Growing through Climate Change: Local Responses to Food Security

Potentials for agriculture and food adaptations in Wales

April 2024

Authored by Dr Elise Wach

Commissioned by Seeding Our Future and Our Food 1200

Growing through Climate Change: Local Responses to Food Security

Potentials for agriculture and food adaptations in Wales

Acknowledgements

This research was commissioned by Seeding our Future, a non-profit initiative exploring resilience and adaptation to climate change, directed by Alan Heeks, and by Our Food 1200, which promotes small-scale regenerative farming in Mid Wales.

Research and reports were produced by researcher and food producer Dr Elise Wach and drew on the experiences and perspectives of research colleagues, fellow gardeners and farmers. Heartfelt thanks to those who took the time to contribute to this report.

For comments and further info, contact Elise Wach at contact@elisewach.com or Alan Heeks at progress@workingvision.com.

Contents

Photo this page: US Department of Agriculture, Flickr / Creative commons
Photo on cover: LSDSL / Creative Commons

Foreword

By Alan Heeks - Seeding our Future

Climate change is already impacting food supplies, and is forecast to create much greater disruption in the years ahead. I commissioned this research by Elise Wach to understand both the threats and the scope for positive adaptation, especially in Wales, one of the focus areas for Seeding our Future's work.

Overall, it's clear from this report that producers and consumers in Wales, and in Britain generally, have plenty of opportunities to increase the resilience of local food supplies: but grasping these will need determination, money, and in particular a willingness to innovate *before* the problems get more severe.

Changing crops and cultivation methods requires time, investment and assured markets. Wales is blessed with a good range of progressive independent producers, a growing number of community food schemes, and strong policy support from the Welsh Government, who understand the urgency of raising our food security.

While climate change will pose challenges to production at home and abroad, the report describes concrete ways in which a range of producers in Wales can adapt, from domestic garden scale to arable and livestock farmers.

Professor Tim Lang and many others highlight the growing risk of Multi Breadbasket Failure, i.e. simultaneous failure of global staples like wheat or soya in the handful of countries which produce most of the world's supplies. Moreover, Britain depends heavily on the Mediterranean basin for fruit and vegetables, but output will fall as rainfall here keeps decreasing. However, Wales is expected to remain a viable location for producing food, provided farmers and growers adapt their practices and products.

Currently the UK produces just over half of its overall food, down from 80% in 1984. Wales is even more import-dependent, and increasing our food security is a priority for the Welsh Government. Given the terrain, soil quality and existing land use, this shift will be a major challenge that needs producers, consumers and the public sector to collaborate, and these conversations are already beginning.

Seeding our Future is a small non-profit initiative which I founded in 2017: we aim to support resilience and adaptation to climate change with communities, individuals, and the public sector. On food security, we are supporting Our Food 1200 and other pioneering work in Wales. To follow our progress and access resources from our work, see www.seedingourfuture.org.uk.

The probability of food shortages and inflation in the years ahead means that radical changes in how food is produced, distributed and consumed in Wales are urgently needed. I hope this report will assist this process.

Summary

Climate change is expected to have significant impacts on all areas of life but could particularly affect food production and food security if practices remain unchanged. Some harvests have already been affected by the changing climate and studies have indicated that more failed harvests could affect food security in the future. However, details have been lacking about what can be done locally to improve food security in a changing climate. With a focus on Wales, this report details the adaptive productive practices, crop choices and market models which could help improve local food system resilience.

This report is targeted for horticultural, arable and livestock producers of various scales and for community groups in Wales who wish to work towards greater food security in the context of our changing climate. The report does not cover housed animal farming operations.

In Wales, farming could be disrupted through warmer wetter winters, hotter drier summers, and more frequent extreme weather events such as heavy rainfalls and storms. Further, future climate scenarios are characterised by uncertainty, so there is a chance of any kind of weather at any time in the year. Climate changes are likely to bring changes to pests and diseases, some positive and others negative.

To adapt to increased aridity in summers in Wales, measures are needed to **conserve soil moisture and manage water appropriately** so as not to deplete groundwater reserves while continuing to produce food. Approaches include:

- Rainwater capture during rainier months to reduce pressure on groundwater reserves
- Better irrigation to improve efficiency
- The use of mulching and intercropping to reduce soil evapotranspiration
- The incorporation of more trees to provide needed shade for animals and crops

Warmer, wetter winters bring increased risks of soil erosion, water logging and farm runoff, which are already at unsustainable levels. Techniques to **improve water management** and **improve soil structure** could help to address these challenges. They include:

- Preventing and diverting runoff through swales and ponds
- Planting shrubs and trees along keylines to improve soil structure and reduce runoff
- Cultivating and/or soil ripping along contours or keylines to increase water infiltration
- Intercropping and the use of green manures to improve soil structure
- In some soil types, shallow till or no dig approaches, implemented without the use of harmful herbicides

The overall levels of uncertainty with climatic conditions, pests and diseases indicate that increasing diversity – at genetic, crop and landscape levels, will help increase resilience. When done well, these approaches can minimise pests and disease, support the regeneration of soils and reduce vulnerability to shocks. This can be done through:

- Using population, heritage and open-pollinated varieties
- Practicing intercropping
- Creating more diverse habitats around and within fields and plots.

Increasing the use of polytunnels has been suggested as a means of securing farming in the face of climate change. Some smaller scale producers may benefit from increased **protective cover** in the form of caterpillar or shade tunnels, and stronger polytunnels for improved storm resistance. However, large scale use of protective plastic cover could increase risks of runoff and negatively affect pollinators. The increased use of plastics may also be unsustainable from an ecological or human health point of view.

Figure 1: Increasing diversity can improve resilience in the context of uncertainty. Photo: Helen Clark

While conditions may be challenging at times, Wales is not expected to face the extreme water scarcity of many of the locations such as the Mediterranean Basin, which currently supply us with veg and fruit, nor the flooding which is predicted to affect a significant amount of England's Grade 1 farmland. There is scope for increased food production for local consumption in Wales, though increasing areas under cropping, particularly horticulture, utilising practices that foster greater resilience to changes to weather patterns and shocks, and choosing crops that will be well adapted to climate changes. It is anticipated that some crops, such as certain brassicas (e.g. broccoli, cauliflower) and orchard fruits (e.g. apples) may not be as viable in Wales with the new climate, but other crops such as certain types of squashes could become more viable. If producers adapt their practices and products, production in Wales could remain substantial and even increase. However, to ensure that farming supports local food security, other changes are needed to reorient land use towards local food needs.

To support producers to supply locally and through the challenges of climate change, local action can help **improve the linkages between producers and consumers**. Community organisations, producer cooperatives and Community Supported Agriculture schemes are some approaches which can ensure that the needs of people and the environment do not get side-lined to supply and demand economics. There is also significant scope for improving local storage and processing facilities to buffer shocks, reduce costs for producers and help shorten and decentralise food supply chains.

Farmers and growers are and always have been adaptive to changing situations and there are many examples of this already happening in Wales. However, some adaptations require upfront investments or incur greater costs in the long-term and therefore need **financial support** in the form of grants, donations or crowdfunding.

While the challenges are significant, they are not insurmountable. Innovative action and greater collaboration could turn climate change into an opportunity for growing better foods in better ways in Wales. However, without adapting our practices or our food supply chains, the threats are very real. This report details the feasible actions for producers and consumers which bring few if any risks, and which must be taken now to avoid food failures later.

1. Context

In the context of climate change, there has been concern about the ongoing availability of food supplies, including in areas of the western world which have been free from food insecurity for some time.[4,5] A 2023 study found 40% of UK food experts believe that civil unrest as a result of food shortages and unequal food distribution could happen in the coming decade.[6] Simulations have indicated that there is potential for simultaneous failures of crop production in multiple breadbasket areas of the world in the future if emissions are not urgently reduced and agricultural practices remain unchanged.[7,8] While production levels are important factors in determining food security, access to food and the ways we prioritise our resources are also paramount.

Access to food: Achieving food security relates not just to producing more (or enough) but requires a consideration of access. Research has demonstrated that incidents of famine and food insecurity have more to do with an inability to *access* foods than a lack of availability of foods themselves.[9,10] In 2023, a staggering 20% of adults in Wales experienced food insecurity in the previous 12 months.[11] People living with disabilities, ethnic minorities and families with children disproportionately experience food insecurity.[12] In the context of food abundance, this points to the insanity of business as usual and an urgent need to consider new mechanisms to ensure everyone has access to sufficient and appropriate food.

Using our resources wisely: In addition to considering equitable access, achieving food security in the context of climate change and a finite amount of land also requires consideration of what we use our resources to produce. At present, agricultural production is oriented not towards meeting the food needs of society but towards feeding into commodity markets. Just as Ireland continued exporting butter and the Scottish Highlands exported sheep during the potato famines of the 19th century,[13,14] at present, Wales uses its farming resources for commodities rather than food security. Potatoes are produced for crisps, 40% of wheat goes to animals, and maize is produced for biofuels and animal feed. Production of highly processed, 'discretionary' foods and biofuels requires significant amounts of agricultural resources and yet contribute little or nothing to human nutrition.[15,16] Further, land used to produce grain for animal feed is highly inefficient,[17] but with support could be transitioned to producing grains or pulses for human consumption. Previous examples of famine and food insecurity tell us that orienting our land use towards society's food needs is important for ensuring that we have enough food, and the right foods, for everyone.

> At present, Wales does not optimise its land use for food security.

At present, **horticulture** is only practiced on less than 0.1% of agricultural land, and horticultural production has halved in the past 40 years. Scaling up horticultural production to meet the '5 a day' requirements of the population living in Wales would require a 30-fold increase in the number of farms engaged in horticultural production. While this is a significant task, in relation to land it would only account for 2% of agricultural land.[18] For comparison, 13% of agricultural land is classified as arable, and portions of this could easily be converted to horticultural use. Further, it is likely that there exist many pockets of land within the grassland and pasture areas (together comprising 82% of Welsh agricultural land) which are suitable for cultivation, as has been the case in the Scottish Highlands and Islands.

