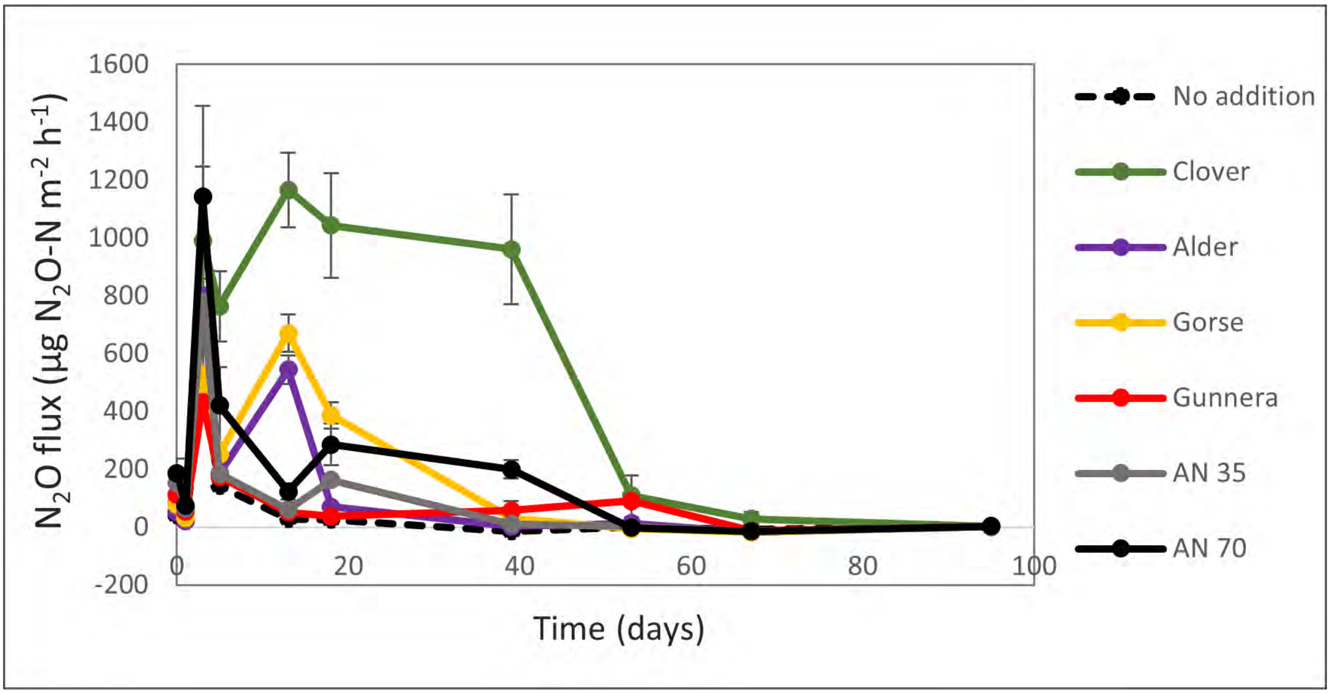


***Fig 4.1** Fluxes N_2O emitted from soil during the first 100 days of the pot experiment. Means ± SEM (n = 5) AN 35/70 = 35/70 kg/ha of ammonium nitrate.*

A carbon conundrum

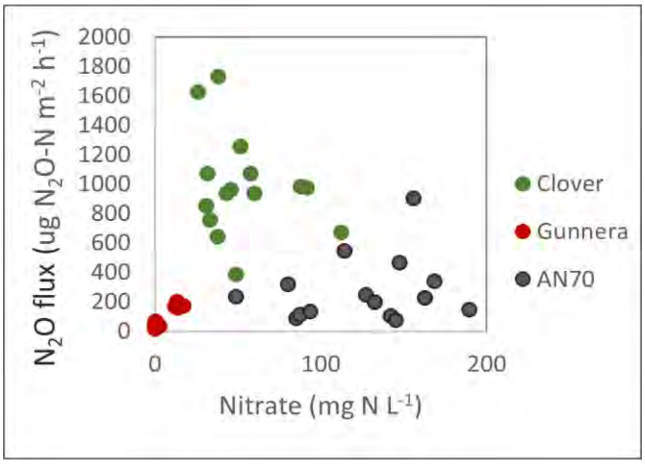
It may seem counterintuitive that the clover treatment resulted in higher nitrous oxide emissions than the ammonium nitrate treatment. However several factors influence the production of N_2O. Emissions are higher in warm and wet conditions, but also when carbon is readily available in soil solution, as this is needed by the microbes which produce N_2O. Figure 4.3 shows the rates of N_2O emission from the soil in the fertiliser-

Pot experiment on perennial (mobile) green manures, at Bangor University

gunnera- and clover-treated pots on the days when emissions were highest. Each dot is the N_2O flux from one replicate pot of soil at one time point. Graph A shows these plotted against the nitrate concentration in the soil, and graph B against the dissolved organic carbon in the soil solution. Though the ammonium-nitrate-treated soil had higher nitrate concentrations, and both gunnera- and clover-treated soil had high dissolved organic carbon, it was only the clover treatment which had high nitrate and dissolved organic carbon at the same time. Both the carbon and the nitrate are needed by the microbes to produce N_2O – it's the recipe for nitrous oxide production. Full experimental details and data are available in **Clo's thesis**.

This is a conundrum as we need to add carbon to the soil for healthy soil functioning and to increase carbon storage within soils. However, it shows the importance of not overloading the soil with nitrogen rich organic matter, especially in warm, wet conditions.

Since the research at Bangor, the gunnera species used has been reclassified as a hybrid *Gunnera x cryptica* and planting it in the UK is now banned as it can be invasive. Fertilising soil with gunnera was very effective in the experiments at Bangor, but sometimes nitrogen-fixing plants are just a bit too successful! However, in places where gunnera is needing to be cleared, such as in some parts of Cornwall or Ireland, perhaps the cleared vegetation could be used as a PGM.



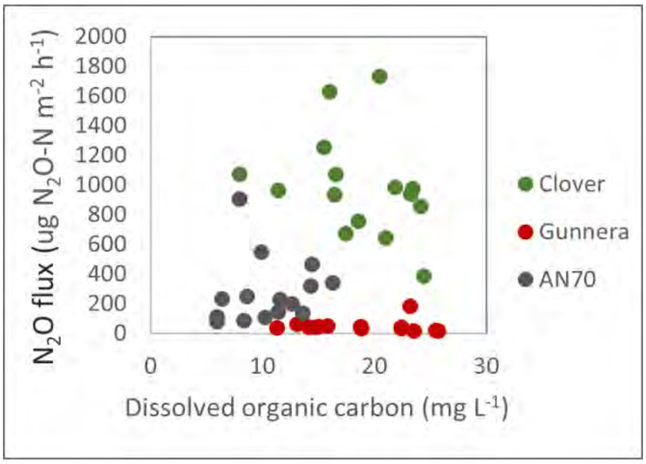


***Fig 4.3** Relationship between nitrous oxide (N_2O) and nitrate (left) and dissolved organic carbon (right) on days 5, 13 and 18 of the pot experiment for the treatments of clover, gunnera and AN70 (ammonium nitrate)*

Field experiment at Bangor University showing gas collection boxes for nitrous oxide analyses

Using grass as a PGM

In 2020, **Ash and Elm Horticulture** took part in an **Innovative Farmers Field Lab** researching alternatives to plastic film mulch.[3]

On a crop of kale, Emma and the team compared treatments of mulched woodchip, mulched grass clippings, under-sown clover **living mulch**, and a biodegradable starch sheeting. There were two replicates of each treatment in randomly arranged plots within two 25-metre long beds. Emma and the team weighed all the harvests over 20 weeks, with the total weight shown in the graph below

The grass treatment resulted in a higher yield than any other treatment (Fig 4.4). This is likely to be because the grass was the only treatment which provided readily available nutrients to the soil, especially nitrogen. Although the under-sown clover was fixing nitrogen it is unlikely that much of this would have been available to the kale while the clover was growing. Before the trial, Emma had always under-sown her kale with clover, but has since discontinued this, and is keen to experiment more with grass clippings which are readily available from the grass paths around the vegetable plots.

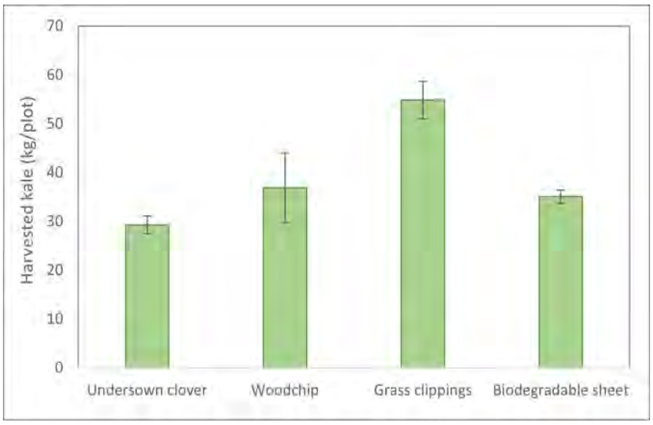


***Fig 4.4** Total kale harvests over the season with various mulched treatments at Ash and Elm Horticulture. Error bars are the range of the values of the two replicates.*

A master's thesis exploring PGMs

In 2023, masters student Maria Cooper researched PGMs for her dissertation on Sustainable Food and Natural Resources, at the Centre for Alternative Technology. Here she summarises her experiment.

I carried out a pot trial to examine the nitrogen provision to crops using leaves of alder (*Alnus glutinosa*), Scotch broom (*Cytisus scoparius*) and gorse (*Ulex europaeus*) on a crop of Red Russian kale. These were compared to red clover (*Trifolium pratense*), ammonium nitrate fertiliser (AN) and a control with no additions. Six replicate pots of each treatment were grown for 20 weeks outside in northern Scotland and monitored for germination rate, crop growth and root growth. Treatments were added at the rate of 200 kg N/ha equivalent, as recommended for a horticultural crop in the sandy soil used for the experiment.

All the kale plants treated with PGMs had significantly more crop growth than the control kale ($P<0.01$, Fig 4.5). There was no significant difference between the growth of kale with alder, broom, red clover and AN treatments, indicating that the nitrogen uptake from those PGMs was adequate for crop growth. Gorse was the only PGM treatment to have significantly less crop yield than the AN treatment ($P<0.05$) at the end of the experiment. Other studies have reported that gorse inhibits germination due to allelopathic compounds in its leaves, but this effect was not noticed in this study.

I also conducted a decomposition experiment, where fresh leaves of each treatment were placed in mesh bags and laid on the soil surface for 100 days, at which point the remaining leaf mass was assessed and weighed. The decomposition rates followed the carbon:nitrogen ratios of the PGMs,

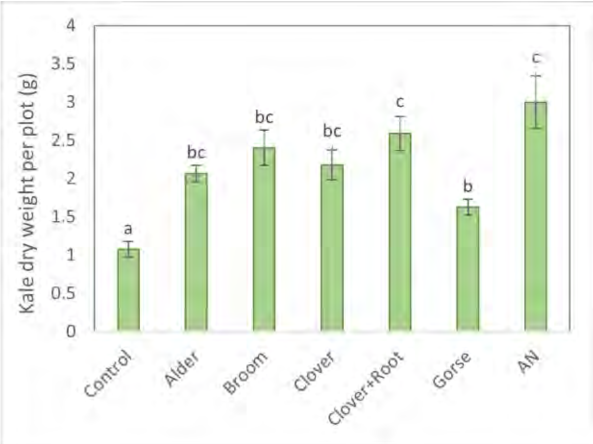


Fig 4.5 Harvests in the pot experiment. *Dry weight of kale crop harvest 138 days after sowing. Means ± SEM (n=6), letters indicate statistical significance at P<0.05*

Setting up the MSc pot experiment

with slower decomposition of leaves with higher ratios. These slower decomposition rates of the PGMs indicate that the nitrogen release rate would have been slower than from clover or AN, therefore reducing the risk of nitrogen loss to the environment.

Kale plants with PGM and clover treatments developed longer and more extensive root structures than AN-treated plants. The larger root structures mean that plants treated with PGMs could have better resilience to climate change and extreme weather events such as drought, flooding and high winds.

References

1. Ward, C. R., Chadwick, D. R., & Hill, P. W. (2023). Potential to improve nitrogen use efficiency (NUE) by use of perennial mobile green manures. Nutrient Cycling in Agroecosystems, https://doi.org/10.1007/s10705-022-10253-x

Ward, C. (2020). An evaluation of perennial mobile green manures for climate change mitigation in agriculture. Bangor University (United Kingdom). https://research.bangor.ac.uk/portal/files/36898345/Ward_thesis_20212020_Ward.C_PhD_Perennial_Mobile_Green_Manures_1.pdf

2. Pardo-Muras, M., Puig, C. G., Souza-Alonso, P., & Pedrol, N. (2020). The phytotoxic potential of the flowering foliage of gorse (Ulex europaeus) and scotch broom (Cytisus scoparius), as pre-emergent weed control in maize in a glasshouse pot experiment. Plants, 9(2), 203. https://www.mdpi.com/2223-7747/9/2/203

3. Innovative Farmers is a farmer-led research network run by the Soil Association. The researchers for this trial were Francis Rayns and Judith Conroy and the co-ordinator in Wales was Tony Little. https://innovativefarmers.org/field-labs/alternatives-to-plastic-film-mulch/

5. PGM Plant profiles

We experimented with six different plant species as PGMs, two trees: alder and willow, one shrub: gorse, and three **perennials**: comfrey, clover and grass.

Alder *Alnus glutinosa*

Alder, sometimes referred to as Black Alder or European Alder, is a nitrogen-fixing deciduous tree native to Europe, commonly found growing near water and tolerant of flooded ground. At maturity it is a large tree which can reach 30 metres in height, but can be coppiced to keep the growth low and shrubby. Alder trees have a **symbiotic** relationship with a nitrogen-fixing microbe called *Frankia,* a microbe in the phylum Actinomycetota. *Frankia* live in nodules in the alder roots, much like the nitrogen-fixing bacteria in the roots of **leguminous** plants. Alder has great wildlife value, providing habitat for a range of species, and was found to be an effective PGM in the experiments at Bangor University. Other species of alder such as Italian alder, *Alnus cordata*, and grey alder, *Alnus incarna*, also fix nitrogen and grow in drier conditions.

Gorse *Ulex europaeus*

Gorse, another nitrogen-fixing legume, is an evergreen shrub, native to Europe, which often grows on exposed ground with thin soils. Though native to the UK, gorse can be invasive, and farmers often cut and remove it to prevent it outcompeting grass for grazing. Gorse was used as a PGM in the experiments by Bangor University, in which it was found to supply nitrogen effectively, but also had an **allelopathic** effect, reducing crop growth.

Willow *Salix* species

Willow is a genus of deciduous trees, which thrive in wet ground and are tolerant of waterlogged conditions. The trees are fast growing and can be coppiced or **pollarded**. There are many species of willow and varieties have been bred for various uses including basketry and biofuels. Willows are not known to have a relationship with nitrogen-fixing microbes in their roots as leguminous species do. However, willows can produce large amounts of biomass even when growing in low-fertility soil, and nitrogen-fixing microbes have been found in willow stem tissue, suggesting that there is a relationship between them and the trees.[1] The willow used in the PGM trials was a mix of *Salix viminalis* and *Salix caprea*.

Red clover *Trifolium pratense*

Red clover is very well known as a traditional green manure used to fix nitrogen in crop rotations. It is a legume (member of the *Fabaceae*) family, and as such has a relationship with nitrogen-fixing rhizobia bacteria which live in nodules in clover roots. Plants live for around two years, but self-seeding allows longer coverage. Clover is usually incorporated into soil, but it is also used as a 'mobile' or 'cut and carry' green manure by mowing, collecting and applying as a mulch. Clover is a good ground cover, protecting soil from erosion, and the flowers are valuable to insects.

Comfrey *Symphytum officinale/S x uplandicum*

Comfrey is a herbaceous perennial, well known to gardeners who use comfrey leaves as an organic fertiliser. It is most commonly made into a liquid feed, but leaves can also be used directly as a mulch or buried in trenches or planting holes. No associations with nitrogen-fixing microbes have been documented, but it grows prolifically and can be cut to ground level several times a year. Comfrey has long tap roots enabling it to access nutrients deep in the soil and it is well known for being rich in potassium. There are various species and hybrids of comfrey, including the cultivar of *S x uplandicum* 'Bocking 14' which is often planted by gardeners as it does not spread by seed so is less invasive than other varieties.

Grass

There are a wide variety of native and specially bred grass species and varieties which thrive in a range of conditions. Grass can easily be harvested for use as a PGM by mowing with a collection box and directly spreading on the soil surface. A mix of grasses with nitrogen-fixing perennials such as clover and vetches provides diversity and grass can also provide ground cover when intercropped with trees and shrubs.

Reference

1. Georg von Wuehlisch (2011) 'Evidence for Nitrogen-Fixation in the Salicaceae Family' https://rngr.net/publications/tpn/54-2/evidence-for-nitrogen-fixation-in-the-salicaceae-family/

6. PGM Harvesting and processing

PGMs were used in the trials fresh, dried and pelleted. Using freshly cut PGMs can be very efficient as the material is only handled once. However, it requires a nearby source of PGMs which are ready for cutting at a time appropriate for the crop. Drying allows flexibility in the timing of application and dried PGMs are lightweight and compact to store. Pelleting gives the advantages that they don't blow away in the wind if applied to the soil surface, as dried leaf fragments can, and they can be easily applied by machinery in the same way as manufactured fertiliser pellets are.