Supporting local actions: While much work on food security needs to take place at a policy level, there is also significant scope for local action to buffer changes, demonstrate the potentials for new approaches, regenerate agricultural ecologies and contribute to improved farmer and grower resilience to climate changes and shocks. To support these efforts, this report identifies the potential vulnerabilities of the UK food system to climate change and identifies possible local approaches for improving food security which could be applied in Wales. It is based on a review of literature and on interviews with climate scientists, experts in agronomy and horticulture and discussions with innovative farmers and growers who are already testing out relevant approaches. The focus is on the crops and foods which contribute to a healthy human diet, but some of the recommendations of adaptive practices (namely improved water management, agroforestry and increasing species diversity) are also relevant to livestock farming.

2. Future Conditions and Disruptions

Climate change predictions for the UK according to the UK Climate Project in 2018[1] include a high likelihood of milder, wetter winters, and hotter, drier summers. Extreme rainfall events are expected to become more common, as are extreme heat events in summer. While the UKCP18 is considered to be the most robust set of climate projections to date for the UK (Eden, 2019), there is an element of unpredictability which must be taken into account in any future planning. More details about climate projections for Wales can be accessed via the Met Office's climate change portal. Here, we focus on the potential implications for food production in Wales.

1. Higher heat and aridity in summers

Average summer temperatures in Wales are expected to increase by up to 1.6°C by 2029 and by up to 5.4°C by the 2070s if emissions continue as they are. Heatwaves and droughts are expected to be more common. Summers in Wales could also become up to 55% drier by 2079, yet there is also a possibility of greater rainfall in summers under both high and low emission scenarios.

Combined, these changes are likely to result in significant soil moisture deficits, which could have negative impacts on the production of certain crops such as wheat, potatoes, salads, brassicas and topfruits.[19-21] It is also expected to continue to affect the productivity of livestock pastures, as experienced in recent droughts.[22,23] However, some crops will respond positively to the increased temperatures, combined with elevated C02 levels.

While summers are expected to be drier overall, there is also increased probability of high intensity summer rainfall events in future decades.

[1] Projections were updated in 2020 to correct a minor computer code error. However, no significant updates have been made to take into account the IPCC's sixth assessment report from 2023.

Table 1: Projected increases in mean summer temperatures in Wales Compared to 1921-2000[1]						
	Lower emission scenario[2]			Higher emission scenario[3]		
Years	10th Percentile	50th Percentile	90th Percentile	10th Percentile	50th Percentile	90th Percentile
2010-2029	+0.3°C	+0.9°C	+1.5°C	+0.3°C	+0.9°C	+1.6°C
2020-2039	+0.1°C	+0.9°C	+1.8°C	+0.2°C	+1.1°C	+2.0°C
2030-2049	+0.1°C	+1.1°C	+2.1°C	+0.3°C	+1.4°C	+2.5°C
2040-2059	+0.4°C	+1.5°C	+2.7°C	+0.8°C	+2.1°C	+3.4°C
2050-2069	+0.5°C	+1.8°C	+3.2°C	+1.0°C	+2.6°C	+4.3°C
2060-2079	+0.6°C	+2.1°C	+3.8°C	+1.3°C	+3.3°C	+5.4°C

Table 2: Projected changes to summer rainfall in Wales Compared to 1921-2000						
	Lower emission scenario			Higher emission scenario		
Years	10th Percentile	50th Percentile	90th Percentile	10th Percentile	50th Percentile	90th Percentile
2010-2029	-25%	-7%	+17%	-26%	-7%	+11%
2020-2039	-26%	-10%	+11%	-27%	-11%	+6%
2030-2049	-28%	-13%	+9%	-32%	-14%	+3%
2040-2059	-33%	-16%	+6%	-39%	-19%	0%
2050-2069	-39%	-20%	+5%	-48%	-25%	-3%
2060-2079	-42%	-22%	+4%	-55%	-29%	-4%

[1] Climate projections are based on probabilities or likelihoods, in a similar way to weather forecasts. They aggregate multiple models whose projections can vary considerably. The 50th percentile is most likely, whereas the range goes from 10% to 90%.
[2] Lower emission scenario assumes global emissions peak around 2040 and decline substantially thereafter (RCP4.5)
[3] Higher emission scenario assumes emissions continue to rise as they have done throughout the 21st century (RCP8.5)

2. Warmer, wetter winters

Winters are also expected to become warmer, though temperature increases are expected to be less than those of summers. Average winter temperatures are projected to increase by up to 2°C by 2049 in Wales. Winter precipitation is likely to increase by about 6% by 2049, though there is a wide range of possibilities, from a 5% decrease to a 18% increase in rainfall.

Warmer winters could affect the production of orchard fruits in Wales. For top fruits such as apples, reductions in winter chilling, essential for inducing bud break, could negatively affect floral bud development and/or result in flowering which is out of sync with pollinators.[21] However, soft fruits such as blackcurrants may be minimally affected.[24,25] Warmer winters also affect the ability to store crops at ambient temperatures. Pests and diseases which are killed off during frosts could become more persistent.

Wetter winters could translate to increased soil erosion, waterlogging and farm runoff. Both have negative impacts on soil fertility as well as impacts on surrounding watersheds. Even with today's rainfall levels, soil erosion rates are high, which not only causes economic losses in terms of clean up but also compromises the ability for soils produce into the future.[26,27] As a result of poor soil and water management, waterways and groundwater are increasingly loaded with sediment and excesses of fertilisers (e.g. nitrogen and phosphorous), causing eutrophication and flooding and also requiring costly water treatment processes.[28-31] Increases in both annual winter rainfall and in the frequency and severity of high rainfall events increase the risk of further soil erosion and runoff problems if land management is not changed. Increased rainfall in winter could also reduce load bearing strength of soils to carry heavy machinery. If not addressed, this could restrict the use of heavy machinery to late summer, which would affect cultivation and harvesting timings.

While temperatures may increase, the increased precipitation (and/or wind) in winters (and springs) may increase cold stress for livestock.[23]

While winters are anticipated to become wetter in coming decades, there is a possibility of some winters being slightly drier.

Table 3: Projected changes in mean winter temperatures in Wales Compared to 1921-2000[2]

	Lower emission scenario			Higher emission scenario		
Years	**10th Percentile**	**50th Percentile**	**90th Percentile**	**10th Percentile**	**50th Percentile**	**90th Percentile**
2010-2029	-0.3°C	0.5°C	1.4°C	-0.3°C	0.5°C	1.4°C
2020-2039	-0.1°C	0.7°C	1.5°C	0.0°C	0.8°C	1.6°C
2030-2049	0.0°C	0.9°C	1.8°C	0.2°C	1.1°C	2.1°C
2040-2059	0.1°C	1.1°C	2.1°C	0.4°C	1.4°C	2.6°C
2050-2069	0.2°C	1.3°C	2.5°C	0.5°C	1.8°C	3.2°C
2060-2079	0.2°C	1.4°C	2.7°C	0.7°C	2.2°C	3.8°C

Table 4: Projected changes to winter rainfall in Wales Compared to 1921-2000

	Lower emission scenario			Higher emission scenario		
Years	**10th Percentile**	**50th Percentile**	**90th Percentile**	**10th Percentile**	**50th Percentile**	**90th Percentile**
2010-2029	-6%	+4%	+16%	-7%	+5%	+16%
2020-2039	-6%	+4%	+14%	-6%	+5%	+16%
2030-2049	-5%	+5%	+16%	-5%	+6%	+18%
2040-2059	-5%	+6%	+19%	-4%	+9%	+23%
2050-2069	-5%	+9%	+24%	-4%	+12%	+30%
2060-2079	-4%	+10%	+26%	-3%	+15%	+36%

3. Rising sea levels

A small proportion of agricultural land may be degraded due to sea level rises which may cause flooding and/or saltwater intrusion. Grade 2 and Grade 3 agricultural land around coastal areas and near the borders could be downgraded to Grades 3 and 4, respectively, and approximately 400ha of agricultural land classed between 1 and 3a could be lost by

[2] See notes below Table 2 on page 6 for explanation.

2100 with a sea level rise of 0.5m.[32] This represents only 0.14% of agricultural land between Grade 1 and 3a across Wales. If sea levels were to rise as high as 1.5m, this figure increases to 0.6% of land classed between Grades 1 and 3a.

4. Changes to pests, weeds and diseases

Patterns of pest populations and behaviour are likely to change with the future climate, bringing greater uncertainty. Pest management expert Dr Rosemary Collier expects that some pest infestations will become more frequent, while infestations by other pests may decrease. Other studies indicate that disease epidemics will increase in severity as pathogens spread northwards with the warming climatic conditions.[33]

Genetically uniform crops (e.g. modern wheat varieties) and monoculture or monocropping type practices (e.g. one crop planted across a large area) are vulnerable to crop failure due to new and/or increased pests and diseases. High levels of genetic diversity within crops (e.g. in population varieties of wheat) and high levels of agrobiodiversity (e.g. intercropping, agroforestry, etc.) provides more resilience to pests and diseases.

Weed pressures on crops are expected to increase with climate change.[34,35] New weed species may also become prevalent, including rapidly evolved invasive weeds.[36] Practices such as intercropping and cover-cropping could help to reduce weed pressures.

5. Higher C02 Levels

As a silver lining, rising concentrations of C02 are expected to enhance photosynthesis. Experimental evidence indicates that growth of young trees could be enhanced by 30 to 50 percent in future decades due to this 'C02 fertilisation effect.'[37] This could in turn lead to increased microbial and root activity and thus improved nutrients access and availability for plants and better soil health. However, ensuring adequate yields and protecting soils depends largely on adapting practices and crops to ensure resilience against climate changes and shocks. The next section presents some of these practices. However, such increases in CO2 might affect the digestibility of pasture, and potentially decrease intake and thus productivity.[38,39]

On emissions and sequestrations

In mainstream **arable farming and horticulture**, greenhouse gas emissions stem from the use of inorganic fertilisers, slurry, pesticides, field fuel (i.e. from tractors) and from processing, storage and transport. Of these, the majority comes from the use of inorganic nitrogenous fertilisers, though the use of slurries is also significant. The emissions of organic and agroecological farms are lower, even where additional land is required for cultivation.[40] However, better management of slurry, manure and reduced soil tillage in these systems could result in even lower emissions. Localising food systems can also contribute to lowering emissions from transport.