Harvesting

In an established system, the PGM material would be cut from mature bioservice areas. Without these in place, we needed to gather material from mature plants of the relevant species. Young branches were cut by hand (with permission) from trees on privately owned land as well as from the Centre for Alternative Technology (CAT) visitor centre, and forestry land managed by Natural Resources Wales. We collected four 'dumpy' bags (each 0.6 cubic metres) full of alder and half a dumpy bag of willow between 29th August and 2nd September 2022. Five dumpy bags of red clover of variety 'Milvus' were harvested for us by staff of the seed company Germinal, from a trial plot at Aberystwyth University's Gogerddan site. Gorse and grass, which were each used in one trial, were harvested from the trialist's own land in the spring preceding the trials. Comfrey pellets were bought in from Agralan.

Alder leaves drying

Drying and separating trees leaves from stems

Alder, willow and clover were dried for storage over winter and for pelleting. The willow and half of the alder were dried outside, spread in 15 cm deep layers on tarpaulins, covered with a second tarpaulin, leaving around 30 cm for airflow above the leaves. Drying took around seven days in fine weather. The clover and half of the alder were dried at 80 °C using an Alvan Blanche biomass dryer at the **Beacon project**, Aberystwyth University. Some smaller quantities were dried in a large oven at 80 °C.

After drying, the leaves became brittle and stamping on the material enabled most of the stems of alder and willow to be removed without leaves attached. As we were interested in material with a low **carbon:nitrogen** ratio we sieved the alder and willow through a 10 mm sieve to remove fragments of stems. The dried clover weighed 76 kg, and was separated into two very full dumpy bags each containing 38 kg. Dried alder leaves weighed 34.5 kg and was separated into two bags of 17 kg each. One bag of alder and clover was stored for use in spring and one further processed into pellets as below. The dried willow weighed 6.4 kg and was stored for use without pelleting.

Dried alder leaves

Alder pellets extruded in the Simon-Barron pellet mill

Pelleting

The dried clover and alder was pelleted by the Beacon project. The first part of the process was milling the dried leaves to a fine powder using a 'Briton' hammer mill. The milling was a very dusty process with some material lost as dust, so 38 kg of dried clover produced 31.5 kg of milled clover, and 17 kg of dried alder produced 15.02 kg of milled alder. The dried material was then adjusted to a moisture level of 15 % as required by the pelleting process and also had an addition of 6 % oil. For this we supplied 'BlodynAUR' Welsh rapeseed oil. Pelleting was undertaken using a 'Simon-Barron' pellet mill, which produced 32.28 kg of clover pellets from 38 kg of dried clover with addition of 900 ml water and 1.8 litres oil, and 16.04 of alder pellets from 17 kg of dried alder with addition of 450 ml water and 900 ml oil. The pelleting process was successful with the pellets holding together well and very compact for storage. The dried and pelleted material was stored in cool, dry conditions in an outbuilding from September 2022 until use in the trials in 2023.

The hammer mill and pellet mill had a power draw of 6.5 and 25 kW respectively, resulting in an energy cost of 0.982 kWh to make 1 kg of alder pellets and 0.976 kWh to make 1 kg of clover pellets. Considering the nitrogen contents this translates to 34.09 kWh and 30.03 kWh to make 1 kg of N within alder and clover pellets respectively. The energy cost of pellet production and possible strategies to reduce it are discussed in **section 11**, and Beacon's report on processing can be found on the website**.**

Pelleted and dried clover

Chemical analyses

Samples of the PGMs in all forms used in the trials (fresh, dried, pelleted) were sent for analyses of carbon, nitrogen and other macro- and micronutrient content by **NRM laboratories**. Gorse and grass, which were used fresh, were also analysed for moisture content to enable calculation of the amounts of nutrients added.

PGM samples sent for analyses of chemical content

7. Characteristics of the Perennial Green Manures

Knowledge of the chemical characteristics of PGMs allows selection appropriate for the soil and crop, for example by choosing high or low contents of particular nutrients. Other chemical attributes have various effects, for example some plants contain allelopathic compounds which reduce germination and/or growth of crops, or phenolic compounds such as tannins which can temporarily prevent nitrogen being available to crops. However, these are complex to measure by chemical analyses.

Nitrogen

Leaves which are dark green in colour tend to contain more nitrogen. The PGMs we used varied in nitrogen content from 2.3 to 3.6 % of dry matter and N contents can be seen in comparison to the composts and manures used in the trials in fig 7.1. A healthy soil will already contain more nitrogen than it will gain by any soil addition, but most soil nitrogen is contained within organic matter and soil fauna, performing vital soil functions and not available for crop growth.

Carbon:nitrogen ratio

The carbon:nitrogen (C:N) ratio is one of the key characteristics which determines how quickly nitrogen within organic matter will become available for uptake by crops. Soil fauna needs to consume around one part nitrogen for every 15 to 20 parts of carbon. Therefore, a soil addition which contains a higher proportion of carbon than this will result in extra nitrogen being taken up from the soil by microbes. This nitrogen becomes part of the **microbial biomass** and so is temporarily unavailable to plants. This is often referred to as 'nitrogen lock up'. Over time, as microbes respire carbon, the C:N ratio of the remaining organic matter decreases, so nitrogen is released from microbial biomass and becomes available for plant growth. If the C:N ratio of a soil addition is lower than 15 to 20, however, nitrogen within it can become available for plant growth as soon as it is decomposed into simpler nitrogen-containing molecules.

Carbon is contained in higher quantities in structural parts of plants, or in parts which are dying off for the winter, generally the brown parts of plants, giving a higher C:N ratio, whereas lush green leaves have a low C:N ratio. Of our PGMs, gorse had high C:N of 23.2, compared to less than 18 for the other PGMs.

Other macronutrients

The differing concentrations of phosphorus, potassium, magnesium and sulphur in the PGMs also affect the soil characteristics and crop growth. For example, true to its reputation, comfrey had a high potassium content (fig 7.3). Potassium is a macronutrient with many roles and is especially important in root and fruit development. The willow had a high sulphur content (fig 7.6), a nutrient which is becoming deficient in some soils as sulphur deposition from atmospheric pollution decreases, especially in light soils where it is easily **leached**. We also tested the PGMs for a whole range of micronutrients, and data are shown in appendix 1.

Nutrient content of materials used in the PGM trials

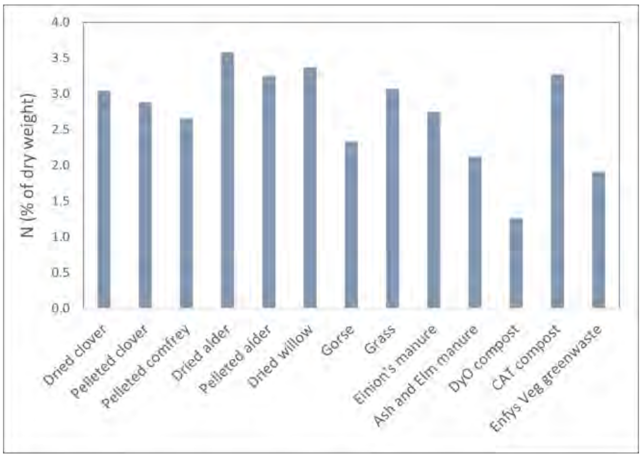


Fig 7.1 *Percentage nitrogen content of the PGMs and growers' own additions used in the trials*

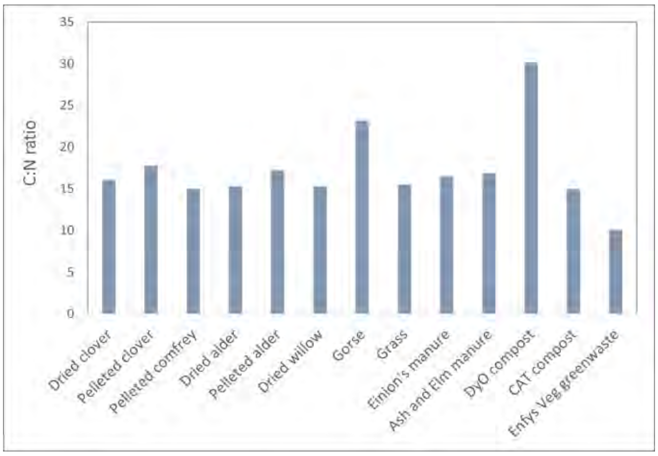


Fig 7.2 *Carbon:nitrogen ratios of the PGMs and growers' own additions used in the trials*

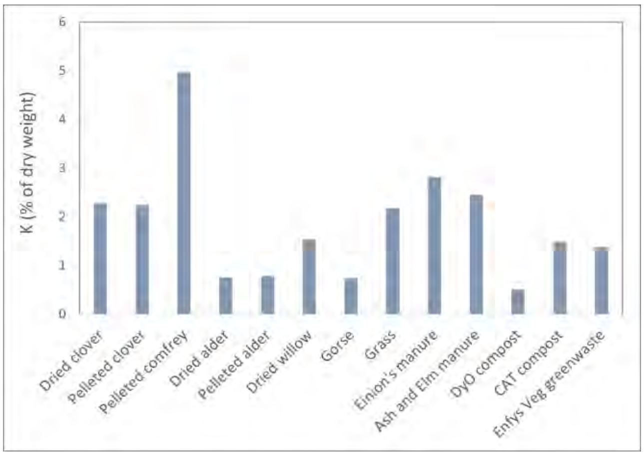


Fig 7.3 *Percentage potassium content of the PGMs and growers' own additions used in the trials*

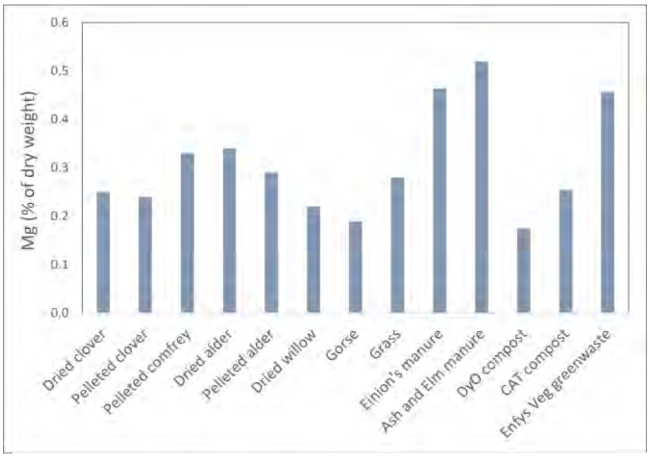


Fig 7.4 *Percentage magnesium content of the PGMs and growers' own additions used in the trials*

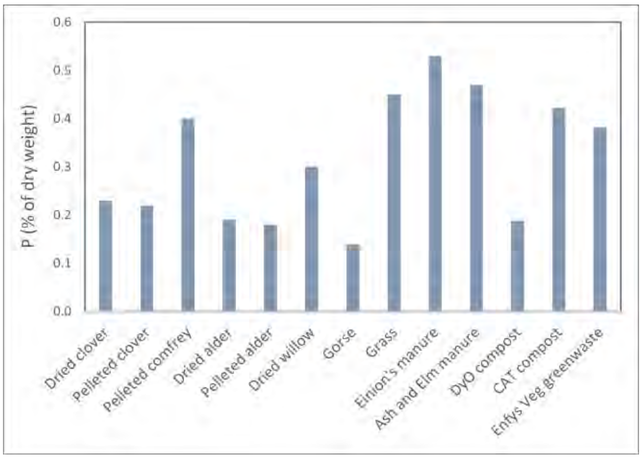


Fig 7.5 *Percentage phophorus content of the PGMs and growers' own additions used in the trials*

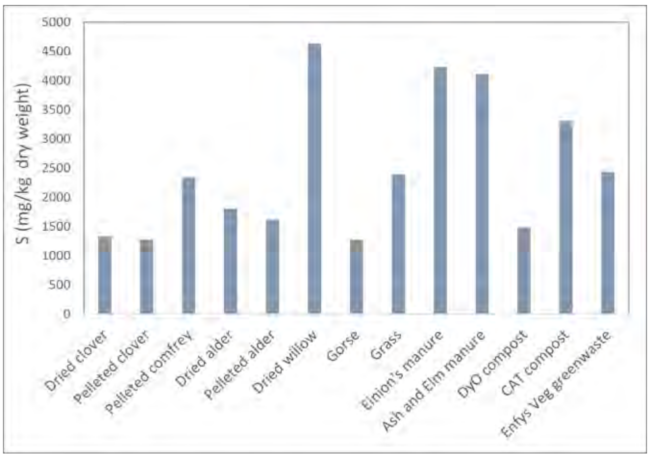


Fig 7.6 *Sulphur content (mg/kg) of the PGMs and growers' own additions used in the trials*

8. The Perennial Green Manure trials

The aim of the PGM trials was to assess their effects in a variety of real-life situations. Though we collected data on crop yields and soil characteristics, the trials were as just as much about gaining insights from the growers' experiences. Unlike the research at **Bangor University**, in which many factors were controlled to single out the effect of nitrogen fertilising, these trials were integrated into the growers' usual practices. We were interested in whatever arose from the trials, including the effects of other macronutrients within the PGMs, effects on soil and crop health and the logistics of using PGMs in real life. The trials also proved to be a great springboard for generating discussion and new ideas.

Trial set-up and monitoring

The Perennial Green Manure trials took place in the Dyfi Valley in Mid Wales, between February 2023 and February 2024. The following are methods common to all the trials, but variations for each can be found in the following sections. Each grower chose one or more of their usual crops to experiment on and we chose the PGMs to suit the nitrogen demand of the crops. Crops fertilised with PGMs were compared with a control (no addition) and the growers' usual method of soil treatment of composts or manures.

Unless requested by the grower, specific amounts of nutrients other than nitrogen were not deliberately added within the PGMs. However, we used the known nutrient contents (**section 7**) to retrospectively calculate the amount of nutrients added within PGMs. The growers applied their usual soil additions without any influence from the PGM project, and these were sampled and weighed to allow calculation of nutrients added.

Three of the trials included two or three replicate plots of each treatment which were randomly arranged to reduce misleading results which can be caused by natural variations in conditions. Space did not allow for this in two of the sites. In some trials a 'half and half' treatment was included, made up of a mix of half the amount of PGMs and half the amount of the growers' usual additions. In each trial there was also an option to add an extra dose of a fast-release PGM later in the season to give the crop a boost if needed.

Before the start of each trial soil samples were taken and sent for analyses of pH, nitrogen and macronutrient content by NRM laboratories.* This was repeated for soil of each treated area of the trials after the final harvests. Crops were grown by the growers' usual methods, and growth was monitored regularly by us or by the growers and all harvests weighed. In each treatment plot measurements were taken in a central area, leaving unmonitored strips around the edges to exclude the influence of adjoining treatments. Growers fed back their observations as they arose during the trial and by written questionnaires after each trial set-up and after the final harvest of the crops.

Five horticultural growers trialled PGMs on crops including potatoes, courgettes, kale, beetroot and lettuce.

* NRM laboratories are part of Cawood Scientific and offer analyses of soil and agricultural materials https://cawood.co.uk/nrm/soil-analysis-nrm/

Nitrogen additions in the PGM trials

We added the amount of nitrogen within the PGMs which we considered necessary for the various crops, using information from the fertiliser guide '**RB209**' as shown in the table below. It must be acknowledged that this way of assessing nitrogen requirements does not take into account the influence of many other soil factors, for example the speed of cycling of nitrogen by soil fauna or the aid to N uptake by soil biota such as **mycorrhizal fungi**.

For most crops we chose a combination of a slow-release PGM (alder, willow or gorse) supplied before or at the time of crop planting, supplemented with a faster-release PGM (clover, comfrey or grass) added when the crop needed it most. We also provided some optional clover or comfrey pellets to be added if or when the crop was showing a need for it.

When farming at field scale, legislation to prevent pollution limits the amount of nitrogen that can be applied to under 250 kg N/ha (kilograms of nitrogen per hectare) per year on land located in a '**Nitrate Vulnerable Zone'** (NVZ). This designation includes large areas of the UK, including all of Wales, and applies to organic additions such as manure as well as inorganic fertilisers. Guidance on the addition of materials which are likely to release nitrogen very slowly is limited, however.

We wanted to trial methods which definitely wouldn't go against legislation if carried out on a large scale, and so we limited our nitrogen additions, even though the slow-release PGMs are not likely to be providing a lot of nitrogen within the first few months (or be a pollution risk). In most trials total the nitrogen addition within PGMs remained below 250 kg/ha, but at CAT all of the optional clover pellets were added during the trial, giving a total N application of 300 kg N/ha equivalent.

For the growers' own treatments we did not want to influence their usual practice, but this resulted in quite large mis-matches between the amounts of nitrogen added. Where trials included a '**half and half**' option the amounts of N added were midway between the PGM and the growers' usual soil additions.

Additions of nitrogen within the PGM materials and the growers' usual additions. *Shown in relation to the soil N status and the recommendations from the RB209 fertiliser guide*

Grower	**Crops**	***** **N index of soil before trial**	****** **Nitrogen recommendation from RB209**	**N added in PGM treated plots**			******* **N added in usual soil additions Kg N/ha**
				Slow-release (Kg N/ha)	**Fast-release** including optional (Kg N/ha)	**Total N** (Kg N/ha)	
Einion's Garden	Second early potatoes 'Charlotte'	5	80 to 120	150 alder	50 clover	200	810 cow manure
Ash and Elm Horticulture	Main crop potatoes 'Carolus'	1	150 to 210	100 alder	150 clover (including 50 optional)	250	330 cow manure
Dan yr Onnen (DyO)	Beetroot 'Boltardy' followed by kale 'Cavolo nero' and chard 'Rhubarb'	0	290 (beetroot) 330 (kale)	250 willow or alder		250	650 bagged multipurpose compost
				100 willow or alder	150 comfrey	250	
Centre for Alternative Technology (CAT)	Kale, 'Cavolo nero' and 'Red Russian', lettuce, daikon 'Mino Wase' and kohlrabi	3	230 (kale) 150 (lettuce)	150 alder	150 clover (including 100 optional)	300	770 onsite-made compost
Enfys Veg	Courgette 'Gold Rush'	3	40 to 115	100 gorse	100 comfrey (including 50 optional)	200	450 'green waste' compost

* The N index is a rating given to the amount of available nitrogen in the soil (from 0 = very low, to 6 = very high) which is used to determine recommended nitrogen additions for the next crop.

** The Nutrient Management Guide, commonly referred to as 'RB209', is produced by the Agriculture and Horticulture Development Board and lists the crop requirements of nutrients according to the current soil nutrient status, RB209 is available to download at https://ahdb.org.uk/nutrient-management-guide-rb209

*** This was added by the grower according to past experience.

Einion's Garden

Einion's Garden is run according to the permaculture principals of people care, earth care and fair shares, and supplies organic veg to the local area. Ann and John Owen have been growing on two-thirds of an acre for 12 years. Their focus is on ecological and societal resilience, showing that veg and fruit can be grown on land normally considered unsuitable – the bottom of a northwest facing slope, prone to waterlogging and historically an industrial dumping ground for the iron furnace in the village.

At present Ann and John mainly use organic cow manure. Ann says "We tend to import nearly all of our fertility in the form of animal manure and I've never been happy with that, as it lacks resilience." They also use small amounts of horse manure, organic pelleted fertiliser, their own home-made compost and **green waste** compost. There is not enough land for long-term fertility-building leys, and in winter many of the beds are too shady for growing traditional green manures. In the surrounding area however there is underutilised land which could be suitable for PGM production.

Ann says "Short term, manure might give the higher yields, but it costs money, putting it on is a lot of very hard work and maybe when you add that into the equation, PGMs might give the best return on the least input."

Ann Owen with dried alder

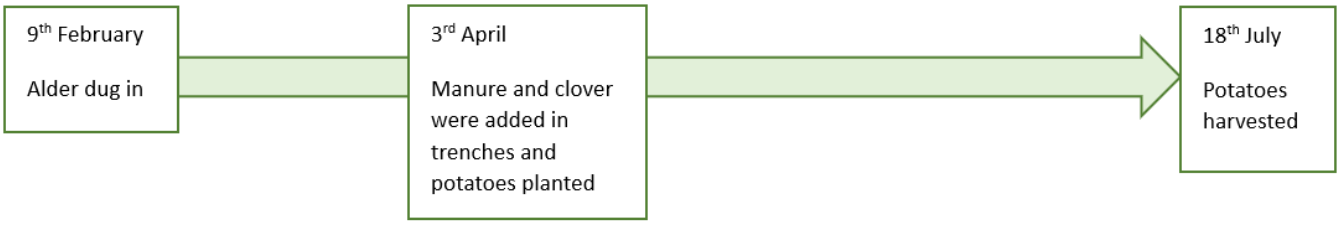
Trial set-up

Ann and John trialled a combination of the PGMs alder and red clover (dried) with a crop of second early potatoes 'Charlotte'. They requested PGMs with a good nitrogen content, but a low potassium (K) to magnesium (Mg) ratio as they've noted that there has been a magnesium deficiency in the past and high soil potassium content may have affected its availability. With this in mind we chose an alder and clover mix as the most appropriate low K/high Mg combination, which also met nitrogen needs. Using a combination of 75 % alder and 25 % clover gave a K:Mg ratio of 3.6:1 compared to 6:1 for manure.

Manure 1 812 kg N/ha	Control 1 No addition	Alder/clover 1 200 kg N/ha
Alder/clover 2 200 kg N/ha	Control 2 No addition	Manure 2 812 kg N/ha

Treatments. Two replicate plots arranged as in the plan (not to scale). *Nitrogen additions are shown as the kg N/ha equivalent. Each plot measured 110 cm by 2 m = 2.2 m²*

Treatments were added as in the timeline. Extra optional clover pellets were not used as there were no clear visible differences in the top growth of the potato plants. The crops grew well until 18th July when blight was observed and potatoes were harvested the same day.



Results

The results indicate that the alder and clover provided some fertility boost to the potatoes, but with only two replicates we must acknowledge the possibility that this is a chance result. Manure clearly gave a boost in yields, however the manure additions contained much larger quantities of nitrogen. John's experience tells him that addition of a good amount of manure always increases yields no matter what the situation, and this trial confirms his view. However, like all good growers, Ann and John don't always agree with each other! Ann's hunch is that the soil biology of the site needs to be improved to help with crop nutrient uptake, and she hopes PGMs could help to do this in the long term.

Analyses of the soil before the trial showed that the K:Mg ratio was not as high as had been previously found by analyses elsewhere in the garden. Therefore this was likely not an issue for the potato growth. However, the PGM-treated soil did have a lower K and lower K:Mg ratio at the time of potato harvest compared to the manure-treated plots, so strategically adding PGMs in this way could be a useful tactic to maintain a healthy soil, as discussed in **section 9.**

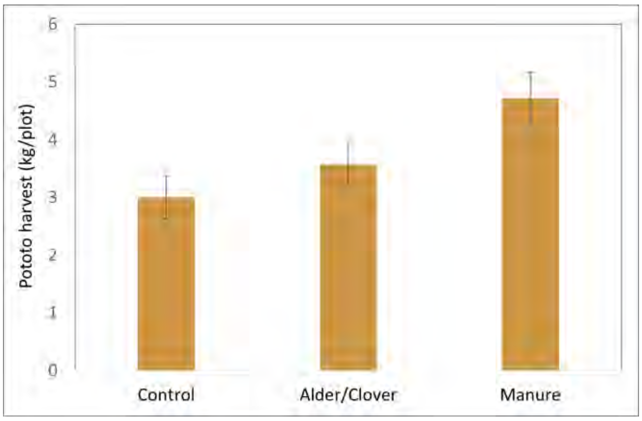


Fig 8.1 Yield of potatoes per plot at Einion's Garden. *Means of two replicates. The error bars indicate the range between the yields of each replicate plot*

- **Potato yields suggest that the PGMs were effective as a fertiliser, but manure produced the highest yields**
- **Adding carefully chosen PGMs successfully lowered the K:Mg ratio of the soil compared to the manure treatment, as requested by the grower**

Ash and Elm Horticulture

Ash and Elm is a diverse market garden which uses agroecological principals to grow fruit, vegetables, nuts, flowers and mushrooms. Emma and Dave have been on their five-acre site, based near Llanidloes, for 11 years, and Anna joined the team in 2021. Volunteers are also a vital part of the team. At present Ash and Elm use horse manure, garden compost, municipal green waste compost, and grass cuttings to fertilise their crops. Emma is always keen to trial innovative techniques and would like to decrease manure use, which can be unpredictable in supply, is bulky, and needs space for storage

Trial set-up

Emma and the team trialled five different treatments on a main crop of potato 'Carolus'. They usually use manure to fertilise potatoes, however they have previously used grass clippings from nearby paths to great effect on other veg (see **section 4**). This inspired Emma to trial their own fresh grass clippings as a PGM. The grass was a mix of species and included some clover. They also tried a combination of alder for sustained nutrient release and clover for a quick boost, as well as a half-and-half mix of horse manure combined with alder and clover. There were three replicates of each treatment, arranged randomly.

The treatments were added to relevant plots as in the timeline, with clover, alder and manure being dug in to a depth of 20 cm and grass clippings and clover pellets added to the soil surface. 10 potatoes were planted in each plot and were observed regularly, with growth monitored by height of plants and ground cover.

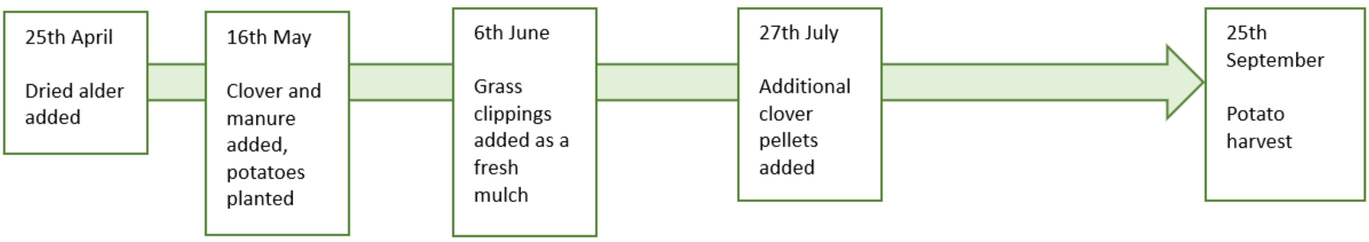
Blight was noted on the plants on 8th August, but as these and the adjoining potato varieties were blight resistant they were allowed to continue growing until all the tops had died off by 12th September. Tubers were dug up on 25th September, and the tubers of the middle six plants in each plot were weighed.

Fresh grass clippings *Unknown N content	Alder plus clover plus horse manure 289 kg N/ha	Control No N addition	Horse manure 329 kg N/ha	Alder plus clover 250 kg N/ha

Treatments: There were three replicate plots of the five different treatments, making a total of 15 plots. *Plots were arranged randomly in a continuous row. Nitrogen additions are shown as the kg N/ha equivalent. Each plot was 1.2 m wide by 2 m long and therefore 2.4 m² per plot. (not to scale)*

**The grass had a nitrogen content of 3.07 % of dry weight, but due to lab error the moisture content of the fresh grass was not measured, so it is not possible to calculate the amount of nitrogen added. Grass moisture content can vary a great deal, and therefore the N content could have been anywhere between 200 and 500 kg N/ha equivalent.*

Tilly taking measurements at the Ash and Elm trial plot



Results

As there were three replicates in the trial, these results can be considered quite reliable (Fig 8.2). There was quite a lot of variation in the results within most treatments, so it is only the manure that had a statically significant higher yield than the control. However, it does indicate a good performance from the fresh grass clippings and likely some benefit from the alder and clover.

Potato blight was first seen in the control plants, and figure 8.3 shows the decrease in plant height and ground cover in these compared to other treatments. Curling of potato leaves in the manure-treated plots was also seen on 16th August. This is likely due to the herbicide aminopyralid which often contaminates manure if the animals have consumed grass which has had applications of the herbicide. There was a strong correlation between the soil potassium concentrations and the potato yield, and this is discussed in **section 9**.

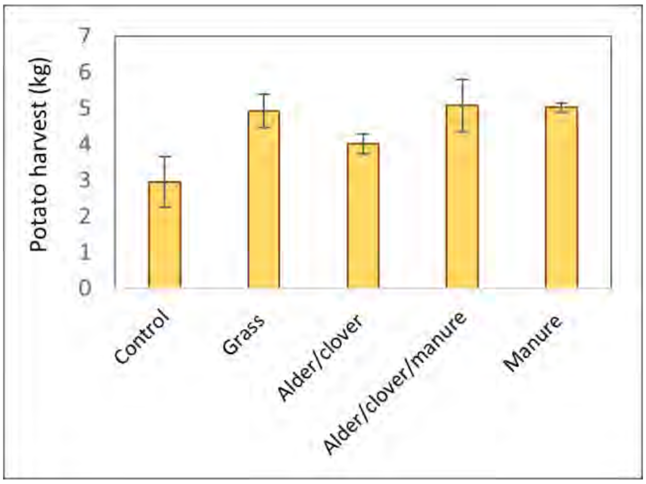
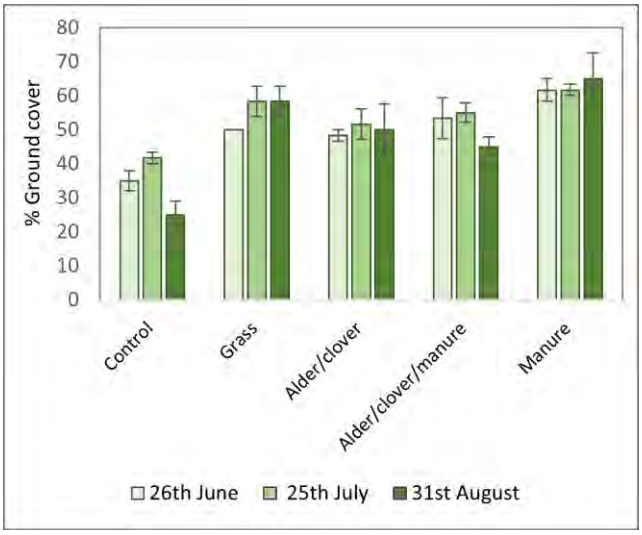


Fig 8.2 Potato harvests from six plants with various treatments. *Error bars are standard errors of the three replicates.*

Emma believes that dry weather at the start of the trial may have slowed down the decomposition of the dried alder and clover, delaying release of nutrients. She is keen to try PGMs again and to irrigate if necessary to speed decomposition.



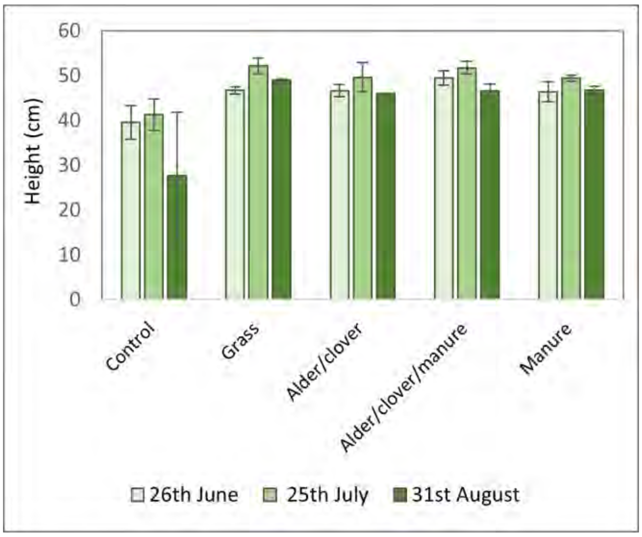


Fig 8.3 Ground cover (left) and height (right) of potato plants. *Error bars are standard errors of the three replicates*

- **Results suggest that grass clippings increased the potato yield over that of the control and it is likely that the alder and clover boosted yields too**

Dan yr Onnen

At Dan yr Onnen they grow fruit and vegetables for the purposes of education, experimentation and inspiration, and the site features on Huw Richards' popular **YouTube channel**. 2023 was the first season at Dan yr Onnen so the terraces were newly created. At the time of the trial the growers were Lucy, Neil and Huw. Up until now they have used manure, traditional green manures and compost to fertilise crops, but were keen to support the development of alternative methods.

Trial set-up

The growers trialled the PGMs willow, alder and comfrey in various combinations with a crop of early beetroot 'Boltardy' followed by kale 'Cavolo Nero' and chard 'Rhubarb'. The soil was a little stony and shallow and initial soil analyses showed very little available nitrogen or phosphorus. This low fertility however made it an excellent trial site as the differences between treatments showed up well in the crop yields.

Dried willow and alder, comfrey pellets, and compost were dug in to soil approximately a month before planting. As it was a new site without an established composting system, the compost was bought-in Melcourt organic peat-free compost. More comfrey pellets were added later in the year when the crops appeared to need a nutrient boost as in the timeline.

Huw Richards with dried alder

Alder and comfrey 250 kg N/ha	Alder 250 kg N/ha	Control	Compost 650 kg N/ha	Willow and comfrey 250 kg N/ha	Willow 250 kg N/ha
Compost 650 kg N/ha	Willow and comfrey 250 kg N/ha	Willow 250 kg N/ha	Alder and comfrey 250 kg N/ha	Alder 250 kg N/ha	Control

Treatments: Two replicate plots arranged as in the plan (not to scale). *Nitrogen additions are shown as the kg N/ha equivalent. Each was 1.5 m by 1.2 m = 1.8 m²*

- 4th April: Alder, willow, comfrey and compost added
- 1st May: Beetroot plugs planted
- 2nd June: Comfrey boost added to relevant plots
- 24th July: Beetroot harvest (thinnings)
- 7th August: Main beetroot harvest
- 8th August: Optional comfrey added. Kale and chard plugs planted. Lime added to increase pH for kale
- 6th December: Kale harvest
- 16th Feb: Kale and chard harvest

Results

Crop growth was overall fairly slow, with low yields of the beetroot and chard, however there were some useful results, especially in the effect of willow. Although the results can only be taken as an indication, Huw was encouraged enough to plant up his own bioservice area of willow, alder, comfrey and clover with which to fertilise future perennial vegetable and fruit crops. Huw says that the trial "has given me confidence in the future to extend production. Results show that I can grow successfully without having to use compost, which is very exciting". Read about the Dan yr Onnen bioservice area in **section 10**.