For **animal farming**, i.e. meat and dairy production, sources of emissions include ruminal methane production (in the case of livestock), manure (in the case of all animals), the use of nitrogenous fertilisers on pastures, and the emissions associated with the production of feed crops, where animals are not raised on forage. At present, animal agriculture is estimated to account for somewhere between 8 and 18% of global emissions, depending on how much of the lifecycle is taken into account.[41] Raising animals on pasture, forage, food waste and crop residues can reduce emissions by reducing the resources needed for animal feed. It can also be a more resilient strategy given that supply of feed crops like soya and maize may reduce with climate change. Reducing nitrogenous fertiliser use for animal grazing would also reduce emissions and can be achieved by switching from monocultured grass to biodiverse pastures which include nitrogen fixing plants. Combining these lower emission practices with **reduced consumption** levels could enable animal agriculture to become more ecologically viable in the long term.[42]

There is potential for **carbon sequestration** in agricultural soils, through building soil organic matter. This can be achieved through maintaining crop residues on the land, leaving plant roots in the soil, manuring, composting, reducing erosion and reducing tillage.[43] Restoration of peat bogs can also lead to net carbon sequestration.[44] However, there are widely differing views about the potential for carbon sequestration in agriculture as a whole: some studies indicate that it could offset up to 100% of emissions, while others indicate that sequestration could be as low as 4 percent of emissions at present, decreasing to 1 to 2 percent by 2100 due to soil saturation.[45]

Cultivating woody plants (shrubs, trees) and deep rooting plants is another way of sequestering carbon and can be integrated into existing farming systems as in **agroforestry**.[46-48] Again, a saturation point is reached eventually, and the use of the trees afterwards must also be accounted for in carbon calculation – if they are burned then carbon is of course quickly re-released.

3. Adaptive practices

The extent to which climate change negatively impacts on agriculture depends in part on the methods of farming and the ability of the agricultural sector to adapt. A study of the impacts of Hurricane Mitch on agriculture in Honduras indicated that producers using agroecological approaches suffered much fewer impacts than farmers using conventional approaches.[49] The agroecological approaches which contributed to this resilience included contoured cultivation, swales and terraces for better water management; intercropping, cover cropping and mulching for building soil structure and soil organic matter; and agroforestry and habitat creation for biodiversity, reduction of runoff and pest management. The more resilient farms had also reduced or eliminated their use of pesticides, herbicides and inorganic fertilisers.

Of course, all strategies for resilience need to be context dependent. This section thus looks at the potential adaptive practices which could enable farmers and growers in Wales to become more resilient to the climate scenarios discussed above. The practices were identified based on interviews with innovative farmers, consultations with agricultural and horticultural specialists and a review of relevant literature. Table 1 provides an overview of the practices reviewed and the extent to which they mitigate anticipated climate-related challenges.

Table 1: Overview of Adaptive Practices

Approach	Reducing runoff	Reducing soil loss / building soil health	Reducing vulnerability to drought	Reducing risks from pests and diseases
i. Better water management	✓	✓	✓	✓
ii. Increased genetic diversity			✓*	✓
iii. Intercropping	✓	✓	✓*	✓
iv. Increased non-crop diversity	✓			✓
v. Improved irrigation			✓	
vi. Reduced soil disturbance and increased mulching	✓	✓***	✓	
vii. Improved crop storage				
viii. Protective cover		✓**	✓	✓

**Depends on plants selected*
***Reduces soil loss underneath the cover but could increase runoff and erosion for nearby areas*
****Depends on soil type, amendments, and practices*

i. Better water management

Given the probability of wetter winters, more frequent and more intense rainfall events and drier, hotter summers, good water management is essential to reducing flooding and soil erosion, reducing pressure on groundwater reserves and protecting against crop losses. Many practitioners of permaculture have explored a variety of methods for managing water on their sites. Popularised by PA Yeomans in Australia, the use of keylines, cultivating on contour and building swales, scrapes and ponds can be used for preventing erosion and runoff during wet times and improving water use efficiency in times of drought. Across the UK, farmers of different scales in arable, horticulture and livestock farming have started adapting these practices.

An integrated approach to water management on farms might entail the use of swales, furrows and/or vegetative strips to prevent water from simply running down off the land. Yeomans recommends that these follow the '**keylines**,' of the landscape which are 'just off' the land's contour. **Swales**, or ditches, can be integrated throughout sites to either simply hold water until it is absorbed by the soil or to channel water into ponds and reservoirs. This reduces flooding and soil erosion while also holding water on the land for longer. With the use of **ponds or underground tanks**, water can be stored for use in drier months, reducing reliance on groundwater for irrigation and increasing water availability during drought.[50] Keyline 'soil ripping' and the planting of trees and shrubs along keylines can be relatively easily integrated into grazing systems. To integrate this approach into arable or horticultural systems would require on-contour cultivation (see Figure 2).

Globally, there is evidence that **contour cultivation** reduces surface runoff, sediment and fertiliser loss in arable farming compared with conventional cultivation up and down the slope, particularly when combined with vegetative barriers such as trees or shrubs.[51-54] In arable production, contour cultivation is best suited to land with gradients of 3 to 8% as there is a risk of tractor overturning for steep slopes. At present, Defra cautions that contour cultivation in the UK could be counter-productive if the contour is not strictly followed.[55] It is also likely that a consideration of soil types is necessary to determine whether contour cultivation would be helpful. Contour cultivation has been shown to be beneficial in loamy soils, silty clay loam and sand clay loam, but evidence is lacking about its effects in heavy clay and poorly draining soils. In horticulture, arranging beds on the contour could require extra mulching on footpaths between rows in poorly draining soil, for example.

On top of capturing water from fields, there is also potential for **rainwater capture** from barn, polytunnel and other roofs. Investing in pressurising this water would make this resource more viable for summer irrigation. Finally, runoff and soil erosion in winter can be reduced or eliminated through the use of **green manures** which provide a cover over soil after the harvest of a crop (see Section iii), reducing tillage (see Section vi), and the integration of trees and shrubs, as in [agroforestry].

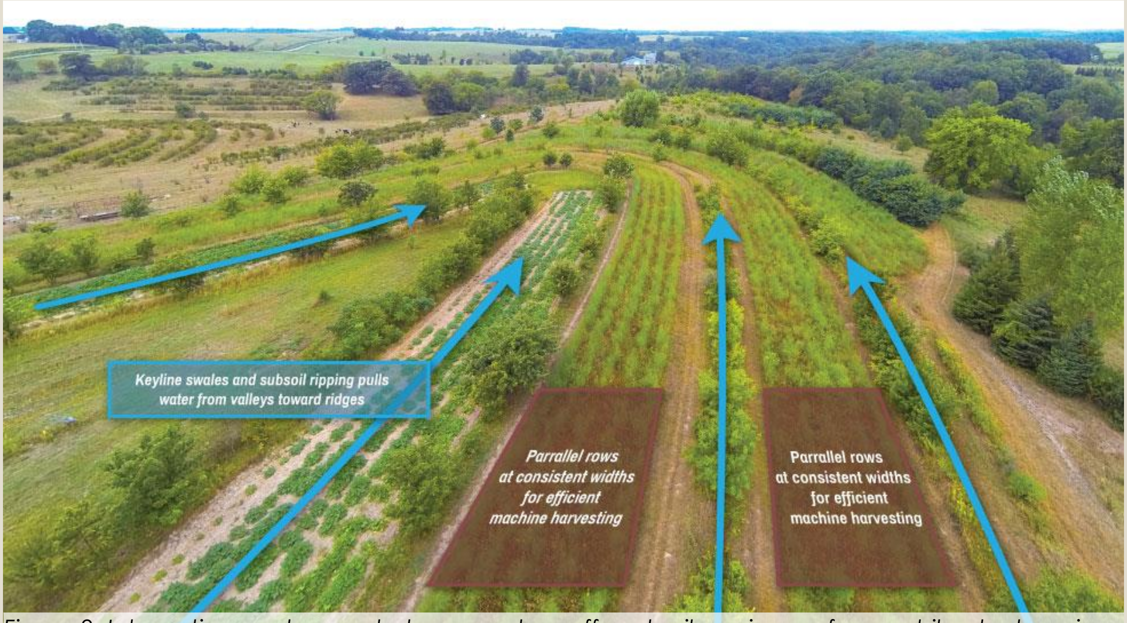

Figure 2: Integrating swales can help prevent runoff and soil erosion on farms while also keeping crops from becoming waterlogged. In this example, shrubs and trees are integrated with arable crops to absorb excess water. Image: Mark Shephard of New Forest Farm.

Case Study 1: Water, soil, community in West Wales
Henbant Farm, Tai'n Lôn Caernarfon

Henbant Farm is home to Matt and Jenny Swarbrick and their children. They moved here in 2013, adopting the principles of permaculture, with the aim of creating a place where people can believe a beautiful future does still exist.

Henbant has adopted a keyline design so that it retains as much water on the 80-acre farm as possible. Nestled in between mountains and the sea, the sloping ground means the water can be held in the landscape without the need for terracing.

This allows water to be drip fed by gravity to the crops and livestock as required which along with holistic management and permaculture methods to produce veg, eggs, milk and meat to offer customers in their on-farm shop and the veg box scheme. Using enhanced contours on the land is an effective way of not only retaining as much water as possible on the farm but it has the added benefit of reducing soil erosion, flooding, retaining soil structure as well as gathering nutrients which build fertility along the way.

Soil health is the foundation at Henbant: building and regenerating degraded soils, integrating with holistically managed grazing to produce 100% grass fed beef along with pastured laying hens and woodland raised pork. The aim is to ultimately produce dynamic and thriving ecosystems across the landscape through building biodiversity, soils and producing food. Henbant seeks to improve resilience and get closer to self-sufficiency for the farm and surrounding community. They fully explore approaches to closing the fertility loops on the farm as far as it's possible such as making composts, bio-fertilisers, compost teas, biochar, etc. Matt believes that by understanding and observing the natural patterns of the farm by trialing different methods/techniques, the land will demonstrate the best way for it to pull people here once again.

Figure 3: Henbant has applied a keyline design to manage water on the 80-acre farm.

Case Study 2: Improved water management through keylines and swales

Landnews Meadow Farm, Kent

Nigel from Landnews Meadow Farm needed to manage his water better given that his farm was located on a hill slope and was prone to waterlogging in the winter and wind erosion in the summer. He tried a combination of keyline ploughing, or 'ripping' and the creation of swales. He explains that while the keyline ploughing seemed to help, the swales in particular were more effective. He didn't find the ploughing to be as suitable for his soil as it seems to be in Australia – given that the soil is heavy clay and riddled with flintstones, Nigel explains, "when we ran the plough it looked like we had a battle with a family of moles." However, he did find that the keylines helped his water management.

The swales were dug on the contour (excavated to about a digger's bucket depth, and deeper going up the ridge), and each diverted water to a small holding pond at the top of the ridge. Whereas water had previously been pooling and flooding on his fields about 5-10 times each winter, it hasn't been happening since he made these landscape changes, with the exception of the heavy rainfall event last year.

Nigel's farm is a pasture livestock farm and thus there would need to be other considerations for putting in swales (or keyline ripping) into an arable farm. In particular, swales and ponds might need to be cleared of sediment occasionally.

Because his ponds and swales are not lined, Nigel finds that there is still dryness in the summer, but that there is a lot less erosion off the fields, so soil has been building up across his pastures. If he had more money to invest, Nigel says that he would have run the swales to a few larger lined ponds, which could be used in the summer. However, it was looking to cost about £40k for digging and lining a couple of ponds, a significant expense.

Figure 4: Swales are essentially ditches on the contour. The soil excavated to make the ditch is mounded up on the lower edge of the swale to prevent water from running over the lip. Water then percolates into the soil or can be diverted to ponds or storage.

Figure 5: Keyline ploughing or ripping allows water to percolate rather than runoff the soil. It can also be used to plant shrubs or trees to increase water absorption further. Photo credit: TreeYo Permaculture

Case Study 3: Wastewater recycling into a productive wetland

Brookside Farm, 7 acres, Warwickshire

In 2013, Brookside Farm asked Biologic Design Ltd. to create a Wetland Ecosystem Treatment or WET System, a constructed wetland, to manage and purify all of the sewage generated by the farm and to 'harvest' rainwater from the farm and the barns roofs. It comprises seven swales. The first three swales purify the sewage from the site, whilst rainwater from the barn roofs is piped directly into the fourth swale. Topsoil, rather than gravel, is used as both the purification and the growth medium for the planted trees and wetland marginals and the WET System is lined with a Geosynthetic Clay liner to protect the groundwater from the sewage. All the swale and pool banks are covered with topsoil, in which wetland species as well as productive plants such as basketry willows, fruit and nut trees, soft fruit bushes and wildflower herbs are planted. A deep layer of woodchip mulch was applied to the planted areas of the swales. This enabled the WET System to immediately accept sewage, as the woodchip acts as a growth substrate for the micro-organisms which help to break down and absorb sewage. The woodchip also absorbs nitrogen and suppresses weeds while planted species become established.

Herb plants are grown on the large adjacent field, which has a traditional ridge and furrow which has existed on the land for centuries. The farm produces herbs whose essential oils are distilled on site. The herb species which like dry conditions are planted on the ridges, whereas moisture loving plants are located in the furrows.

The Brookside Farm WET system has been successful in purifying sewage and harvesting and recycling plant nutrients while also producing biomass resources and enhancing local biodiversity. The system was inspired by Bill Mollison's work on permaculture and is more fully documented in a write up by Jay Abrahams[56] of Biologic Design. Jay also installed a similar system at Monkton Wyld in Devon, which, in addition to fruit and willows provides forage for dairy cows.

Figure 6: Wastewater treatment area before (compacted horse paddock) and 10 months after, with shrubs and other plants beginning to be established. Photo credit: Jay Abrahams

ii. Greater genetic diversity of crops

> *"I think we spent a lot of years over-complicating things when fundamentally it's very straight-forward - uncertainty is the one certain element in all future climate scenarios, and climate is only one among many challenges for future food systems. The best way to address uncertainty is through system resilience, and the easiest way to achieve that is through diversity."*
>
> *–Josiah Meldrum, Hodmedod's*

Increasing diversity is one of the best ways to reduce risk to shocks. Higher levels of genetic diversity are linked to lower vulnerabilities to disease epidemics, pest, and to climate related changes.[57-59] For each type of crop there exists a large number of varieties or cultivars. Crops such as maize exist in over 27,500 varieties. Rather than planting a single variety of a given crop, increasing the number of varieties planted improves resilience to shocks. Given that there is no singular condition to be resilient to (i.e. there is unpredictability in future scenarios), having a range of varieties is likely to be preferable to choosing one or two varieties resistant to a scenario which may or may not manifest in a given season. Further, increasing number of farmers in the UK have been using populations of wheat such as YQ and Mariagertoba which combine both considerations of yields with considerations of resilience – see Case Study 4.

In addition, heritage varieties have higher levels of genetic diversity within the variety itself. In other words, one variety of a crop, such as black oats in Wales, has more genetic diversity than one modern variety of a crop. This is because modern breeding certifications require that a variety be proven as 'uniform,' and also because modern breeding techniques lend themselves to this uniformity.[60,61] With higher genetic diversity, heritage varieties are better able to adapt and evolve to changing climatic conditions. The downside is that these varieties can produce lower yields, because in farming systems of the past, resilience was valued over yield. In the case of grains for example, heritage plants put much of their energy into better root systems. This comes at some cost to yield but has a result of greater resilience to both flooding and drought. Heritage varieties of grain are also much taller, meaning that they grow above weeds in a way that modern varieties (i.e. those developed since the 1950s) do not do. This is helpful for an agroecological system which does not rely on herbicides. In contrast, high yielding wheat varieties were bred to be shorter to support the higher mass of grains on their heads. These dwarfed varieties thus tend to be cultivated with the use of herbicides to manage weeds.

For vegetables, 'open pollinated' varieties (both heritage and new) also allow for evolution over time and can be saved by growers. Llafur Ni (Our Cereals) is a network of farmers across wales working to increase oat diversity. Wales Seed Hub (Hwb Hadau Cymru) is a cooperative selling open pollinated, ecologically produced seeds, and the Gaia Foundation runs an informal Vegetable Seed Network across Wales.

Figure 7: Llafur Ni has been reviving black oats and other heritage oat varieties in Wales. Photo: Andy Pilsbury

Case Study 4: Increasing Adaptability through Genetic Diversity in Wheat

Wakelyns Farm, 56 acres, Suffolk and many other farms using YQ population.

Normally, in a conventional farm, only one or possibly two varieties of wheat are sown at a given time. In contrast, some agroecological farmers in the UK have been cultivating 'populations' of wheat. The late Professor Martin Wolfe selected 21 wheat varieties that were important either for high yield or good qualities (e.g. resistance to drought or rust). He then crossed these for all possible combinations, resulting in about 200 different varieties, which as a population is referred to as 'YQ' or 'yield quality.' All of these varieties were sown and allowed to grow. In other words, they were not selected or reduced down by the farmer from this stage; any selection was done by 'nature in the field.'

In 2017, a comparison was conducted between the population wheat field and three monoculture fields of modern varieties. The modern varieties did not last through the difficult drilling season, but the population field was thriving. This video explains the Organic Research Centre (ORC) trial: Wheat Populations at Wakelyns Agroforestry Farm. The YQ wheat has been considered a success for baking, and also has above average mineral contents. Its flour is sold via Hodmedod's amongst other outlets.

Another wheat population is Mariagertoba, which has been developed specifically for its bread making properties. It is used by 'Cann Mills' in SW England, a grassroots collective of producers supplying locally grown and milled flour to bakers. The collective seeks to embed principles of transparency, connectivity and risk sharing in its work and has been supported by the Gaia Foundation's Seed Sovereignty programme.

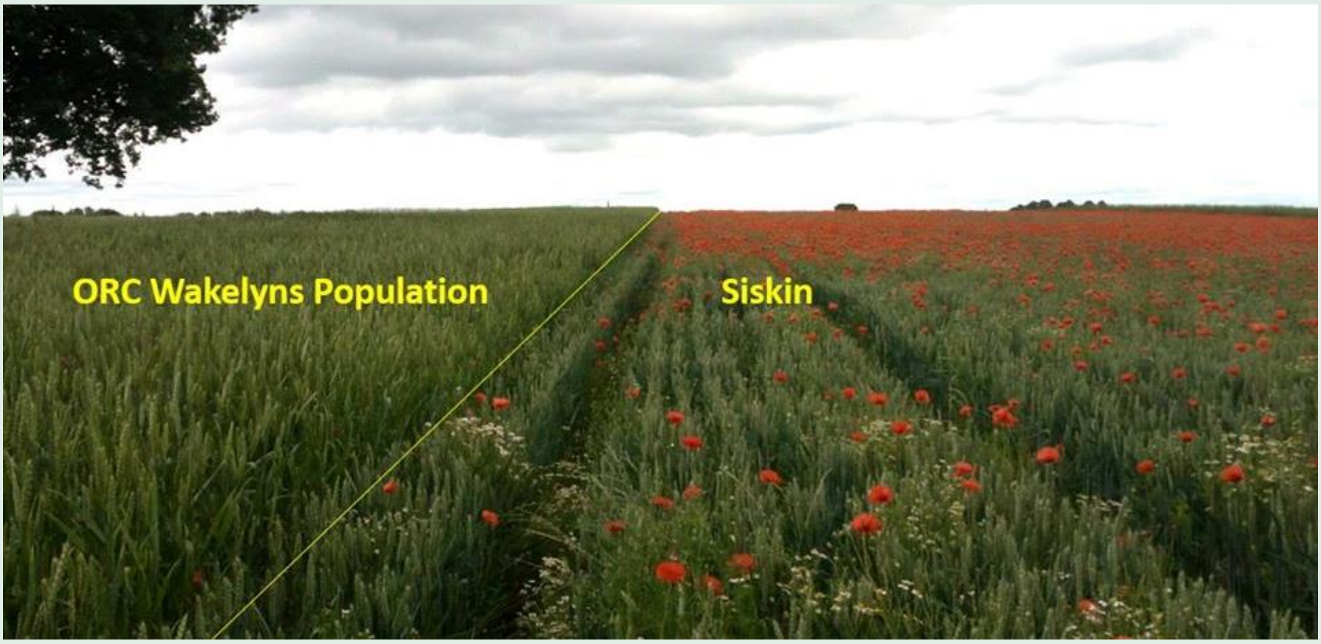

Figure 8: Data from the Liveseed farm network variety trial showed that the ORC Wakelyns Population wheat performs as a group 1 (top quality) variety, whilst yielding more than the other "conventional" group 1 varieties. Photo credit: Ambrogio Costanzo/ORC