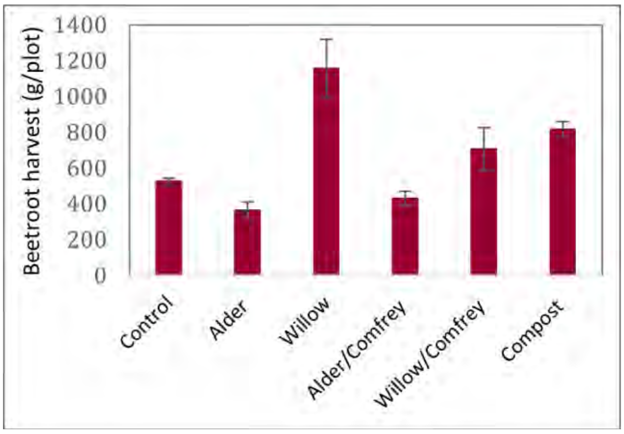
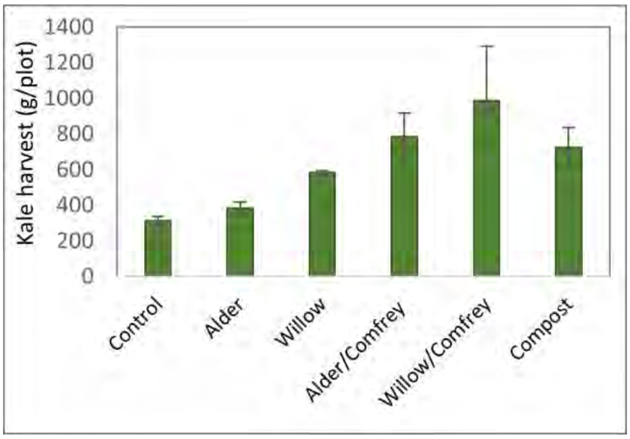
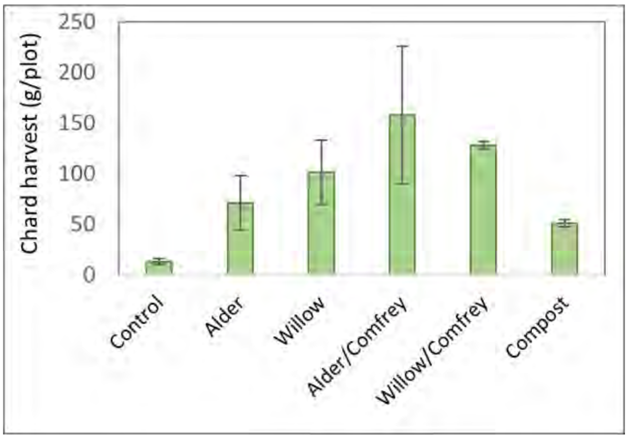


Fig 8.4a Yield per plot of beetroot harvested in July.
Means of the two replicate plots with bars showing the values of each replicate harvest





Figs 8.4b and 8.4c Kale harvested December to February (left) and chard harvested in February (right).
Means of the two replicate plots with bars showing the values of each replicate harvest

- **Willow leaves as a single treatment appeared to have a fast effect, boosting the yield of beetroot harvested in July**
- **Yields of the winter-harvested kale and chard crops were increased by comfrey**
- **Alder as a single treatment appeared to have no effect until late in the trials when it may have boosted chard growth**
- **The soil increased in potassium in response to comfrey additions**

Centre for Alternative Technology (CAT)

The Centre for Alternative Technology (CAT) is an educational charity dedicated to researching and communicating positive solutions for environmental change. Founded in 1973 on a disused slate quarry in Mid Wales, CAT has evolved from a community to a visitor centre to an educational charity specialising in sharing practical solutions for sustainability.

The display gardens at CAT have been demonstrating organic methods for over 30 years, to day visitors, school groups and course participants. They are tended by Petra Weinmann and a team of volunteers and supply food to CAT's onsite restaurant. CAT has been a pioneer in composting methods, especially 'high fibre compost', and produces much compost from vegetable peelings and food waste from CAT's restaurant.

CAT gardeners Petra, Abbi and Jody checking out the PGMs

Trial set-up

Petra was keen to be involved in research that supports the development of new alternatives to manufactured fertilisers, and also to explore the issue of greenhouse gas emissions from composts or green manures. The gardeners at CAT feel that they can never get enough compost for the vegetable plots. Green manures are grown in winter where possible, but it can be hard to get them established after the vegetable harvests in the autumn.

Petra and the team trialled alder and clover PGMs on a crop of various **brassicas** and lettuce, in comparison to CAT's own compost. The size of the plot didn't allow for replicate treatments, so the results of yields and soil characteristics are an indication rather than robust scientific data.

Control
Alder/clover 300 kg N/ha
Alder/clover/compost 535 kg N/ha
Compost 770 kg N/ha

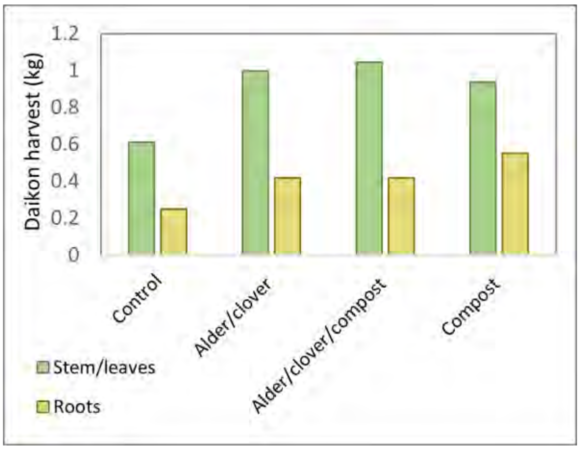
Treatments: (not to scale) *Nitrogen additions are shown as the kg N/ha equivalent. Each plot was 4 m by 1.2 m*

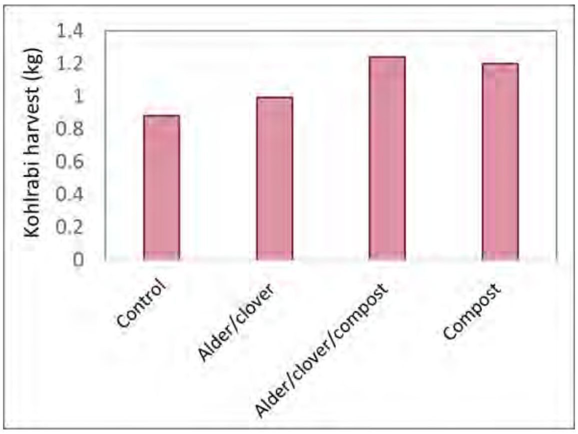
3rd May – Alder dug in → 29th May – Added clover, compost and planted kale and lettuce → 21st June – Mulch of compost added → 21st July – Last lettuce harvest → 1st August – Clover pellets added. Kohlrabi and daikon planted → 1st November – Last kohlrabi and daikon harvest → Kale destroyed by rats → 24th January 2024 – Harvested kale stems and roots

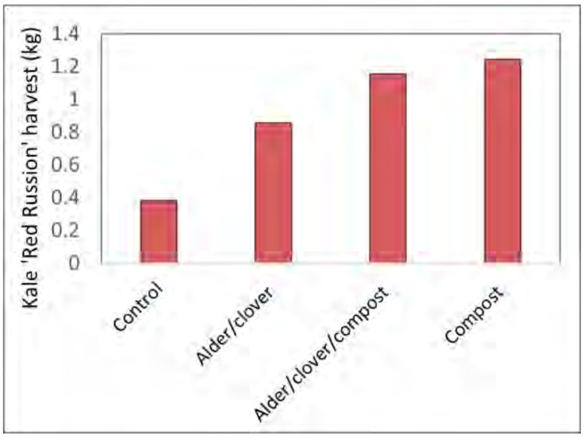
Dried alder was dug in to about 20 cm depth by hand on 3rd May, and the other treatments added as shown in the timeline, with the dried clover dug into the soil and the CAT compost put into planting holes as well as mulched on the soil surface. Each plot was planted with kale ‘Cavolo Nero’ and ‘Red Russian’, and lettuce, with kohlrabi and daikon planted after the lettuces were harvested. Unfortunately, the kale suffered from various pest problems, from caterpillars and aphids to a dramatic stripping of the leaves in late December 2023. Petra concluded that this stripping was likely to have been by rats, as teeth marks were seen.

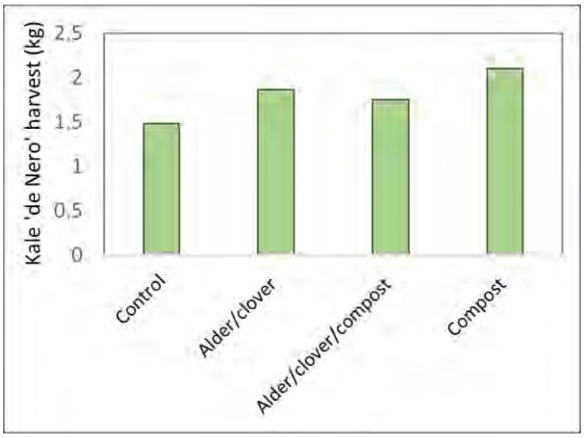
Results

The gardeners found the dried PGMs easy to handle and apply. However dried alder was prone to blowing away if mulched on the soil surface and so Petra made an exception to her usual no-dig methods. She’s now planning to continue the trial over the four-course vegetable rotation. In early 2024 she added PGMs again as a mulch, and covered the area over with a sheet mulch, so preventing them blowing away until they had rotted into the soil. Petra says “If it turns out to be equally effective or better than our compost alone (as I suspect it will), I plan to build PGMs into the regular fertiliser/soil-care regime in our rotation.”









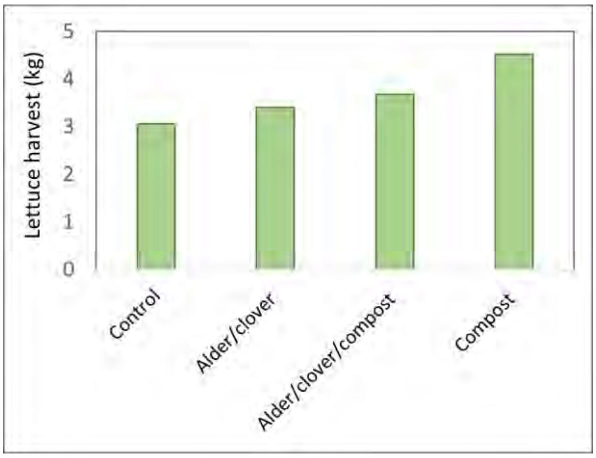


Fig 8.6 Harvests from the PGM trial plots at CAT. *NB The daikon crop had bolted, so both the tops and roots are shown*

- **PGMs boosted the crop growth above the control, but yields were mostly lower than from compost which contained over twice the amount of nitrogen as the PGMs did**
- **The mix of half PGMs and half compost gave good yields of some crops**
- **Results of the later kale growth were unfortunately lost due to pest damage**

Raking in PGMs on the CAT trial plot

Enfys Veg

Enfys Veg is situated on Llety Llwyd farm which specialises in pasture-fed beef kept using regenerative principals, and includes chickens and a small-scale leather tannery. Ruth Kernohan began Enfys Veg in autumn 2022, focusing on soil, wildlife and human health. Produce is sold via local market stalls and direct sales.

For soil care, Ruth uses outputs from other parts of the farm such as cow and chicken manure, sheep daggings (matted wool/dung cut from sheep tails), and spent bark from the tannery. She also uses green manures, her own home-made compost, green waste compost, and compost teas. Ruth is interested in the possible benefits to the farm ecology of growing PGM species, such as contributions to habitat and structural diversity, soil protection, increased water infiltration and erosion control. She sees these functions of trees and shrubs as so important that then using them as PGMs would be “almost an added bonus”.

Gorse/comfrey/ green waste compost 325 kg N/ha	Control	Gorse/comfrey 200 kg N/ha	Green waste compost 450 kg N/ha

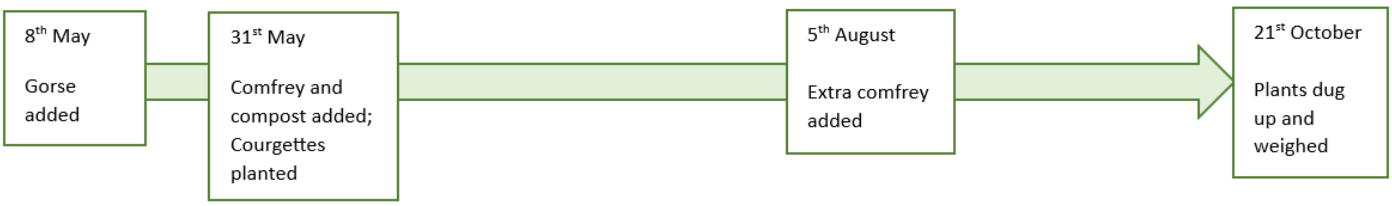
Treatments (not to scale) Each plot measured 1 m by 2.5 m *Nitrogen additions are shown as the kg N/ha equivalent.*

PGM trial at Enfys veg after treatment addition

Trial set-up

The trial took place on newly-made beds, created on formerly grazed land, by mulching with cardboard and green waste compost. Ruth trialled fresh gorse which was harvested on site, mixed with pelleted comfrey on a crop of courgette ‘Gold Rush’. This was compared with fertilising with green waste compost alone, alongside a ‘half-and-half’ treatment. These PGMs were chosen because the farm has plentiful gorse growing on site and Ruth has previously grown and used comfrey as a fertiliser. Gorse was used in the trial in Bangor University, but did not work well as a PGM, possibly due to **allelopathy.** However, other research has found that an allelopathic effect is not always disadvantageous and can prevent weed competition.[1] The gorse with its tough leaves and higher carbon:nitrogen ratio was likely to have a fairly slow nutrient release rate, so the comfrey was added in to give a quicker nutrient boost.

Fresh gorse cut from elsewhere on the farm was roughly chopped into pieces of around 5 to 10 cm, as an easy method which did not require machinery. It was incorporated into the top 10 cm of soil as best we could with the spiky nature of the material. Five courgette plants were planted per bed. Green waste compost and comfrey pellets were added to the planting holes. Harvesting began on 29th June and continued until 26th September. Courgettes from the middle three plants in each treated plot were weighed.



Results

As the trial did not have replicates, the results can only be treated as a guide, however the growth and harvests suggest that the PGMs reduced the courgette crop to lower than that of the control and Ruth observed that “the gorse didn’t really fertilise the courgette plants and may have had some stunting effect.” This fits with previous research, but possibilities on how gorse might be used as a PGM are discussed in **section 9**. The PGM/green waste treatment however resulted in a similar harvest to that of green waste only, so the results are not clear cut. There were no differences observed in weed growth between the plots. It is worth noting that the majority of the weeds in the plots were creeping buttercups which were often rooted outside of the area.

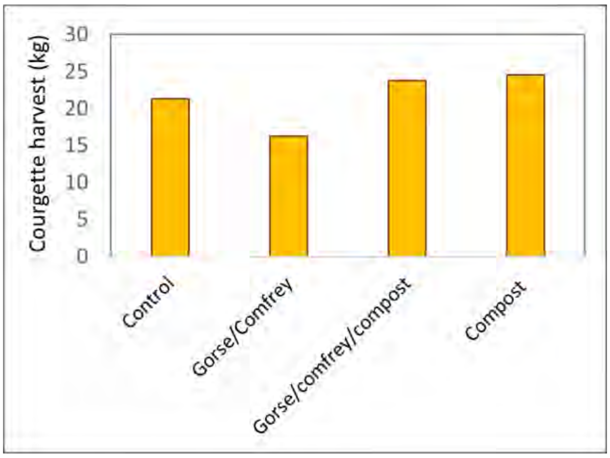


Fig 8.6 Total saleable* courgette harvest from central three plants in each plot

**** Some courgettes were a bit darker in colour and had a tougher texture, so the results are given as ‘saleable courgettes’ which lack this discolouration. These were less than 5 % of the crop but there was no correlation with the treatments.***

PGM trial plot at Enfys Veg

Reference

1. Pardo-Muras, M., Puig, C. G., Souza-Alonso, P., & Pedrol, N. (2020). The phytotoxic potential of the flowering foliage of gorse (Ulex europaeus) and scotch broom (Cytisus scoparius), as pre-emergent weed control in maize in a glasshouse pot experiment. *Plants*, *9*(2), 203. https://www.mdpi.com/2223-7747/9/2/203

- **The roughly chopped spiky gorse was difficult to work with and did not soften quickly in the soil**
- **All plots yielded well including the control**
- **The PGM treatment of gorse + comfrey produced a lower yield than the control**

Home gardeners’ trials

There was much interest in PGMs from home gardeners, who were not cropping on the scale needed for the main trials but were keen to be involved. We made up and distributed research packs, so people could join in at home. The packs included dried or pelleted PGMs (species of their choosing) and instructions (see appendix 2).

We suggested two possible trials:

1. **Plot trial: Do PGMs fertilise your crop as effectively as your current type of fertiliser?** A smaller-scale version of our main trials, with half the row or patch of vegetables to be fertilised with PGMs and the other half using the gardeners’ usual method e.g. home compost.