iii. Intercropping

In addition to increasing the number of varieties of each crop, the number of crops produced and general agrobiodiversity can be increased through intercropping, the cultivation of two or more different plants in the same space. Intercropping has been shown to help minimise pests and diseases and reduce weed problems while regenerating soils.[62,63] Intercropping can also increase yields due to the better soil nutrient management. Planting cereals with legumes, for example, increases the nitrogen available to the cereals, which can help to reduce reliance on inorganic fertilisers and reduce associated leaching into waterways. Lastly, intercropping can reduce risks – if one of the crops fails, due to late frost or drought, for example, it is possible that the second crop will survive. However, intercropping must take into consideration a range of factors. Each location and soil type will require different combinations. For example, some combinations of crops result in more shading, leading to a moister canopy. This could have a positive effect in dry summers, or a negative effect in wet winters.

In arable farming, for example, oilseeds can produce lower oil content if intercropped with nitrogen fixers, though this can be made up for by increased yields resulting from the beneficial interactions. A variation of intercropping is '**relay cropping**,' in which a second crop is sown before the first one is harvested. In arable farming, this requires machinery which allows for the second crop to be planted without disturbing the first, and machinery which can harvest the first without disturbing the second.[64] **In gardening**, this is sometimes referred to as interplanting. Charles Dowding, for example, suggests that fennel can be planted before spinach is done producing, and similarly that dwarf French beans can be planted between almost-ready fennel.

Under-cropping with **companion crops** which are not necessarily harvested can reduce above ground competition (i.e. weeds), reduce pest problems and reduce or eliminate the need for fertilisers. Of course, the selection of the under-crop / companion crops depends on the soil and the main crop being sown. **For cereals**, clover, vetch and mustard are a few possible companion under-crops. See Case Study 5 for an example. Many **field scale vegetables** can benefit from an undersowing of clovers during the summer season. For corn beans, creeping and climbing vines such as squashes and cucumbers can provide soil cover while also optimising productive space. Companion crops like marigolds, nasturtiums and calendula provide benefits for many vegetables.

Under-sowing is when the second crop is not harvested but allowed to be either pasture or a cover crop for the following summer or winter, such as in the case of a '**green manure**.' Undersowing works well with mixed farms (i.e. where livestock are integrated in to arable) and is also important for both fixing nitrogen into the soil and reducing soil runoff and erosion. Late autumn plantings of veg can benefit from an undersowing of cover crops.

Green manures are valuable for improving the availability of nutrients for crops (including nitrogen but in some cases also phosphorous, calcium and trace minerals), and for controlling weeds and reducing soil erosion and runoff. Planting them via undersowing can help to address problems of timing, if the main crop is sown late. Alternatively, a rotation system with leys allows the green manures to be in the soil for longer (i.e. up to 1 or 2 years) and can thus bring more benefits to the soil. Tydden Teg, a regenerative farm near Caernarfon in north Wales, uses a 7-block rotation system including a 2 year ley on its field crops.

In terms of **pastures**, replacing monocultured ryegrass with more diverse mixes, including legumes and herbs could help counteract drought effects through increasing feeding value. They may also increase the resilience of pastures to drought, have been shown to reduce weeds and suppress disease.[65,66] However, it is not simply a matter of increasing the number of species: the kinds, amounts and arrangements of species must be carefully considered.[23,67,68]

Case Study 5: Improving yields and resilience through intercropping

Robin Griffeth, Kansas and Scott Chalmers, Manitoba

Farmer Robin Griffeth in Kansas, US plants over 15 companion crops with his sunflowers. The first year of this approach, the companion cropped sunflowers had higher yields than the monocropped ones, and in the second year the monocropped sunflowers completely failed while the companion cropped ones survived. He now only companion crops his sunflowers. Nuffield Scholar Andrew Howard suggests that in the UK, a spring oilseed rape could be planted along with low growing legumes and winter varieties of cereals.

Another example of companion cropping is practiced by Friedrich Wenz, who plants spelt wheat with red fescue, red clover and white clover. Importantly, he does not add inorganic nitrogen to this system: doing so might cause the companion crops to overtake his wheat.

Figure 9: Scott Chalmers in a field of sunflower crop undersown with vetch as a companion. The vetch provides 60kg/ha of nitrogen, 80% improved weed control, 25% improved soil organic matter and no yield deficit. Photo credit: Andrew Howard

Scott Chalmers, considered a pioneer in the area of intercropping oilseed rape with peas (referred to as 'peola' in North America), has also found that adding nitrogenous fertiliser does not increase yields. He notes that peas and oilseed rape can be mixed within the same row but not in separate rows. The mixture can also use excessive soil moisture, which could be helpful for wet conditions. Intercropping also reduces the incidence of seed borne disease and harvest split damage in peas, while oilseed rape benefits from reduced risk of shatter during wind storms. Scott tends to view the peas as the main crop and the oilseed rape as a subsidiary crop, which additionally prevents the peas from going flat by serving as a trellis. Scott also uses undercrops with his sunflowers, shown in Figure 8.[64]

Given that inorganic nitrogenous fertiliser depends on the extraction of fossil fuels (typically natural gas) in its manufacture, and contributes to climate change through the emission of nitrous oxide (N_20), reducing or eliminating its use is an important component of reducing climate impacts.[69] Further, the application of inorganic nitrogen fertilisers to farms is linked to the pollution and eutrophication of streams, rivers and lakes.[70]

iv. Increasing non-crop diversity

Increasing biodiversity between and around fields can help to reduce problems with pests and help with pollination. While cultivated fields can represent habitat loss for some species, enhancing natural habitats beyond the fields can counter these effects. This can be helpful for ensuring more balanced ecosystem dynamics, particularly of predator and prey relationships. Integrating trees around the edges of cultivated areas can also provide windbreaks, reduce soil erosion and runoff and sequester carbon while simultaneously improving biodiversity and creating new habitats.

For pest management, habitat creation and manipulation has been shown to reduce or eliminate the need for pesticides or the use of biological pest control (i.e. the release of imported exotic or mass-reared natural enemies or predators of pests).[71] The creation of habitats can supply natural enemies of pests with resources such as overwintering habitat, refuge from practices such as tillage, and additional nutrition (which has been shown to increase their fecundity).[72,73] Studies have also shown that more complex landscapes can help reduce the density and impact of pests,[74-76] though for specific pest problems, it can be helpful to work with an expert to ensure that landscapes include certain habitat features. The creation of non-crop diversity is also helpful for supporting pollinators.

Figure 10: Increasing non-crop diversity can help support predators of pests and pollinators. Photo: Elise Wach

v. Improved Irrigation

Integrating irrigation into arable production could help to overcome the challenge of higher aridity in summers. However, it is important that any irrigation consider groundwater reserves. Ideally, irrigation relies primarily on water harvested from other months of the year through rainwater and runoff catchment systems (see Section i).

In horticultural production, irrigation is already widely used but could be improved. Scheduling irrigation to match plant demand with water supply can result in 40% to 70% water savings, according to field trials at East Malling Research. Better irrigation scheduling in strawberries has also been linked to improved flavour and berry fitness.[77] Another technique for improving water efficiency in horticulture is to use 'deficit irrigation.' In this approach, less water is applied than the plant needs at each irrigation event. The roots then produce chemical signals which limit water loss from the canopy of the plant. If applied too severely, however, this approach can reduce yields.[21]

For field-scale or arable irrigation, boom irrigators are recommended over rainguns, as the latter can irrigate very unevenly, particularly in windy weather. Boom irrigators also apply water closer to the ground, reducing soil erosion and evapotranspiration losses. The most efficient type of irrigation is trickle or drip irrigation, which presents minimal risk of erosion when appropriate timings and water quantities are used.[55]

Case Study 6: Improving diversity around fields for pest management

RBOrganic Farm, 500 acres, Norfolk

Joe Rolfe at RBOrganic Farm, the largest supplier of organic carrots in the UK, generally takes a preventative approach to pest problems. However, in 2015 the farm had a massive infestation of aphids, at the same time that a few organic insecticides became unavailable for organic production. This forced them into thinking that their approaches to pest control needed to change to go beyond insecticides.

Through learning about the life cycle of aphids, including their mating patterns and habitats in collaboration with Rosemary Collier at Warwick University, they realised that they needed to enhance biodiversity on the farm as well as introduce beneficial insects. Now, 30% of the farm is out of production and hosts wildflower meadows as well as some specific plants to benefit the introduced insects. Insects introduced included ladybirds, lacewings, parasitic wasps and hoverfly. While insect introduction is typically done in greenhouses rather than at field scale, they found a complete control of the aphids within the first year with this approach.

They also learned to control carrot fly through the introduction of endoparasitic nematodes, applied via their irrigation system. This type of nematode did not negatively affect the plants but was successful in controlling the carrot fly from affecting 20-25% of the crop down to 3-5%. The introduced insects and nematodes might not have been successful if the farm did not have adequate habitats for them. The increase in off-field diversity was considered an important component in the farm's ability to address their pest problems. In ecological terms, having a host of diverse habitats is important for fostering and maintaining the biodiversity which is not only inherently important but also crucial to thriving farming systems.