2. **Pot trial: Does adding PGMs to your potting compost improve seedling growth?** The idea for this trial arose out of a conversation with one of our trialists, Ann Owen. Many growers still report that the available peat-free composts do not give seedlings as good a start as they would like. We wanted to know if adding small amounts of PGMs to the composts could give seedlings a boost.

Four people requested to take part in the pot trial and five in the plot trial. They were sent trial packs with instructions and materials. We had two sets of results returned for the pot trial, but only one for the plot trial and this was on a perennial crop which needed a longer time period for results to show.

Pot trial

Two skilled growers, Karen Smith and Sue Stickland, undertook the pot trial. Karen grew various beans in pots with and without an addition of dried willow. Sue grew kale seedlings with and without dried clover in modules.

Karen’s trial: Willow for bean seedlings

seedlingsKaren sowed pre-sprouted bean seedlings on 7th May 2023: two runner beans (of her own self-saved seeds) per pot into six 9 cm pots. Pots were filled with Lidl's peat-free compost. Three of the pots had a tablespoon of dried willow added to them, and three were left without. She also sowed two pots each of climbing French bean ‘Blue Lake’, ‘Hunter’ and ‘Pea Bean’, with two seeds per pot, and one pot of each with the willow addition and one without. The pots were positioned alternating compost plus willow and compost only, so that all recieved equal sunlight. Karen regularly observed the seedling emergence, and measured the plant height and maximum leaf width of the runner beans on 27th May.

Results

Of the six climbing french beans sown with willow added, none emerged from the compost, whereas without willow three out of the six emerged – two ‘Blue Lake’ and one ‘Pea Bean’. Of the runner beans all emerged, but there was more growth and larger leaves in plants grown without the willow as shown in figure 8.7.

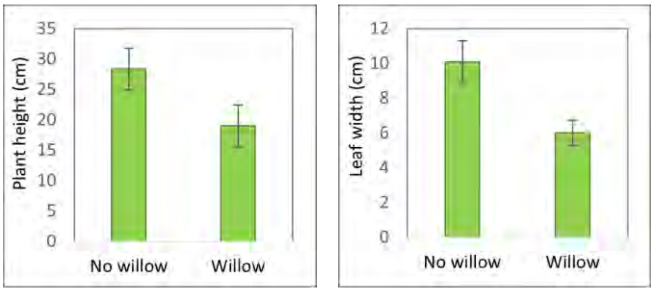


Fig 8.7 Heights (left) and maximum leaf width (right) of runner beans grown with and without dried willow added to compost. *The difference between leaf width is statistically significant (P = 0.016)*

Bean seedlings without willow (left of each pair) and with willow (right of each pair)

Sue's trial: Red clover for kale seedlings

Sue grew kale 'Silly Frilly' (a home-saved variety), sown direct into 80 modules, half of which were treated with dried clover. The modules, measuring 4 by 4 cm wide and 5 cm deep, were filled with Melcourt multipurpose peat-free compost, with a teaspoon of dried red clover mixed into each module in one tray of 40 modules. Some of the clover stalks were too long to fit into the modules so were discarded.

Sue sowed the kale on 14th May 2023, three seeds per module, which on emergence she thinned to one per module. They were placed on a greenhouse bench and the two trays were switched around to prevent differences in the growing environment. Sue made note of the kale growth and took measurement of the height of 5 randomly chosen plants in each treatment on the 18th June.

Results

On the 30th May there were no differences between the control and the clover-treated modules, but by the 10th of June Sue noted that the clover-treated plants were "lusher green" with quite a few producing a fourth leaf. The control plants were more pot-bound with some purple tinging and none had produced a fourth leaf. There was also a difference in height as shown in figure 8.8.

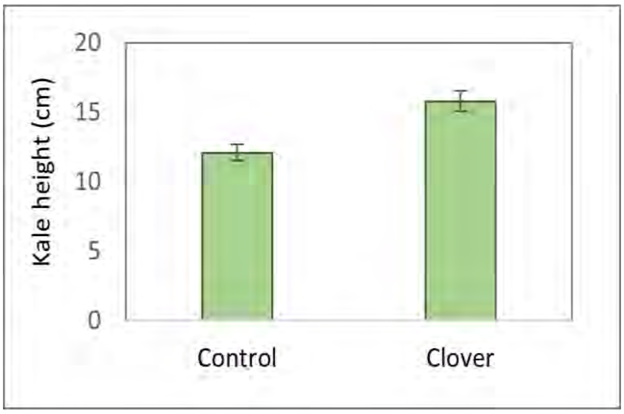


Fig 8.8 Height of kale plants grown with and without clover measured from the compost level to the top of the longest leaf. Results are statistically significant (P = 0.005)

Kale seedlings grown with dried clover (left) and without (right).

Conclusions

Both experiments had statistically significant results, with the willow reducing germination and growth of the beans, but the clover increasing the growth of the kale plants. The poor germination and growth in beans grown in willow-treated compost indicate that the willow may have an **allelopathic** effect. Bean seedlings are also less likely than some other vegetables to benefit from an increase in nutrients in the compost as bean seeds are large and rich in protein, thus enabling seedlings to grow without needing a large external nutrient supply.

Kale seeds however are very small so seedlings must gain nutrients from their environment. The improved growth in the kale seedlings suggests that the right PGM used for the right crop could benefit seedling establishment and this could be an easy method for home and commercial growers to adopt.

The contrasting results show the need to experiment with different PGM species and different combinations of crops and species. Sue found that some of the clover had crumbled to very fine particles so the process was dusty and she commented that she would wear a mask next time. No growers returned results for pellets, and it would be useful to know if clover pellets have a similar effect as they would be easy and efficient to add to pots and modules in large-scale nurseries.

9. Insights from the PGM trials

The PGM materials

The PGMs had a similar nitrogen content to the manures and composts and comparable amounts of other nutrients. The quickest method of harvesting and application was mowing and directly mulching the grass. Use of comfrey, clover or other leafy plants would likely be similarly easy if mown, strimmed or scythed from a nearby area. The gorse which was also directly harvested and applied was problematic as it was spiky to handle, difficult to incorporate and did not soften in the soil as we had hoped. Shredding would overcome this, or if the gorse is cut regularly it may be possible to harvest only young soft growth.

The time and energy costs of harvesting and processing the dried and pelleted PGMs (**section 6**) were high, and efficiency of this needs to be improved as discussed in **section 11**. However the clover and alder pellets were very compact to store, and easy to transport and apply evenly to soil. Dried clover, alder and willow were also fairly compact, being about one-fifth of the volume of the fresh material, and lightweight to transport. The clover was easy to apply as mulch or dig in, but the alder and willow were prone to blowing away in the wind if mulched. Application in wet weather, with irrigation or between rows of crops, may prevent this as would mixing with composts or manure if PGMs were used to part-replace them.

Performance of the PGMs as fertiliser

Although field trials are essential for giving real-life results the downside is that they may be affected by unusual conditions and 2023 was the warmest year on record for Wales. It was also unusually wet, but rainfall was very uneven with prolonged dry weather in May, June and September.

The fertility of the soil at the beginning of the trials varied greatly between sites, both in available nitrogen and in macronutrient content (Tables 6.1b/c). There was a general trend across the trials that PGMs increased the yields of most of the crops, though usually did not produce as high yields as the grower's standard method of fertilising. Interpretation of the results is complicated, however, by the very large amounts of manures and composts that most growers were adding. The nitrogen application rate varied from 328 to 812 kg N/ha in growers' usual additions, whereas PGM nitrogen was applied at 200 to 300 kg N/ha. The amounts of manure and compost added are likely to be typical of many small-scale growers who by experience know that adding more nutrient-rich organic matter increases yields, but have no way of knowing just how much nitrogen they are adding. The trials at CAT and Ash and Elm however showed that replacing half the manure or compost with PGMs had little effect on yields, and strategies for further reducing inputs are discussed in **section 11**.

Previous research has shown the influence of PGMs on the root:shoot ratio of crops, which is a useful factor to manipulate in crop nutrition, however no clear results showed up in our data. There were also no effects of the PGMs on pests, diseases or the quality of the crops.

Alder

Though previous research has found that alder needs a long time period after addition to release nutrients, there was more of a delay than expected in these trials, suggesting that alder is best used to provide fertility over a very long timeframe. As the alder leaves had a similar carbon:nitrogen ratio to the other PGMs used, it is likely that another factor slows the decomposition. This could be other compounds such as tannins in the leaves. However as a nitrogen-fixing tree alder can play an important part in PGM systems, and could contribute to **carbon sequestration** and soil health in the long term as discussed in **section 11**.

Willow

We had assumed that the willow leaves would be slow to decompose, so it was unexpected that the beetroot harvest at **Dan yr Onnen** was higher from the willow-treated plots than from any other treatment. It must be noted that the 'usual addition' comparison was bagged compost which had a high carbon:nitrogen ratio of 30, and therefore would have been slower to release

Dan yr Onnen PGM trial

nitrogen than other composts or manures. However the beetroot harvests which were just four months after adding willow suggest that it might be a useful PGM for fairly quick nutrient release.

The willow contained a high concentration of sulphur compared to other PGMs (Fig 7.6). Measurement of sulphur in soil is technically difficult, but it is an essential nutrient for good yields. Deficiencies are increasingly occurring due to a reduction in deposition of sulphur as an atmospheric pollutant, especially in areas of high rainfall,[1] so it is possible that the sulphur content of the willow increased beetroot yields. Willow is also known to contain salicylic acid in leaves and bark[2], which plays a role in plant defence against fungal pathogens, and willow mulch has been trialled by the farmer research group Innovative Farmers against apple scab.[3]

Gorse

Although we only trialled gorse in one trial, the possible yield suppression agrees with **previous research**, and could be due to an **allelopathic** effect or to nitrogen unavailability due to a high **carbon:nitrogen** ratio. There may be other ways to use gorse as a PGM effectively. For example previous research has found that the allelopathy can be an advantage if it affects weeds more than crops[4] and we were hoping this may be the case in the courgette trial. As gorse grows easily in poor ground and often needs controlling by farmers or conservationists, it might be worth research into specific ways to enable gorse to be used as a PGM.

Clover, comfrey and grass

Clover, comfrey and grass, being long-used as soil additions, boosted yields as expected and the effect of comfrey on soil potassium concentrations is discussed below.

Timing of nutrient supply

Although a key advantage in using PGMs over traditional green manures is that they can be added at any time, skills and knowledge will be needed to match the nutrient release rate to the crop demand. This will require using knowledge of the PGM characteristics and effects of the soil environment. As an example potatoes need a good nutrient supply early in the season for fast leaf growth to capture sunlight and make tubers. At Ash and Elm, the alder and clover were added in April and May which we judged would feed the potato plants from June onwards, but Emma noted that the soil was very dry in this period, which would likely have delayed decomposition of the PGMs and therefore nutrient release. Emma says "The crops grew well, but yields were down when using PGMs on their own. I think we may have had improved yields with irrigation during the dry early months. The farmyard manure would have retained more moisture in the soil, and therefore aided crop growth."

Effects on macronutrients in soil

There were some interesting interactions between treatments, soil potassium and crop yields. Potassium (K) is vital for many plant functions and is particularly important for root and fruit development. It's reassuring to see that addition of

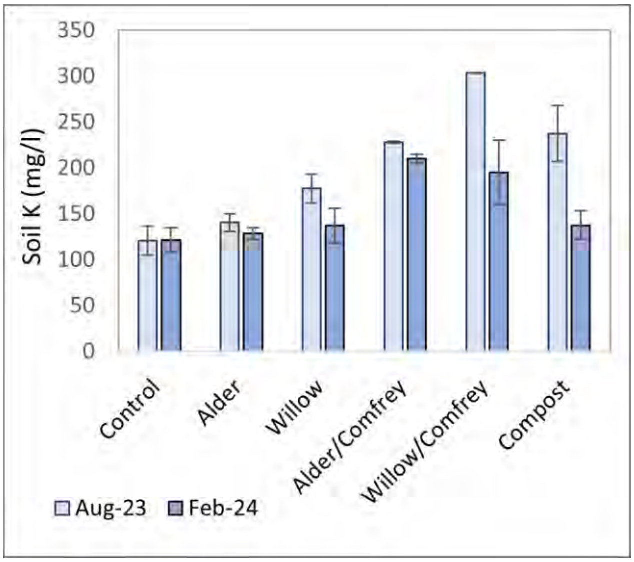


***Fig 9.1** Potassium (K) content of the soil in treated plots at Dan yr Onnen in August after harvesting of beetroot; and in February after the final harvest of kale and chard. Error bars represent the range between the two reps*

high K content PGMs did indeed increase the K content of the soil, especially from comfrey. At Dan yr Onnen the soil K concentrations in August reflected the K contents of the PGMs added: alder 0.76 %, willow 1.53 % and comfrey 4.97 % (Fig 9.1). The compost addition also increased the K content, which although it had a lower K content of 0.51, was added in a greater quantity. As the original soil had a good potassium content for vegetable growing (index of 2+) this did not influence the crop yields. K concentrations in soil are highly influenced by offtake of K within harvests, and this can be seen in the soil K in February after the final harvests, with the biggest K losses being in the plots with the highest yields during the winter.

Einion's Garden also had a high initial soil K index of 3, and the growers requested that we choose PGMs which would not be likely to increase K concentrations, as they suspected previously high K:Mg ratio of possibly reducing Mg uptake. With the choice of alder with a low K content, along with some clover to give a nitrogen boost, the K level and K:Mg ratio were maintained at a similar level, whereas they increased in the manure treated plots. This shows the potential to intentionally alter the macronutrient ratios by our choice of PGMs, for future crop and soil health.

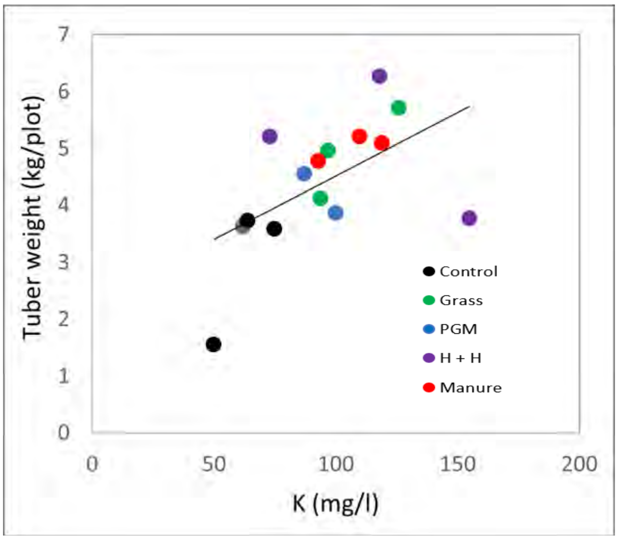


Fig 9.2 *Yield of potatoes at the Ash and Elm trial site in relation to potassium (K) concentrations in each bed*

In contrast the soil at the Ash and Elm potato trial began with a low K index of 1 (**Appendix 3**) The PGM treatments here were also alder and clover, but with a higher proportion of clover (K content of 2.3 %) which added a useful amount of K, and a separate grass treatment with a K content of 2.18 %. At the time of the potato harvest, the K had

Overall conclusions:

- **The practicalities of using PGMs in fresh, dried or pelleted forms have various advantages or disadvantages in time consumption, ease of application and seasonal availability, and further research is needed to increase efficiency**
- **There was a general trend of higher yields for PGM fertilised crops than control crops but yields were not as high as that from large nitrogen-heavy applications of composts and manures**
- **Willow, grass, comfrey and clover boosted crop yields. Alder didn't appear to benefit crops until late in the trials and gorse had a stunting effect**
- **Dry weather may have delayed the speed of PGM decomposition so that nutrient release was slower than it would be in a wetter year or with strategic use of irrigation**
- **Careful selection of PGMs allows alteration of soil macronutrient content which could have beneficial effects for crop health**

decreased further in the control plots, but were mostly higher in the treated plots. Figure 9.2 shows a correlation between the potato harvest of each plot and the K concentration of the soil at harvest time. Care needs to be taken in interpreting these results as the K concentration is affected both by additions to soil and also by the crop offtake. However this correlation suggests that higher yields were produced in plots where the treatments had increased the K content. Therefore the addition of a high K PGM in K-deficient soils, could enable a reduction in the overall quantities of soil additions needed. Ash and Elm have since designed and planted their own bioservice area which includes comfrey for future PGM supply.

Soil health

There were no clear observations on the effect on soil structure or soil health of addition of PGMs. Growers commented that the dried or pelleted PGMs did not appear to benefit soil structure in the way that compost or manure did. Emma says "The pellets probably didn't add much bulky organic matter compared to other inputs, but as an organic material it would have provided something for soil micro-organisms. The grass cutting mulch would have provided nutrients and organic matter." Useful future research would be to measure the effect on soil fauna e.g. by using an indicator such as earthworm counts, especially if carried out over many years. Ann of Einion's Garden comments "I'd like to try them (PGMs) over a longer period of time, fresh, just put through a small shredder as a thin surface mulch. In summer, I see a lot of worm activity, I find a lot of leaves pulled into the ground by worms and I'd like to see whether they'd do that with alder or willow."