Figure 11: RBOrganics switched from organic insecticides to an integrated pest management approach which includes the creation of more diverse landscape ecologies in addition to the introduction of beneficial insects. Photo: Joe Rolfe

Case Study 7: Integrating trees into farming systems

Whitehall Farm, 125 acres, Cambridgeshire, Wakelyns Farm, 56 acres in Suffolk

Agroforestry is the practice of integrating trees into farming systems. This can be done with both arable (silvoarable) and pasture (silvopasture) systems, and of course with mixed farming as well. This can range from integrating trees as windbreaks and buffer zones to the alley cropping of orchard trees, coppice trees or other varieties into crops or pasture.

Figure 12: Stephen Briggs at Whitehall Farm has integrated 4,500 orchard trees into 52 acres of his arable farm. Photo credit: L. Briggs

The on-farm benefits of integrating trees into farming systems include protection against soil erosion, reduction of runoff, and the creation of microclimates which might be cooler and more humid in the summers and less windy in the winters. Some farms can benefit economically as well, through the sale of wood or orchard fruits, for example. Animals can benefit from the shelter, reducing their energy needs, and can also nutritionally benefit from coppicing. Integrating trees can help improve biodiversity and create necessary habitats for beneficial insects including pollinators and predators of pests. Additionally, the planting of trees can help sequester carbon.

Whitehall farm, in the fens, has established agroforestry on their 125 acres. Apple trees are intercropped with combinable crops in widely spaced rows. There are 3m wide strips under the trees, which are seeded with wildflowers and other plants to encourage pollinators. The varieties of apples were chosen as they are late in maturing, allowing for alley crops to be harvested first. The trees will be pruned into a hedge-like structure to ensure that cultivation does not damage the trees.

Wakelyns farm is another site of agroforestry (see Case Study 4 for their work on population varieties of wheat). The farm has incorporated hazel coppicing, willow coppicing, fruit and nut trees and mixed hardwood into their arable farm. This yields several products, including bioenergy, nuts and fruits, timber and craft materials. The trees are also planted in rows with wide alleys (10-12m) between them.

vi. Reduced soil disturbance and increased use of mulching

Shallow till agriculture, no dig gardening and direct drilling in pastures are approaches used to reduce the extent to which soil is ploughed or dug. These approaches have been promoted for building soil organic matter, protecting soil microbiology, reducing erosion and maintaining soil moisture. Globally, studies vary in terms of the effects of minimum tillage on runoff and sediment loss of tilled vs. non-tilled field scale farming, though no-till farming shows significant differences in terms of phosphorous retention compared to ploughed farms.[51] Anecdotal evidence from Soil Association innovative farmers studies on no-till agriculture in the UK indicates that it can help reduce runoff and soil erosion.

Figure 13: In Germany, using mulches, rather than herbicides for potato cultivation has been shown to suppress weeds while also improving drought resistance and preventing runoff and erosion. Photo: Organic Research Centre

Mulching and manure matters

The availability of animal manures for mulching and building soil organic matter depends in part on the animal agriculture industry, which could see declines in the future. In any case, changes are needed to the collection and storage of animal waste. At present, much of this is mixed with water within the barns, to form a slurry, which, when applied to fields generates runoff and ammonia emissions.

Alternatives include two different approaches which are both called 'bokashi', a Japanese word for fermented organic matter. In one, the collection and processing of manure is done through **aerobic processing**, which requires adding dry materials (straw, woodchip) sources of minerals (ash, rock dust), and yeast and turning regularly for two weeks. This technique has been promoted by Jairo Restrepo, who has supported regenerative farming for decades in Latin America. However, as with composting, it requires significant labour and/or machinery for turning.

For processing manure from animals held indoors while minimising labour inputs, Innovative Farmers is running a field lab on **anaerobic processing** that can be done on site through the addition of microorganisms and additional bedding, which requires no turning.

However, no-till agriculture is often combined with the use of herbicides (typically glyphosate) to kill off the residues of previous crops and cover crops where these are used. Given the negative ecological and health impacts of glyphosate and the development of weed resistance to it,[78,79] trials have been run by the Soil Association to identify alternative methods to terminating these plants without ploughing or using chemicals. Rolling and crimping appear to be more effective than flailing, and are best undertaken when there is a frost. Alternatively, simply tilling at a shallow level can be effective. A study in Finland has shown that **shallow tilling** on clay and silty clay soils increased yields on the tested spring wheat and spring oats.[80] For **pasture**, drilling in the autumn or after land is grazed hard can offer better chances for sown seeds to germinate.

In horticulture and at garden scales, **no dig** approaches typically entail the use of either mulches or shallow tilling to terminate cover crops and suppress weeds. **Mulching** consists of applying a layer of organic matter on top of the soil, such as compost, manures, and hay and crop residues. Adding organic matter to fields in this way not only suppresses weeds but has been shown to increase earthworm numbers, improve crop yield and increase the stability of soils.[81] While mulching is typically used at garden scales, it can also be applied at field scales and can be an effective way of reducing evapotranspiration and thus improving resilience to drought. It can also reduce runoff and soil erosion during heavy rains and could be an important component of sustainable root crop cultivation. However, in the case of adding compost, there are some concerns about generating nutrient imbalances, and there are also questions about the sustainability of bringing in large amounts of compost into gardens from off-site (see Case Study 8).

Case Study 8: No-dig gardening – New Perspectives

No-dig gardening has taken off in popularity in recent years and has been promoted as a method for managing weeds, maintaining soil moisture and preventing soil compaction. Charles Dowding is one of the go-to examples of no dig gardening in practice. Charles is located in Somerset and has run a number of trials comparing dig and no dig gardening. Some of these have shown statistical differences in yields, with no dig yields being higher, despite the same amount of organic matter being applied to each area. Beds which were not dug also showed lower prevalence of weeds. Charles' website and his colleague Stephanie Haggerty's no dig blog provide details about the trials as well as helpful information about how to apply this method at garden scale.

However, there is increasing concern about the viability of no dig gardening, particularly related to the sourcing of and quantities of compost or manures brought in for garden and horticultural production. Overuse of compost can also overload soil with too much carbon and phosphate, ultimately leading to nutrient deficiencies and imbalances in microbiology. Some gardeners are finding that no dig gardening is not a viable long-term strategy on heavy soils, and that digging in green manures has been a more sustainable strategy for increasing soil fertility and improving soil drainage on these types of soils.

Figure 14: A trial comparing no dig gardening (right bed) with normal digging (left bed), by Charles Dowding. But no-dig gardening has come under question in relation to sustainability of sourcing and nutrient balances.

Case Study 9: Adaptive methods for soil regeneration

Cynefin Farm, Pembrokeshire, 7 acres

Cynefin farm is a smallholding within the Pembrokeshire National Park and is a permaculture farm and homestead exploring how to live in harmony with the natural world whilst meeting human needs, looking forward to a future living with climate change. Nim Robins moved here with her family in 2019 and she is passionate about inspiring others through permaculture education and experience, empowering and supporting people to design a regenerative, ethical and resilient lifestyle.

The site was very neglected when Nim moved here, and the once compacted and degraded soils are becoming deeper and more biodiverse through a mixture of rotational grazing (firstly with sheep, and more recently with ponies and hens) cover cropping and soil amendments. These all add fertility via organic matter, beneficial microorganisms and minerals, with the animals managed carefully to avoid overgrazing and poaching. The soil's microbiology is also supported through making and applying soil inoculants using milk and seawater. Where possible, nutrients on the farm are cycled back in - the horse manure is composted and the overgrown brambles on the farm are turned into biochar, which go into no-dig garden beds. Thousands of native trees have been planted for windbreaks, shelterbelts, wildlife corridors, future firewood and habitat, whilst integrating deep rooted nitrogen fixing plants and edible and medicinal hedgerows.

The farm retains water wherever possible through rainwater harvesting, mulching and avoiding bare soil. In this way they minimise soil erosion so that they can ensure resilience in the face of a changing climate and so that new habitats can continually develop.

Figure 15: Cynefin farm uses a combination of approaches to build soil fertility and manage water, including digging in green manures and building up no dig beds.

vii. Protective Cover

Horticulturalists utilise a variety of protective covers for improving their yields and field scale farmers are beginning to adopt these as well. While protective cover on small scale can afford many benefits, there are concerns about the widespread use of plastics on larger scales. This section is thus broken down into small scale and large scale considerations.

Small Scale: The design of **horticultural polytunnels** may need to be reconsidered in the face of climate changes. High winds pose a risk of damaging structures and summer temperature increases could also lead to overheating. Polytunnel designs which are wind resistant include Keder greenhouses and Polycrubs. However, both options are more expensive than normal polytunnels and thus represent a significant investment for growers.

Small scale producers can also benefit from the use of so-called caterpillar tunnels, which can extend the growing season and can also protect crops from insects. The caterpillar tunnels are a low-cost option for small scale producers. They can be made of either mesh (primarily for insects, but also providing some warmth) or impermeable plastic. Shade tunnels could also be helpful in instances of high heat, for certain crops.

Field Scale: To cope with the hotter drier summers, Pablo Servigne suggests that **field scale polytunnels with shading and irrigation** may play an important role in continued food security. He suggests that root crops could be grown under these tunnels. This approach is used in horticulture to reduce evapotranspiration losses, and extend the growing season. The suggestion of protective cover for arable crops is based on the premise that these benefits could transfer to field scales, in addition to reducing the negative effects of extreme summer weather (i.e. storms). Shading could help reduce extreme heat which often occurs in polytunnels.