References

1. Farm Advisory Service (2017) Sulphur Recommendations for Crops. Technical Note TN685 https://www.fas.scot/downloads/tn685-sulphur-recommendations/

2. Warmiński, K., Stolarski, M. J., Gil, Ł., & Krzyżaniak, M. (2021). Willow bark and wood as a source of bioactive compounds and bioenergy feedstock. *Industrial Crops and Products*, *171*, 113976. https://www.sciencedirect.com/science/article/pii/S092666902100741X

Haj-Zaroubi, M., Mattar, N., Awabdeh, S., Sweidan, R., Markovics, A., Klein, J. D., & Azaizeh, H. (2024). Willow (Salix acmophylla Boiss.) Leaf and Branch Extracts Inhibit In Vitro Sporulation of Coccidia (Eimeria spp.) from Goats. *Agriculture*, *14*(5), 648. https://www.mdpi.com/2077-0472/14/5/648

3. Percival and Little (2019) 'Using willow woodchip mulch to manage apple scab'. Download from https://innovativefarmers.org/field-labs/investigating-the-efficacy-of-willow-woodchip-mulch-as-a-control-for-apple-scab/

4. Pardo-Muras, M., Puig, C. G., Souza-Alonso, P., & Pedrol, N. (2020). The phytotoxic potential of the flowering foliage of gorse (Ulex europaeus) and scotch broom (Cytisus scoparius), as pre-emergent weed control in maize in a glasshouse pot experiment. *Plants*, *9*(2), 203. https://www.mdpi.com/2223-7747/9/2/203

10. Planting the bioservice areas

The final stage of the project was the planting of five bioservice areas for the future provision of PGMs. Three of these were planted by trialists: Enfys Veg, Ash and Elm Horticulture and Dan yr Onnen. In addition the Black Mountains College in the *Bannau Brycheiniog in South Wales* and Wilder Pentwyn Produce in Radnorshire planted bioservice areas for their new horticulture plots.

The final stage of the project was the planting of five bioservice areas for the future provision of PGMs. Three of these were planted by trialists: Enfys Veg, Ash and Elm Horticulture and Dan yr Onnen. In addition the Black Mountains College in the Bannau Brycheiniog in South Wales and Wilder Pentwyn Produce in Radnorshire planted bioservice areas for their new horticulture plots.

Ruth at **Enfys Veg** planted two 10-metre by 0.75-metre beds of comfrey within her vegetable-growing area. Emma and Dave of **Ash and Elm** Horticulture also planted a comfrey patch of 200 plants, under-sown with clover, and some alder trees planted along the edge for extra nitrogen fixing. Although comfrey is commonly used as a liquid feed, cutting and adding the comfrey direct to beds as a PGM saves work and adds bulky organic matter to soil.

At **Dan yr Onnen**, Huw Richards and the team planted two terraces of PGMs to provide fertility to their new perennial vegetable terraces. They planted alder on the top terrace, on wetter ground next to a leat. Inspired by their trial results they planted a mix of willow and alder on the next terrace down with an underplanting of comfrey. From here the PGMs can easily be harvested and moved downhill to the vegetable terraces. At the end of each vegetable terrace they put in comfrey under-sown with clover for a close, handy supply and to take up and retain any **leachate**. (See appendix 4 for the plan)

"Once we have established alder, willow and comfrey patches on our site, we will have access to this fertility whenever we need it, free of charge for many years". Lucy, grower at Dan yr Onnen

Planting the bioservice area at Dan yr Onnen

Comfrey, being a vigorous plant and easy to harvest by hand or machinery, is an excellent PGM, but it does spread very easily. Therefore, the comfrey planted in all bioservice areas was the variety 'Bocking 14' which does not spread by seed. Designs also included strips of grass or clover around the comfrey which can be regularly mown to prevent the comfrey spreading out of its allotted spaces.

Wilder Pentwyn Produce is a new market garden run by Lisa and John Hextall at Wilder Pentwyn Farm, Radnorshire. Pentwyn Farm is being developed by Radnorshire Wildlife Trust as a model of ecological best practice for food production and wildlife restoration. Lisa and John have taken on seven acres of land on which they are setting up a small commercial market garden, orchard, and campsite. Planting a bioservice area is one of the first stages in building up the farm ecology and will also provide fertility for vegetable growing. They planted a mix of 57 trees of alder (*Alnus glutinosa*) and willow (*Salix vimilalis*) which they plan to underplant with a mix of perennials.

Black Mountains College in Bannau Brycheiniog in South Wales provides further and higher education with sustainability at the heart of its ethos. Their courses include horticulture, greenwood working and coppicing, and nature recovery, and students learn practical skills at Troed yr Harn, their 50 hectare farm. Horticulture tutor Rashid Benoy and his students planted a one hectare bioservice area to provide fertility to the college's vegetable and fruit plot, but also as an ongoing research project with student participation.

Rashid designed diverse bioservice areas integrated into the productive area as shown in the plan (Fig 10.1). The short rotation coppice is planted with sweet chestnut and poplar trees, interplanted with white clover (*Trifolium repens*) and bird's-food trefoil (*Lotus corniculatus*). The trees act as a windbreak for the plot, and to be harvested every 3-4 years to provide woodchip. The nettle patches were already growing, so the design makes use of the landscape's existing vegetation.

The two main PGM beds span the width of the horticultural plots and are planted with a mix of nine different species. The land slopes towards the northwest, so the trees are planted along the topmost edge of each bioservice area (on the southeast) to enable easier harvesting from the path on higher ground. Rashid chose the nitrogen-fixing trees Italian Alder (*Alnus cordata*) and Grey Alder (*Alnus incana*), as they grow in drier soil than the alder (*Alnus glutinosa)* used in our trials. These are grown alongside a fast-growing willow *(Salix viminalis)*.

The lower edge is planted with herbaceous perennials: large-leaved lupins (*Lupinus polyphyllus*), Jerusalem artichoke (*Helianthus tuberosus*), comfrey 'Bocking 14' and Elephant grass (*Miscanthus x giganteus*) under-sown with white clover and bird's-foot trefoil. This mix of nitrogen fixers and fast-growing plants should provide lots of bulky organic matter in years to come. A three-metre-wide track on the northwest side of the bioservice plots will provide access for harvesting and room for processing PGMs, e.g. by chipping.

Rashid has devised trials to compare different methods of processing and applying PGMs. One of the PGM beds is divided into three 14- by 20-metre blocks which each have a corresponding vegetable plot. In plot 1 the PGM material will be composted for one year before application, in plot 2 it will be cut and applied as a surface mulch, and in plot 3 it will be cut and incorporated with a mechanical tilther. The PGMs from the test plots will be added to their partner vegetable plots, and the soil and crops of each will be regularly sampled for monitoring of soil fauna by light microscope and DNA analyses, and for nutrient content by standard soil analyses. Crops will also be measured for yield and nutrient content.

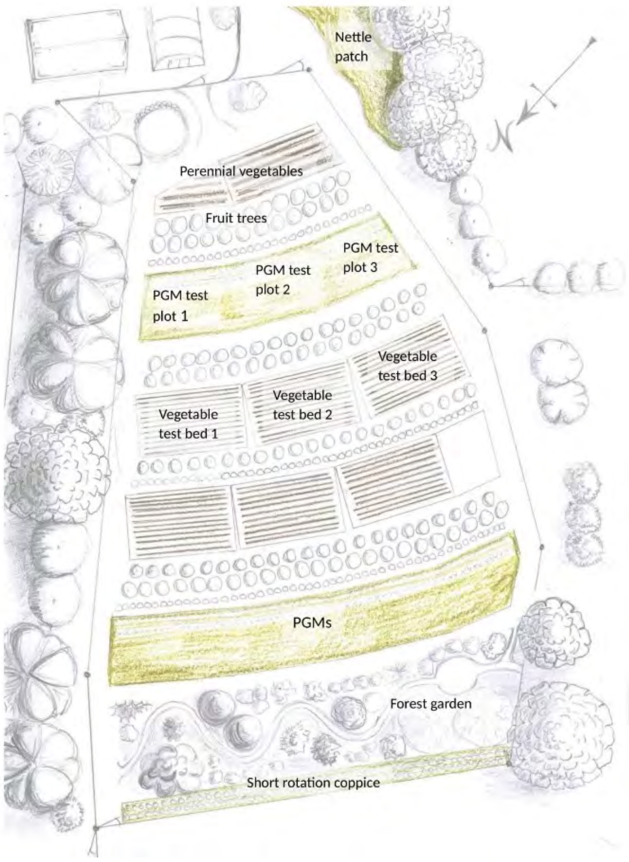


***Fig 10.1 Plan of the horticulture plot at Troed yr Harn, Black Mountains College, showing locations of the PGM plots**. Drawing by Rashid Benoy.*

Rashid and students planting the bioservice areas at Black Mountain College

11. Insights from the PGM project

The PGM project successfully harvested and processed PGMs for easy storage and application, and participant growers fertilised vegetable crops with PGMs in a small-scale trial, results of which are described in **sections 8** and **9**. The project gathered a wide variety of opinions and visions of how PGM use could progress, which are discussed below alongside issues of practicality and sustainability.

PGM harvesting, processing and application

Direct application of PGMs straight after harvesting, for example by mowing and mulching plant clippings, was the most efficient method. However, the practice of pre-harvesting PGMs gives more versatility in the timing of additions. Emma of Ash and Elm commented “I think the pellets are a great idea, for ease of use, convenience. On-farm production would be tricky, but these could be produced on scale at a dedicated **coppice** woodland and sold as a fertiliser boost.”.

Fertilising crops with PGMs

The growers’ trials showed that, as expected, clover, comfrey and grass are effective as fertilisers and results are also encouraging on the value of willow leaves. Alder leaves provided little or no fertility in the short term. It may be that alder is best used within bioservice areas to fix nitrogen, therefore increasing the overall nitrogen content of the area, but for other plants to be harvested to transfer that nitrogen to crops as outlined on page 51. However, longer term research is needed to assess the effect of adding various PGM species over many years. Those that don’t release nitrogen quickly may build up supplies in the soil which could become available in the future.

The results from gorse were similar to those from the research at Bangor University in that gorse either reduced crop growth or had no effect, and it was the least effective PGM trialled in Maria Cooper’s **MSc thesis**. However, Maria’s results using broom in her pot trial are encouraging, and more research would be beneficial.

These PGMs are just a few of the plant species which could potentially be used. Experimentation with various potential PGM species of different growth habits, environmental preferences, and properties would be valuable. Knowledge of the properties such as nutrient content, chemical characteristics and nitrogen release rates of a wide range of plants would enable tailoring of the right PGM or mix of PGMs to the right crop.

PGMs would not be used in isolation, however. Best practice would likely be to use them in combination with a variety of other methods, for example with **cover cropping** over winter and **living mulches** between crop plants. They could also be used along with addition of waste organic material and inorganic fertilisers.

PGMs as a potting compost addition

The **home gardeners’ trials** showed that addition of dried clover to potting compost boosted the growth of kale seedlings, whereas addition of dried willow to compost reduced the germination rate and growth of bean seedlings. The use of dried plant matter or pellets of appropriate plant species as bespoke additions to seed or potting compost at the time of sowing or potting on could help growers making the transition to peat-free growing media.

Crop and soil health

As well as supplying the right amount of nitrogen at the right time, key to efficient nitrogen use is crop and soil health. For example, a crop which is under water stress cannot optimally use the nutrients available, and adding organic matter is known to keep the soil both well drained and water retentive. Targeted use of specific PGMs could address soil deficiencies such as lack of potassium or phosphorous. This would increase crop health, so making more efficient use of nitrogen and reducing the overall amount of inputs needed.

The right balance of soil life can also balance out excesses in soil, and release nutrients when needed. For example, **mycorrhizal** networks can increase uptake of nitrogen and other nutrients by crops. It has also been shown that mycorrhizal

This project explored PGM use in small-scale horticulture. But could PGM use be scaled up to suit arable production? Could this increase farm resilience to an unstable climate, while also mitigating climate change by carbon sequestration and carbon neutral nitrogen fixing?

fungi can take up excess nitrate in soil and effect the activity of other micro-organisms, so reducing nitrous oxide emissions[1]. Therefore good practice to promote soil health such as reducing tillage and using **cover cropping** can work with PGMs to increase benefits.

PGM use, as with other organic amendments, may benefit from work to increase crop affinity for organic nitrogen uptake. Although most nitrogen is taken up by crops as ammonium or nitrate, plant roots and associated mycorrhizal fungi have been shown to take up larger nitrogen molecules such as amino acid or short peptides. Uptake of intact organic molecules has the advantage that nitrogen from organic matter can enter the roots without first being converted to inorganic forms. This reduces the opportunities for nitrogen loss and pollution. Selecting or breeding crops for greater affinity for organic nitrogen uptake could increase nutrient use efficiency and reduce nitrogen pollution in the future.[2]

Feedback from stakeholders

Throughout the project we discussed possible opportunities and implications with farmers, foresters, ecologists, and others with an interest in the rural landscape. Feedback from the growers who took part in the trials is summarised in **sections 9** and **11.** Farmers were keen to reduce expenditure on fertilisers, but expressed reservations about the cost-effectiveness of growing, harvesting and applying their own PGMs. Many saw opportunities in mixing in plant wastes from other sources such as from roadside hedge trimmings, forestry waste and clearing of bracken or invasive species. One large-scale organic vegetable grower who currently uses rotational **leys** to build fertility commented that it is a necessary part of the system to rest the soil periodically. However, many small-scale growers said they do not have enough land to periodically take land out of cropping.

Some expressed concerns over the possible visual impact on the landscape if PGM production were to become more common, for example if trees were grown in lines to enable harvesting. A fear was also raised that PGM production could be taken on by large businesses who may not grow them in an ecologically sensitive way, but instead create monocultures for industrial production. Farmers also raised the issue that tenancy agreements often do not allow the planting of trees.

Siting and design of bioservice areas

Integration of bioservice areas into farms could be done in many different ways according to the crop needs and landscape. Figure 11.1 gives an example of how PGMs could be sited to make use of land which is less suitable for crops. Good design would be crucial to ensure bioservice areas resulted in benefits to biodiversity and farm resilience. Land which already has high wildlife value would not be suitable for bioservice areas and needs to be preserved as it is.

In some situations bioservice areas would need to be designed more for nutrient retention and redistribution than for nitrogen fixing. For example, on lower ground which may be receiving **leachate** from upslope, it may not be suitable to include nitrogen-fixing plants at all, and instead the role of the bioservice areas would be to take up and redistribute nitrogen. Many areas of valuable habitat are already too rich in nitrogen, which threatens biodiversity. Appropriate PGM plants could be grown near to these to mop up and redistribute excess nitrogen to farmland. The different effects on the environment of various tree and plant species can be used for maximum benefit, for example poplars and willows are thought to be especially good at taking up nitrates. Some trees, including alders are known to acidify the soil and so need to be limited in some areas, such as in riparian zones next to watercourses.[3]

In more uniform agricultural landscapes hedgerows could be restored or widened into

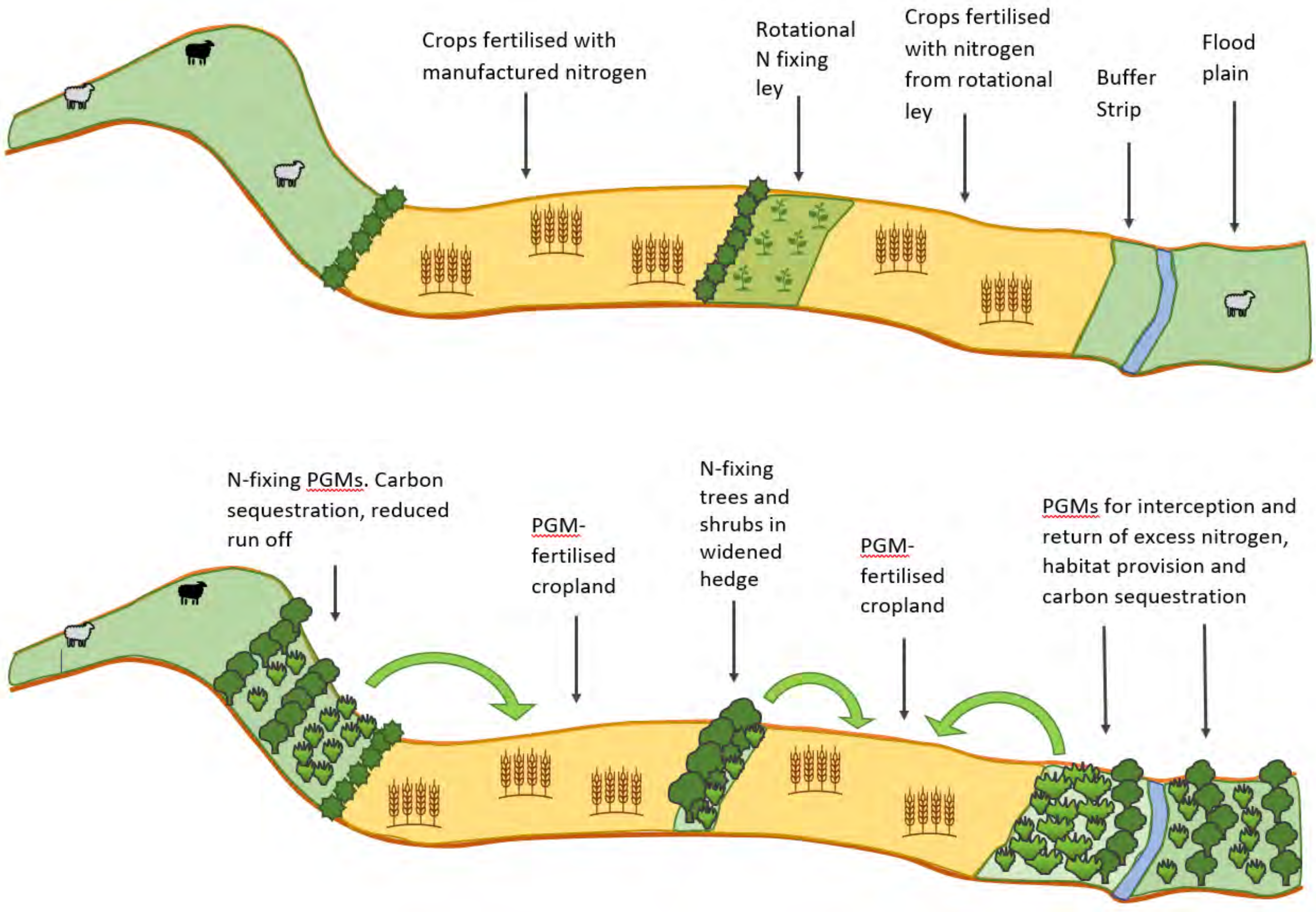


Fig 11.1 Representation of a current agricultural landscape (top) and after changing crop fertilising to using PGMs and incorporating bioservice areas (bottom). This has been amended from a diagram included in Ward st al (2023). https://doi.org/10.1007/s10705-022-10253-x

bioservice areas, increasing protection against soil erosion. To supply a larger amount of PGMs, and to enable easier application, alley systems with alternating strips of cropping area and bioservice area could be used. Alley cropping of fruit/nut trees and for **ramial** wood production is being experimented with on farms in the UK, from which we can gain insights on good system design.[4] Methods of farming on lowland peatland with a high water table, known as 'paludiculture', are being developed as a way to preserve peatlands and still produce a crop. Some flood-tolerant PGMs might be suitable for this, and may be a useful area of research into appropriate species and growing methods. However, good management of this is crucial to prevent high nitrogen emissions from the soil.[5]

Issues of biosecurity to prevent transmission of tree diseases need to be considered, both when planting bioservice areas, and when harvesting and moving PGM material. Because of this, we commissioned tree pathology consultant Alistair Yeomans of FloraSec to assess and advise on the mitigation of any risks that PGM systems may pose. **Alistair's report** outlines measures to reduce these risks and advises on future research on specific risks if moving PGMs far from the bioservice area. Care must also be taken to avoid planting PGM species which can become invasive – not just those which it is illegal to plant, but others such as varieties of comfrey which can spread easily and might not be appropriate in some areas.

How much land would be needed for bioservice areas?

The amount of land which would be needed for PGM production is hard to predict and would depend on many factors including the climate, soil and harvesting methods. Nitrogen-fixing rates for traditional green manures are estimated at around

100 to 250 kg N/ha per year, which is a similar amount to that typically applied to crops. Harvested nitrogen from regular cutting of alfalfa, white clover, red clover, and red clover/ryegrass mix has, however, been measured to be as high as 300 to 640 kg N/ha per year in Denmark.[6] With this rate of nitrogen offtake a hectare of cropland, if fertilised solely by PGMs, would need around half a hectare of bioservice area to supply it.

In theory including nitrogen-fixing trees and shrubs would result in more nitrogen fixing due to greater capture of sunlight energy in a three-dimensional system. However, some of this energy would be used by the plant for wood production. Cutting tree branches in summer takes more nutrients from the tree than cutting in winter, and long-term research is needed on how much harvesting of leafy tree PGMs is possible in the long term. Nitrogen fixing would restore the nitrogen needed for growth, but eventually there may be need for replenishing other nutrients, for example phosphorus or potassium, to the bioservice areas.

Methods of direct application from bioservice area to cropland

There are several ways that the PGMs could be cut and distributed from alleys or bioservice areas to nearby cropping areas, and experimentation is needed to determine the most efficient methods. Leafy ground covers can be mown and mulched directly onto the cropping area. Tree PGMs can also be directly applied, by using hedge trimming and shredding machinery. Harvesting of green leafy tree PGMs needs to be timed so that nesting birds are not disturbed. This could be undertaken during September after the nesting season. Harvesting of coppiced or pollarded material which has grown that summer, or foliage which is not compact enough for nest sites, may also be possible during mid-summer without affecting nesting. The reports of the WWOOFs project which explored the use of ramial wood,[7] and the Productive Hedges report,[8] give useful calculations on harvesting and applying hedge trimming, and guidance on protecting wildlife.

Tree branch trimmings have a higher **C:N ratio** than leaves alone, so could be chipped and used for slower nitrogen release, or mixed with high nitrogen PGMs to reduce the C:N ratio as required.

If a high-nitrogen content of tree PGMs is required, there are various methods worth experimenting with to separate the nitrogen-rich tree leaves from the carbon-rich branches. An example could be cutting leafy branches, laying them in rows next to cropland until dry and then using a leaf blower to blow the lighter leafy material off the branches onto the cropland. In small-scale systems roughly chopped leafy tree branches could be laid between rows of crops in late summer until leaves have fallen and the remaining branches then raked off in winter after the crops have been harvested. Decomposing leaves would then be incorporated into the soil by soil fauna to increase fertility for the following spring.

Another strategy would be to harvest only the leafy non-woody plants for nitrogen-rich material and cut the woody tree growth in winter for chipping into ramial wood. In this way nitrogen-fixing trees would still contribute to the nitrogen production of the whole system, because each time they are coppiced their own nitrogen demand is reduced. Thus nitrogen fixed in the roots becomes available to neighbouring plants.

Growing PGMs as a product for sale

Processed PGMs can be grown some distance from where they are applied. Therefore, there may be scope for PGMs to be widely grown in areas of lower-grade agricultural land, particularly in areas of higher rainfall which are naturally less suited to arable and horticultural production. A PGM product would likely be similar to the pellets currently on the market for small-scale gardeners, which are made from various plant materials or waste products. It may be possible to mix in other nutrient-rich waste materials with PGMs, for example crop residues or plant trimmings from horticultural services or from the cutting of invasive species. Batch testing of the finished product for nutrient content and having a variety of different mixes with different properties to choose from would enable growers to use them appropriately for best effect. For large-scale use a PGM pellet would need to be of appropriate size and robustness to be used by fertiliser-spreading machinery.

For processed PGMs to be environmentally beneficial as a nitrogen fertiliser, the energy costs

of production should be lower than that of industrial nitrogen fixing. Development of technologies such as powering nitrogen fixing by electrolysis using renewal energy could make industrial nitrogen fixing almost carbon neutral in the future.[9] However, it is also possible that PGM processing could be powered by renewables. The energy costs of PGM pellet production also need to be considered alongside other factors, for example provision of organic nitrogen for carbon sequestration and supply of other nutrients such as phosphorus and potassium.

To make a saleable product, the process would typically include harvesting, drying, chopping/milling and pelleting. Research is needed on the combined energy, labour and financial costs of these, which would vary considerably depending on the material and machinery used. The first stage would be mowing, tree trimming or brash cutting. If PGMs were to be grown on steep slopes or boggy areas, specialist machinery would be necessary for harvesting. A wide variety of machinery has been developed by the forestry and aligned industries for difficult terrain, some of which may be suitable.

Drying may be possible in the open air, or under temporary covers without an energy cost. Otherwise, crop-drying machinery is available, such as the Alvan Blanche biomass dryer used in our trials at the Beacon project. Milling and pelleting would likely be an energy-intensive part of the process. For the pelleting in our trials the hammer mill (for grinding the material) and pellet mill had a power draw of 6.5 and 25 kW respectively, resulting in a total energy cost of 0.982 kWh to make 1 kg of alder pellets and 0.976 kWh to make 1 kg of clover pellets (**section 6**). This translates to 34.09 kWh and 30.03 kWh to make 1 kg of N within alder and clover pellets respectively. This energy cost does not compare well with industrially produced nitrogen.

Milling and pelleting, however, vary greatly in energy consumption, depending on the material, scale and efficiency of the machinery used. Literature on the production of pelleted material for biomass or animal feed shows much lower energy use is possible, for both grinding (in the region of 0.005 to 0.04 kWh per kg) and pelleting (in the region of 0.044 to 0.09 kWh per kg).[10] Research into the feasibility of powering PGM processing by renewable energy may also be worthwhile.

"Farmers need to go further than current 'best practice', for effective nutrient management that meets society's needs and challenges. Such significant change is unlikely to be achieved without considerable support from policy." Nutrient Management Expert Group[12]

How could policy and economics affect PGM use?

As with any other agricultural system, the feasibility and financial implications for farmers are influenced by land-use regulations and available subsidies. Agricultural policy in the UK is currently in flux due to new subsidy schemes being drawn up in each devolved nation after Brexit. Bioservice areas may be eligible for economic support aimed at encouraging tree planting, hedgerow restoration and increasing biodiversity, but as the concept of PGM production is a new one eligibility is unclear.

Regulations on tree felling may be relevant to PGMs if larger material is being cut. A felling licence is required if the wood harvested is over five cubic meters in volume and the girth of the tree at 1.3 metres high is over 8 cm diameter if a single tree, 10 cm for thinning woodland, or 15 cm for coppicing.[11]

Across the UK there are regulations to prevent nitrogen pollution, especially in sensitive areas called 'Nitrogen Vulnerable Zones' (NVZs) which cover large areas including the whole of Wales. Legislation on NVZs is set by each devolved nation, but generally restricts nitrogen application, whether in mineral fertiliser or from organic sources, to below 250 kg per hectare within any 12-month period. Guidance for farmers on the application of slower-release organic nitrogen in less conventional materials is limited and the applicability of NVZ rules to PGMs is unclear. For slow-release PGMs such as alder it may be appropriate to add larger amounts than presently allowed under the NVZ rules. Though it is unlikely that this would be a risk to nitrogen pollution, NVZ rules do not presently take account of the speed of nitrogen release, and so there may be a case for policy change in relation to a variety of slow nitrogen-release materials.

Next steps for PGMs

Throughout the PGM project we worked with many people with an appetite for finding solutions. We think that the trials showed that PGMs could have real potential to increase the sustainability of crop production. We don't however want to create a fad, without sound scientific evidence for its benefit. There is still much to consider, explore and research. Growers and farmers can contribute to this if space and time are available. This could be by planting bioservice areas or experimenting with fertilising crops with similar materials such as alfalfa pellets, or baled hay or silage.

The growers who have planted the five bioservice areas as part of the PGM project will continue to experiment with growing and applying PGMs. The **Field Lab**, part of the Innovative Farmers network, is currently in the early stages of designing their trial.

Increasing the sustainability of food production needs to be treated as urgent. Nitrogen use has been a neglected issue with far-reaching consequences for the environment, food security and livelihoods. Using PGMs to fertilise crops takes a big shift in thinking, and requires very different systems to be put in place. Could a technique which at present seems niche and impractical become a commonplace and common-sense practice in the future? Both formal scientific research, and practical logistical innovations are needed, some of which are listed below.

Calling growers, farmers, researchers, environmentalists and policymakers. Do you think PGMs could contribute to sustainable food production? If you are involved in land management or food production could you incorporate exploring PGMs into your work?

Ideas for research:

- collating a database of nutrient content, chemical characteristics and nitrogen release rates of a wide range of potential PGM species
- the impact of PGMs on soil health and nutrient cycling, in the short term and over many years
- lifecycle analyses of PGM systems for climate change mitigation
- quantify nitrogen fixing in diverse bioservice areas including trees and shrubs
- the effect of long-term continued harvesting on the bioservice areas, for example possible depletion of phosphorus or potassium
- design and management of bioservice areas for maximum wildlife value
- crop breeding for affinity for organic nitrogen uptake

for innovation:

- efficient methods for harvesting PGMs in a variety of situations including steep slopes and boggy land
- processes for efficiently separating nitrogen-rich tree leaves from carbon-rich branches and applying to cropland
- energy-efficient processes for drying or pelleting PGMs
- creating pelleted PGMs which are robust enough to be used in a conventional fertiliser spreader
- dried or pelleted PGMs as bespoke additions to seed and potting compost as appropriate to type of seedling

for discussion:

- how to maximise the benefits of slow-release organic additions and how this relates to current legislation on nitrogen vulnerable zones
- would PGM systems be eligible for subsidies for environmental services on farms such as tree-planting or hedgerow-restoration grants?
- could farming subsidy schemes offer more support for practices such as bioservice areas which combine habitat creation and benefits to agriculture?
- how could legislation prevent poor design or mismanagement of PGM or other woodland-creation projects which would not be environmentally beneficial?

References

1. Bender, S. F., Plantenga, F., Neftel, A., Jocher, M., Oberholzer, H. R., Köhl, L., ... & Van Der Heijden, M. G. (2014). 'Symbiotic relationships between soil fungi and plants reduce N_2O emissions from soil.' *The ISME journal*, *8*(6), 1336-1345. https://academic.oup.com/ismej/article/8/6/1336/7582521

Qiu, Q., Bender, S. F., Mgelwa, A. S., & Hu, Y. (2022). 'Arbuscular mycorrhizal fungi mitigate soil nitrogen and phosphorus losses: A meta-analysis.' *Science of the Total Environment*, *807*, 150857. https://doi.org/10.1016/j.scitotenv.2021.150857

2. Congreves KA, Otchere O, Ferland D, Farzadfar S, Williams S, Arcand MM (2021) 'Nitrogen use efficiency definitions of today and tomorrow.' Front Plant Sci. https://doi.org/10.3389/fpls.2021.637108

Farzadfar S, Knight JD, Congreves KA (2021) 'Soil organic nitrogen: an overlooked but potentially significant contribution to crop nutrition.' Plant Soil 462(1–2):7–23. https://doi.org/10.1007/s11104-021-04860-w

3. Tom Staton et al (2024) 'Tree species guide for UK Agroforestry Systems' https://cdn.forestresearch.gov.uk/2024/02/Agroforestry-Tree-Species-Guide-v5.pdf

4. Smith, Westaway, Caldbeck and Simonsen (2024) Wakelyns 'Agroforestry: Resilience through diversity' https://wakelyns.co.uk/orc25years/

5. International Union for the Conservation of Nature (IUCN) (2023) 'Principles for Sustainable Peatland Paludiculture' https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2023-09/Principles%20for%20Sustainable%20Peatland%20Paludiculture.pdf

Sutton, M. A., Howard, C. M., Mason, K. E., Brownlie, W. J., & Cordovil, C. M. D. S. (2022). 'Nitrogen opportunities for agriculture, food & environment. UNECE guidance document on integrated sustainable nitrogen management.' https://nora.nerc.ac.uk/id/eprint/534033/

6. Lynge, M., Kristensen, H. L., Grevsen, K., & Sorensen, J. N. (2023). 'Strategies for high nitrogen production and fertilizer value of plant-based fertilizers.' *Journal of Plant Nutrition and Soil Science*, *186*(1), 105-115 https://tinyurl.com/Lynge-plantfert

7. Organic Research Cente (2020) 'WOOdchip for Fertile Soils, Technical guides' 1/2/3 https://www.organicresearchcentre.com/our-research/research-project-library/woofs-woodchip-for-fertile-soils/

8. Westaway S, Smith J (2019) 'Productive Hedges: Guidance on bringing Britain's hedges back into the farm business' https://zenodo.org/records/2641808#.XxF-PZNKhsO

9. IEA (2021) 'Ammonia Technology Roadmap Towards more sustainable nitrogen fertiliser production' https://www.iea.org/reports/ammonia-technology-roadmap

10. Wilson, J. M., McKinney, L. J., Theerarattananoon, K., Ballard, T. C., Wang, D., Staggenborg, S. A., & Vadlani, P. V. (2014). 'Energy and cost for pelleting and transportation of select cellulosic biomass feedstocks for ethanol production.' *Applied Engineering in Agriculture*, 30(1), 77-85. https://core.ac.uk/download/pdf/20522756.pdf

Abo-Habaga, M., Bahnassi, A., ElShabrawy, T., & ElHaddad, A. (2017). 'Performance evaluation of pellets forming unit in local feed pelleting machine.' *Journal of Soil Sciences and Agricultural Engineering*, *8*(9), 431-435. https://tinyurl.com/Abo-Habaga-pellets

Çitil, E., & Marakoğlu, T. (2023). Effect of Feed Materials on Pellet Properties, Capacity and Energy Consumptions Values. Journal of Agricultural Faculty of Gaziosmanpasa University/Gazi Osman Pasa Üniversitesi Ziraat Fakültesi Dergisi, 40(3). https://tinyurl.com/Citil-pellets

Tumuluru, J. S., Tabil, L. G., Song, Y., Iroba, K. L., & Meda, V. (2014). Grinding energy and physical properties of chopped and hammer-milled barley, wheat, oat, and canola straws. Biomass and Bioenergy, 60, 58-67. https://tinyurl.com/Tumurulu-straw

11. Gov.uk website 'Tree felling licence: when you need to apply' Accessed 9th August 2024 https://www.gov.uk/guidance/tree-felling-licence-when-you-need-to-apply

12. Defra (2024). 'Improving policy and practice for agricultural nutrient use and management' https://tinyurl.com/Defra-policy-nutrients

Glossary

Agroforestry Agricultural systems which integrate trees with crops or pasture

Allelopathy An effect of chemicals within some (**allelopathic**) plants which reduces germination or growth of other plants

Bioservice area A permanent area in which plants are grown to produce perennial green manures (PGMs), as well as providing other biological services to nearby agricultural land such as shelter, erosion control and habitat for beneficial insects.