The use of protective cover on field scale crops is famously applied in Spain, and a particular type of polytunnel, colloquially referred to as 'Spanish polytunnels' are designed for extended coverage without requiring that the tunnel touches the ground between rows (see Figure 13). This allows for workers and machinery to move between rows more easily and is also conducive to large scale irrigation systems. These tunnels have been applied to the strawberry industry in England. Large scale strawberry growers claim that the use of the tunnels reduces the amount of fungicide normally applied to their crops. However, the University of Hertfordshire did not find that strawberries under protective cover used lower quantities or frequencies of fumigation.[82]

Figure 17: Spanish style polytunnels join without touching the ground allowing for field-scale use. Photo: David Smith

In addition, when plastic is used at scale, the **runoff effects** can be very significant. If used at field scale, polytunnels or other plastic coverings would need to be combined with a rigorous water management system (see Section i, above). Further, the large-scale use of plastic coverings on crops could have a negative effect on insect populations, including but not limited to pollinators. Given the intricate nature of ecological systems, it is worth assessing the potential ecological effects of field scale tunnels and the extent to which they might prevent the access of pollinating species to food sources and in turn affect other plant and animal species dependent on these insects. Lastly, there are concerns of course about increased plastic usage (see box below).

Figure 18: The region of Almeria in Spain is home to 30,000 hectare of plastic covered land and is known as the 'sea of plastic.' This aerial photo gives a sense of the scale of use of polytunnels. Photo: NASA/Wikimedia

Plastic mulches are already widely used in horticulture in the UK, including in organic production. Through suppressing weeds, they reduce or eliminate the need for herbicides. Through covering the soil, they help to reduce water requirements and reduce soil erosion and the runoff of soil and/or fertilisers. They also warm the soil and thus extend the growing season. Plastic mulches thus offer some benefits for coping with high rainfall events, reducing water needs during droughts and increasing production. However, as with polytunnels, the high usage of plastics poses some environmental sustainability concerns. As an alternative, the Soil Association's Innovative Farmers initiative is trialling biodegradable films and natural mulches (i.e. woodchips and grass clippings) in collaboration with the Centre for Agroecology, Water and Resilience. In addition, green manures and intercrops, as discussed in Section iii, could be an important option for arable farmers.

Shade can also be provided through increasing the integration of shrubs and trees into agricultural systems (i.e. **agroforestry**), which can be beneficial for livestock and certain crops as well as protecting soils and sequestering carbon.

Problems with Plastic?

Plastics used for mulching and for polytunnels may provide some benefits for cultivation but also come with environmental disadvantages. Plastic mulches and polytunnel skins require high levels of energy and water to manufacture, even when made from recycled materials. In China, the energy and water costs associated with recycling the films add up to be more expensive than manufacturing films new from fossil fuels.[1] Plastics are also found to leach chemical residues such as phthalates into soil and water,[2] which can have adverse effects on both ecological systems and human health.[3]

ix. Improved and localised storage and processing

While the above adaptive measures have the potential to reduce risks of crop failures from climatic conditions, agriculture always entails a degree of risk and uncertainty. That uncertainty is expected to be greater with future climate change scenarios. To buffer potential shocks, certain crops such as cereals and legumes can be stored for one year or longer. While many countries previously had nationally funded grain drying and storage facilities, these have since been privatised and the UK is no exception. With globalisation, the incentives to store grain over extended periods of time have decreased. Thus, farmers tend to either store on site (often in sheds which are used for other purposes for part of the year), sell their grain, or store it in cooperatives. Pooling resources for drying grains—which is a significant expense for farmers—could help allow for grain to be used for human consumption and be stored longer.

> "Pooling resources for drying grains—which is a significant expense for farmers—could help allow for grain to be used for human consumption and be stored longer."

Grain and legumes for animal feed does not need to be as dry as that used for human consumption and thus many farms producing animal feed have not developed the capabilities for cleaning and drying grain to standards required for human use (see Case Study 10). Storage for other crops also needs to be considered. Squashes, onions, potatoes and similar crops need to be stored for several months at a time. It has been estimated that most existing seed and crop storage facilities would need to be improved to account for changing moisture and temperature levels.[19] Warmer winters in particular pose new challenges to crop storage (see Case Study 11).

In Dorset, Tamarisk Farm in Dorset is one example of local processing of grains and pulses, where wheat and rye are grown, cleaned and milled on site and where a new barley polisher means that pot barley can also be sold direct to customers. Also in Dorset, Fivepenny Farm hosts a producers cooperative for processing (primarily apple pressing and bottling, cheese making and meat processing) which saves producers the cost of having to invest in both equipment and environmental health certifications individually. In addition to buffering against shocks and losses, more local storage and processing facilities would help to decentralise the food system and prevent all our eggs from being in one basket, so to speak.

Figure 19: Local storage of harvests is an important consideration for food security and may become more challenging with climate change. Photo: Wikimedia

Case Study 10: Local Grain Processing and Storage

Transition Town Totnes

As part of the Transition Town movement in Totnes, a local group of citizens got together to try to localise grain production for human consumption. All the farmers in the area were producing grain for animal consumption and recalled that their parents had done the same. As there was no infrastructure in place for the storage, processing and milling of local grains, the group organised to provide this. With £100k funding from Esmée Fairbairn to cover salaries and equipment, they rented a small industrial unit and purchased a dryer and a mill. Their learning curve was steep, and they are writing up a guide to the process now (to be available on Grain Lab).

Challenges they faced included the following:

- **Different standards**: Standards for 'clean and dry' grain are lower for animal consumption than human consumption. Farmers in the Wales tend to lack facilities to dry and clean grain to the level required for human consumption.
- **Transport costs**: Transport costs of grains are very high. Given that grains are very cheap in the market, it was not economically viable to send them further afield and they therefore had to sell their flour very locally.
- **Steaming vs. drying**: Rolled oats (and other rolled grains) are normally steamed upon rolling in order to prevent them from going rancid once their oils are exposed to the air. As the group did not have the facilities to both dry and steam grains (you can't do both in the same place!), they did not steam them. To maintain freshness, Schumacher college, who had purchased some of the oats, kept them in the freezer.
- **Sorting grains**: They encouraged their farmers to intercrop wheat and peas, which gives a better yield. However, the farmer did not separate the crops post-harvest. The group tackled this labour-intensive job by throwing a party and enlisting community support to separate the grains.
- **Baking needs**: Bakers need time to adapt their recipes and baking processes to different grains. This was a barrier for a local baker who in principle wanted to try the new grains but did not find the time to trial them.
- **Contractor constraints**: Keeping the grains free of pesticide (and gluten in the case of oats) posed challenges for harvesting and seed cleaning, as equipment is owned and managed by contractors who service all the grain farmers in the area. Combined with their small amount of land, this meant the group was on the bottom of the priority list and some of their oats were not harvested in time.

As words of advice, one member of the organising group stated, '**It's all about relationships** - for example, plants and the soil, one place and another. Whichever relationship it is, it needs to be looked at and understood. Anywhere that money is involved there probably needs to be a contract of some description.' Charlotte believes that local grain projects like this are feasible (and hopes to prevent other groups from repeating their errors) but they do need extra funds to get up and going.

In Wales, the Welsh Grain Forum is a community of growers, millers, bakers, maltsters, brewers, thatchers and friends committed to using and promoting Welsh grain.

Case Study 11: On-Farm, Off-Grid Crop Storage

Chagfood, 6 acres, Devon

Chagfood is a Community Supported Agriculture (CSA) farm in Devon which started in 2010 and has experimented with various crop storage arrangements over the years. As the farm is off-grid, they have no access to refrigerated storage. For the first few years they only stored their produce in an uninsulated garden shed. While they attempted to protect crops like squashes from frost by wrapping them in several layers of fleece, they were still losing a significant amount of their harvest.

They later tried storing their potatoes in a root clamp, based on what people had done in the past in the area. A root clamp is a mound of root crops covered with soil, straw and/or other materials in the field. However, they soon discovered that winters in the 20s and 30s, when this technique was popular, were much colder and drier than winters today. Unfortunately, their potatoes went mouldy in the warm and wet winters of today.

Figure 20: An uncovered root clamp of sugar beet. Today's climate is becoming less suited to this approach. Photo: Markus Hagenlocher

The following year they stored their produce in the threshing barn, which was dry, but had a problem with rats. While they stored their harvests in wooden crates lined with chicken wire, they still lost 40% of their harvest. Next, they tried bagging their harvest in 25kg sacks with sand on top and storing them in a shipping container. The container was rat proof, but it was not free from frost or damp. The temperature of the root crops after harvest seemed to cause condensation in the container.

From there they tried using a passive cellar, which was fine for frost and condensation but once again had a problem with rats. They lost 70 to 80% of their squashes in the week between Christmas and New year to rats. One of the founding directors of Chagfood, Ed Hamer toured small-scale farms in the north-eastern part of the US to find out how they stored their produce. He found that most people used underground cellars (located under homes and thus frost free) but that they all had plenty of cats around to control the rats.

Now, Chagfood has access to an insulated shipping container. Once used as a meat chiller, it has a proper rubber sealed door which means no rodents. In the summer they use it as a chiller to store their leafy greens and other vegetables and in the winter, they use it as a root store. They are a bit concerned about ventilation, however, and will need to work out a system to avoid condensation.

Overall, Ed hopes that the experiences at Chagfood can help prevent other small farms from losing their harvests. He stresses the need for crop storage to be free of damp, frost and rodents. Even one of these three factors can cause significant post-harvest losses.

4. Potential food disruptions and alternatives

Estimations of food security problems due to climate change tend to be based on models which seek to predict the effects on existing crops, based on existing production practices, varieties and locations of production. What these models do not account for is that farming practices and products can, and inevitably must, adapt to changes to the climate. The adaptive practices discussed above can help increase resilience to climate shocks. Further, the regions suitable for certain crops will shift, which is not always considered in modelling. Lastly, many models predict decreases in food availability based on an anticipated increase in food prices,[83,84] but government and local intervention have the potential to help to avoid a situation in which prices determine food access and instead ensure that everyone has access to adequate healthy food for a nutritious diet.

While there is a great deal of uncertainty about future scenarios, this section identifies the potential for the production and supply of mainstay foods to be disrupted, the adaptation measures which could ensure continued supply in Wales, and the new crops which could potentially become more viable in future climate scenarios. At present, the UK produces approximately 60 percent of its own food. In terms of imports, nearly 70 percent come from EU25 countries. This section therefore focuses primarily on the possible changes to agricultural production in the UK and Europe, with consideration of other major food suppliers to the UK where notable.