Brassica A plant belonging to a group which includes cabbages, kale, cauliflower, turnips and radishes

C:N ratio (Carbon:Nitrogen ratio): The amount of carbon compared to nitrogen within an organic material such as plant tissue.

Carbon sequestration Storage of carbon within stable compounds in soil

Coppice/coppicing The periodic cutting of deciduous trees to near ground level, which regrow from the remaining stump. Coppicing is a traditional way of harvesting wood products and managing woodland

Cover crop A ground-covering plant grown to protect soil and build up fertility when a productive crop is not present

Ecosystem services Benefits provided by ecosystems to human society such as pollination of crops by insects and nitrogen fixing

Green manure A plant grown and used to increase the fertility of soil

Green waste compost Compost made from waste from gardening, largely consisting of plant trimmings, sometimes also including food waste

Humus A stable compound in soil which is the product of breakdown of organic matter and binds soil particles together

Leaching The loss of nutrients within water run-off from soil

Leguminous A plant of the **legume** (*Fabaceae*) family which fixes nitrogen in association with rhizobia bacteria

Ley Cropland on which a grass or green manure mix is grown for a season or more, sometimes with grazing

Living mulch Ground-covering plants, grown among crops to improve and protect soil

Microbial biomass The part of soil which is made up of the bodies of living microbes

Mulch a layer of material applied to the soil surface. Functions of a mulch include weed control, addition of nutrients and organic matter, reducing erosion and conserving moisture

Mycorrhizal fungi Fungi which live in association with plant roots, gaining sugars from the plant from photosynthesis and enabling the plant to increase its uptake of water and nutrients

Nitrate Vulnerable Zone (NVZ) Areas of the UK designated as being as risk from nitrate pollution, with legislation limiting the nitrogen which can be added to land

Nitrogen fixing The process of converting nitrogen gas in the air to nitrogen compounds, carried out by bacteria, often within plant roots, and by industrial processes using fossil fuels

Nitrogen fixing bacteria Bacteria which fix nitrogen, often living within plant roots, which use sugars donated by the plant partner to fuel the process, with the plant partner gaining nitrogen compounds

Nitrogen lock-up/immobilisation A limitation of nitrogen availability in soil. This can result from an excess of carbon-rich material which causes microbes to use up available nitrogen temporarily immobilising it within microbial biomass

Organic matter Any material added to or within soil which is made up of once-living matter and therefore contains carbon e.g. compost, manure, dead roots or leaves, humus etc

Perennial plant A plant that grows for more than two years. Many perennials live for decades or longer.

Perennial Green Manure (PGM) A perennial plant grown to be harvested and added to soil as a fertiliser. The harvested material used as fertiliser

Phenolic compounds A group of chemical compounds found in plants. Their functions include defence against pests and protection from ultra violet light

Pollarding The practice of removing tree branches leaving a bare trunk from which the tree regrows

Rotation (crop rotation) The practice of growing different types of crops in sequence on the same piece of land, to manage soil fertility and reduce pests

Silage Grass or other plants used as fodder which can been preserved in airtight conditions by fermentation

Soil carbon Carbon contained within soil within organic matter

Soil health The capacity of soil to function as a living system to sustain crop productivity

Symbiotic An interaction between two or more organisms which each gain from the other e.g. plants with nitrogen fixing bacteria or mycorrhizal fungi

Abbreviations

C	Carbon
CO_2	Carbon dioxide
GHG	Greenhouse gas
K	Potassium
Mg	Magnesium
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
PGM	Perennial Green Manure

Appendix 1 Nutrient content of PGMs used in trial

Chemical	Unit	Alder	Alder (pelleted)	Clover	Clover (pelleted)	Comfrey (pelleted)	Gorse	Grass	Willow
Total Nitrogen	% w/w	3.58	3.25	3.04	2.88	2.66	2.33	3.07	3.37
Total Phosphorus	% w/w	0.19	0.18	0.23	0.22	0.40	0.14	0.45	0.30
Total Potassium	% w/w	0.76	0.78	2.28	2.24	4.97	0.74	2.18	1.53
Total Calcium	% w/w	0.91	0.85	1.49	1.51	1.43	0.65	0.68	1.83
Total Magnesium	% w/w	0.34	0.29	0.25	0.24	0.33	0.19	0.28	0.22
Total Sulphur	mg/kg	1806	1615	1328	1276	2344	1278	2394	4636
Total Carbon	%	54.6	55.9	49.0	51.3	39.9	54.2	47.6	51.5
Carbon:Nitrogen Ratio	:1	15.3	17.2	16.1	17.8	15.0	23.2	15.5	15.3
Total Manganese	mg/kg	544	459	35.1	39.0	167	82.0	298	80.0
Total Copper	mg/kg	15.2	14.5	11.1	12.2	14.3	3.4	9.9	8.2
Total Zinc	mg/kg	73.1	75.1	28.9	46.8	55.3	34.0	39.3	267
Total Iron	mg/kg	249	383	441	374	3795	120	655	208
Total Boron	mg/kg	12.4	12.1	22.9	21.8	30.5	12.0	18.3	31.8

Does adding PGMs to your potting compost increase seedling growth or help root establishment?

Thanks for taking part in trials of Perennial Green Manures!

If you think that your young plants are not quite getting enough nutrition from your potting compost we'd love you to try adding PGMs to some of your pots and record the results for us. Your trial can be as simple or as complicated as you want to make it. For example, you could add PGMs to half of your pots or modules and leave the other half without. Or you could try them alongside other treatments e.g. a liquid comfrey feed.

Clover is likely to release the nutrients quicker than alder or willow, so if your plants are in the pots for just a few weeks please use clover. Alder has a slower release rate, so best use it for plants which are in the pots for at least 6 weeks.

Each pack contains enough PGMs for 50 small (9cm) pots or 300 modules, but don't feel you need to use it all.

For vegetable or flower seedlings grown in the standard 9 cm plant pots, we suggest you add 3 grams, which is about 10 pellets, or a heaped tablespoon full of dried PGMs per pot. If using modules, add about 0.5 grams, which is one pellet or a heaped teaspoon full near to bottom of each module. You may also like to experiment with different quantities.

So that natural variation in the greenhouse, or on the windowsill isn't mistaken for an effect of the PGMs, please mix up the positions of the pots, either randomly, or in alternate rows of pots. Remember to label them all carefully, and take a photo or draw a plan, in case the labels fade or get lost.

How to monitor your trial

There are lots of different ways you can monitor your trial. We'd like you hear about your overall impression of plant health, any effect on pests etc as well as formal measurements if you get time. We suggest that you check your pots at least weekly or fortnightly depending on how fast they grow. Perhaps decide now and set yourself some phone reminders.

Please choose the way of monitoring which seems most common sense to you. You could estimate the coverage of the plants over the soil of each pot or module in % and/or measure the height e.g. of 3 average plants in each group. You may notice that some plants are a darker shade of green than others, or wilt sooner that others when they are dry. When you plant out, please take a good look at the roots and send us any observations.

Photos are a very valuable record of the experiment.

Included are a couple of monitoring sheets which you can adapt to your own treatments and measurements, or draw up your own as appropriate.

You can feed your results into us via email or through the trials whatsapp group or facebook group. Please contact us for access or use the links: https://www.facebook.com/groups/568412352063046/ or https://chat.whatsapp.com/Itni79ZKnRh2EGsKQFymiV

If you use Instagram you can also follow our account @perennial_green_manures and tag us in your trial photos. Use the hashtag #pgmtrials

We'll send out reminders to you to send us your results, but we hope to gather all pot trial results in by August.

Thank you!

The Perennial Green Manures project is an Ecodyfi project as part of the UNESCO Dyfi Biosphere and is funded by the Co-op's Carbon Innovation Fund.

PGM Trials Record Sheet

Name **Site** **Crop** **Date**

	Treatment 1 e.g. clover pellets			**Treatment 2** e.g dry alder			**Treatment 3** e.g. control (no addition)		
You might want to choose some individual plots or modules for observations	e.g. Pot/row 1	e.g. Pot/row 2	e.g. Pot/row 3	e.g. Pot/row 1	e.g. Pot/row 2	e.g. Pot/row 3	e.g. Pot/row 1	e.g. Pot/row 2	e.g. Pot/row 3
Measurement e.g. height, Width: cm, inches etc									
Root growth, note this when planting out.									
Your observations on crop growth, health, pests etc.									

Appendix 3 Soil Characteristics before and after trials

Einion's Garden

Treatment	Before	Control 1	Control 2	PGM 1	PGM 2	Manure 1	Manure 2
pH	6.3	5.4	5.9	5.5	5.9	5.5	6.2
P (mg/l) (index)	94.6 (5)	108 (6)	102.6 (6)	108.6 (6)	102.2 (6)	113 (6)	109.6 (6)
K (mg/l) (index)	352 (3)	183 (2+)	175 (2-)	215 (2+)	145 (2-)	310 (3)	468 (4)
Mg (mg/l) (index)	285 (5)	228 (4)	273 (5)	264 (5)	267 (5)	210 (4)	321 (5)

Ash and Elm

Treatment	Before	Control 1	Control 2	Control 3	Grass 1	Grass 2	Grass 3	PGM 1	PGM 2	PGM 3	H + H 1	H H 2	H H 3	Manure 1	Manure 2	Manure 3
pH	5.5	5.9	5.8	5.7	5.7	5.6	5.8	6	5.8	5.7	5.9	5.7	5.7	5.9	5.8	5.6
P mg/l (index)	22.2 (2)	21.2 (2)	31.2 (3)	25.6 (3)	25.8 (3)	27.8 (3)	27.6 (3)	20.2 (2)	26.2 (3)	25.6 (3)	31 (3)	26.6 (3)	27.8 (3)	28.4 (3)	28.6 (3)	28 (3)
K mg/l (index)	106 (1)	50 (0)	64 (1)	75 (1)	94 (1)	97 (1)	126 (2-)	62 (1)	87 (1)	100 (1)	118 (1)	73 (1)	155 (2-)	110 (1)	93 (1)	119 (1)
Mg mg/l (index)	109 (3)	134 (3)	116 (3)	110 (3)	119 (3)	121 (3)	105 (3)	143 (3)	120 (3)	100 (2)	140 (3)	121 (3)	111 (3)	138 (3)	117 (3)	116 (3)

Dan yr Onnen Aug 2023

Treatment	Before	Control 1	Control 2	Alder 1	Alder 2	Willow 1	Willow 2	Alder/ Comfrey 1	Alder/ Comfrey 2	Willow/ Comfrey 1	Willow/ Comfrey 2	Compost 1	Compost 2
pH	5.7	5.4	5.5	5.5	5.6	5.5	5.3	5.5	5.5	5.7	5.6	5.7	5.6
P mg/l (index)	8.8 (0)	9.8 (1)	10.8 (1)	9.2 (0)	12 (1)	10.6 (1)	9.6 (1)	9.4 (0)	10.4 (1)	9.8 (1)	10.6 (1)	13 (1)	12.4 (1)
K mg/l (index)	200 (2+)	137 (2-)	105 (1)	131 (2-)	150 (2-)	193 (2+)	162 (2-)	229 (2+)	227 (2+)	304 (3)	303 (3)	268 (3)	207 (2+)
Mg mg/l (index)	121 (3)	107 (3)	98 (2)	111 (3)	117 (3)	99 (2+)	91 (2+)	119 (3)	112 (3)	123 (3)	116 (3)	122 (3)	113 (3)

Dan yr Onnen Feb 2024

Treatment	Before	Control 1	Control 2	Alder 1	Alder 2	Willow 1	Willow 2	Alder/ Comfrey 1	Alder/ Comfrey 2	Willow/ Comfrey 1	Willow/ Comfrey 2	Compost 1	Compost 2
pH	5.7	6.8	6.6	6.3	6.7	6.3	6.6	6.4	6.7	6.6	6.6	6.6	6.6
P mg/l (index)	8.8	8.4 (0)	10 (1)	9.4 (0)	10.6 (1)	10.6 (1)	9.6 (1)	13.2 (1)	9.4 (0)	13 (1)	11.6 (1)	11 (1)	10.6 (1)
K mg/l (index)	200	135 (2-)	108 (1)	135 (2-)	122 (2-)	156 (2-)	118 (1)	215 (2+)	205 (2+)	230 (2+)	160 (2-)	153 (2-)	122 (2-)
Mg mg/l (index)	121	94 (2)	88 (2)	102 (3)	91 (2)	92 (2)	86 (2)	122 (3)	98 (2)	106 (3)	90 (2)	102 (3)	92

Centre for Alternative Technology

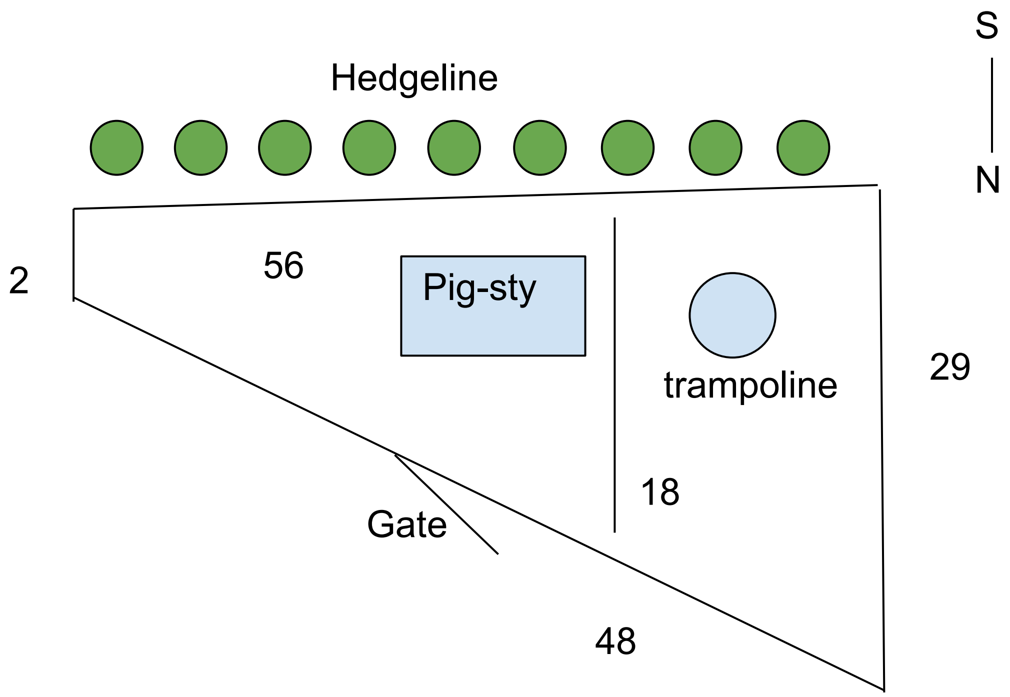
Treatment	Before	Control	Alder/Clover	Half and half	Compost
pH	7.3	7.5	7.4	7.5	7.8
P mg/l (index)	58.6 (4)	85 (5)	88.2 (5)	79.4 (5)	48.2 (4)
K mg/l (index)	86 (1)	27 (0)	73 (1)	81 (1)	101 (1)
Mg mg/l (index)	216 (4)	173 (3)	201 (4)	183 (4)	177 (4)

Enfys Veg

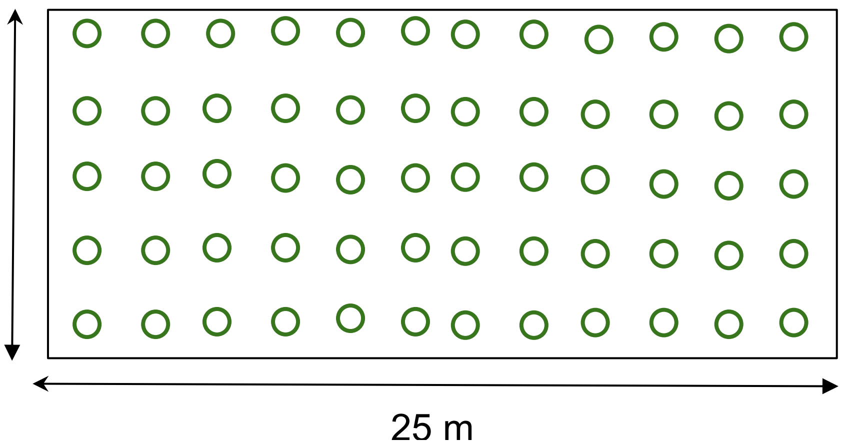
Treatment	Before (soil)	Green waste	Control	PGM	PGM/GW	Green waste
pH	5.8	8	6.7	6.6	7	6.7
P mg/l (index)	33.4 (3)	144.2 (7)	53.8 (4)	60.8 (4)	57.2 (4)	62.6 (4)
K mg/l (index)	454 (4)	4511 (9)	551 (4)	594 (4)	452 (4)	674 (5)
Mg mg/l (index)	101 (3)	378 (6)	196 (4)	198 (4)	167 (3)	222 (4)

Appendix 4 Bioservice area designs

Ash and Elm bioservice area



200 comfrey plants @ approx 1 x 1 m spacing (can be planted as close as 0.5 m)



Dan yr Onnen bioservice area