For a plant-based diet, the main sources of nutrients are assumed to come from tubers, cereals, peas and legumes, vegetables, fruits and seeds and nuts. These staples had been included in Simon Fairlie's 2008 update[85] on Mellanby's 1975 book, *Can Britain Feed Itself*?

i. Tubers and root crops

Roots and tubers provide large amounts of calories per unit of land and are also the plants which are likely to have a strong positive response to increased C02 levels. Their ability to benefit from carbon is expected to balance out the negative effects of drought and temperature changes[86] though care is still needed to reduce risks from extreme weather events and pests and diseases. Further, even in today's climate, when root crops are cultivated without intercrops or the use of mulches, soil erosion and runoff can be a significant cause of flooding and soil loss.[87,88]

Potatoes are of course one of the most consumed foods in Wales at present. Warmer winters are not expected to negatively impact on growth or yield of potato crops and warmer summers may increase yields. As with all root crops, they are expected to benefit from increased C02 levels. However, water is one of the limiting factors potato cultivation of potatoes and other root crops such as beetroots and drought can significantly impact on potato harvests. A simulation for Ireland indicated that maintenance of current potato yields would require irrigation to a level of 150-300mm per year. Mulching, in combination with other practices to build soils, could help prevent both drought-related losses and reduce the need to irrigate. **Beetroots** on loam soils are likely to be less vulnerable to drought than those grown on sandy soils, which are less common in Wales.[89] **Onions** may be negatively affected by the higher temperatures but their response to C02 levels could level this out.

Going beyond potatoes, other crops which could help diversify the food base include **winter radish** and **salsify**. For all root crops, additional care might be needed for winter storage as ambient stores may not be cool enough to maintain quality.[90]

Crop	Climate change impacts	Adaptation measures needed
Beetroot	• Warmer summers and increased C02 may increase yields • Summer droughts may pose problems • Warmer winters may affect storage	• Use mulches to reduce evapotranspiration and runoff • Consider irrigation systems for extreme drought • Consider cold storage in warm winters • Adapt better water management systems
Carrot	• Production likely to benefit from warmer summers and increase availability of C02 • Can be negatively affected by drought • Patterns of pests could change	• Increase / foster landscape diversity to protect from pests • Consider mulching to reduce water needs
Onion	• Could be negatively affected by heat but this could be offset by increased C02 availability	• Consider cold storage in warm winters
Parsnip	• Warmer summers and increased C02 may increase yields • Summer droughts may pose problems • Warmer winters may affect storage • Patterns of pests could change	• Use mulches to reduce evapotranspiration and runoff • Consider irrigation systems for extreme drought • Consider cold storage in warm winters • Adapt better on-farm water management • Increase / foster landscape diversity to protect from pests
Potatoes	• Warmer summers and increased C02 may increase yields • Summer droughts may pose problems • Warmer winters may affect storage	• Use mulches to reduce evapotranspiration and runoff • Consider irrigation systems for extreme drought • Consider cold storage in warm winters • Adapt better on-farm water management
Salsify	• Can be grown in a variety of soils (preferably stone free) • Can be affected by summer droughts • Bolting can occur in summer heat but can be mitigated through bolt-resistant varieties	• Use bolt-resistant varieties • Consider irrigation in drought • Consider cold storage in warm winters
Swede	• Warmer summers and increased C02 may increase yields	• Use mulches to reduce evapotranspiration and runoff
Winter Radish	• Relatively pest and disease resistant • Winter varieties are large, mild and suited to cooking	• Consider cold storage in warm winters

ii. Grains

Grains comprise a significant portion of the diet in Wales and the Eatwell Guide has recommended an increase in the proportion of the diet coming from grains and other starches for better public health.

> "If wheat production were only oriented towards direct human consumption for a healthy diet, only about half as much wheat would be needed in the UK."

The main grain consumed in Wales at present is **wheat**. A total of 11-16 million tonnes of wheat is produced per year in Britain, most of which is winter wheat (sown in autumn). The UK is a net exporter of wheat, though also imports some varieties (15-20% of milling requirements) for their particular breadmaking qualities.[91]

About 40% of UK wheat is used for animal feed, and a significant amount of wheat is also used to produce glucose.[3] Further, much more white bread (50g per person per day) is consumed than wholemeal bread (18g per person per day). There is thus significant scope for optimising the nutritional outcomes of grain production and consumption. If wheat production were only oriented towards direct human consumption for a healthy diet, only about half as much wheat would be needed in the UK. Similarly, maize in the UK is grown primarily for biodigesters or animal feed, barley is produced primarily for animals and 1/3 of oats produced are for animal feed. Thus, there is scope for improving food security by reorienting grain production to human consumption. This requires producing different varieties in some instances, and improving drying, storing and processing facilities (see Section 3).

Improving diversity and supporting the emergence of climate adaptive varieties of grains may help to reduce vulnerabilities. Older varieties are also less reliant on high quantities of inorganic fertilisers and pesticides and are thus more ecologically viable in the long-term. While the yields of these varieties tend to be significantly lower, it is possible that any trade-offs in yield could be balanced by increasing the use efficiency of wheat production (i.e. not feeding it to animals or turning it to glucose or ultra-processed foods). In addition to diversifying the varieties of wheat itself, there is scope for other grains to be produced more. Rye, buckwheat and quinoa are minimally produced in the UK at present, but their production could be increased to diversify the grain base for greater climate resilience. In the table below, wheat is listed first as it is the main grain produced, and other grains are listed alphabetically.

Crop	Climate change impacts	Adaptation measures
Wheat	• Warmer drier summers could increase yields but extreme climate events (e.g. high temperatures, drought and overly wet weather) may threaten crops. • Wheat stem rust could increase, and only 20% of the wheat varieties commonly grown in the UK are resistant to this rust • Modern varieties are dependent on the use of synthetic fertilisers and phosphates. However, nitrogenous fertilisers are based on fossil fuels and supplies of phosphates from Morocco could decrease.	• Orient production more towards human consumption and less towards animal consumption • Orient production towards less processed foods • Increase the diversity of varieties produced, including via populations • Improve farm drainage and water management • Consider intercropping for better soil health • Utilise green manures to reduce reliance on nitrogenous fertilisers

[3] 1.4 million tonnes of grains are used annually in the UK to produce glucose and starch

Crop	Climate change impacts	Adaptation measures
Amaranth	• High heat and drought resistance • Grows best in well-drained loam but can also be cultivated in poorly draining clay soils • Responsive to nitrogen levels, so consider using a green manure • Leaves can be used as a vegetable	• Use green manures to reduce nitrogenous fertiliser needs
Barley	• UK productivity could increase in projected climate conditions, but extreme climate events may threaten crops	• Same as for wheat
Buckwheat	• Quick growing crop • Does not require highly fertile soils but does benefit from moderate amount of nitrogen • Can tolerate wet soils but does better with well drained soils • Low susceptibility to pests and diseases	• Consider increasing production • Use green manures to reduce nitrogenous fertiliser needs • Consider intercropping (e.g. with sunflower)
Maize	• Could benefit from warmer, drier summers • Wetter winters increase the risk of soil erosion and runoff	• Same as for wheat, and, • Only plant if under-cropped with a winter cover or green manure given high erosion risks[92]
Oats	• No specific threats to oats themselves, though land competition could decrease global supplies • Heritage varieties are being revived in Wales	• Same as for wheat, and, • Increase production to diversify grain base
Quinoa	• High in protein, not technically a grain • Production occurring in Shropshire but not yet significantly in Wales • Grows best in well-drained loam but can be cultivated in other soils • Leaves can also be eaten	• Consider sowing an undercrop to prevent blackgrass or fat hen from taking over[93] • Use green manures to reduce nitrogenous fertiliser needs
Rye	• Drought tolerant and relatively high resistance to diseases • Benefits from warmer winters • Majority of UK rye currently cultivated for biodigesters, livestock or unharvested cover crop	• Same as for wheat, and, • Increase production to diversify grain base

iii. Legumes

At present, legumes such as beans, peas and lentils do not form a significant part of the British diet. However, legumes are an excellent source of plant protein and increase the availability of nitrogen in soils and are thus an obvious choice for agricultural scenarios which entail less animal agriculture and improve soils. The majority of legumes produced in the UK are currently used for animal feed. However, there are initiatives seeking to increase the production of peas and beans for human consumption. In 2012, Suffolk based Hodmedod's formed to stimulate and assess demand for indigenous pulses. From their first trial of fava beans in partnership with Transition Norwich, it has now expanded to other lesser known pulses such as 'Black Badger' Carlin Peas, which make an excellent substitute for chickpeas. They also source grains from English farmers including Martin Wolfe's 'YQ' population variety of wheat and British quinoa. The Transition Totnes group included peas in their local grain initiative and sold pea flour in their local shops. There is scope for much more local production and consumption peas and beans, and for these to be integrated into multi-cropping systems (e.g. intercropped with grains or oilseeds).

The production of peas and beans could be affected by pests spreading north and possibly also by powdery mildew during hotter summers. Choosing heat tolerant varieties, increasing the number of varieties produced, building in landscape-level diversity and using intercropping and mulching are ways to continue and expand pea and bean production in Wales in the face of climate change.

Crop	Climate Impacts	Adaption Measures
Peas and Beans	• Temperature changes increase risk of powdery mildew • Some risk of Bruchid pea beetle extending to Wales from France • Negatively affected by drought	• Increase / foster landscape diversity to protect from pests • Consider intercropping with grains, sunflowers, etc. • Consider mulching for soil moisture conservation • Use a diversity of varieties for resilience

iv. Fresh Fruits and Vegetables

At present, the UK supplies 55% of its own fresh vegetables, and 17% of its fresh fruit, by monetary value.[94] Domestic production of fresh fruit and veg has fallen by 60% since 1990, though demand has increased during this time. Water availability is a key issue for continued supply of UK's fresh fruits and vegetables. Research from the University of East Anglia has found that current supply of the UK's fresh fruit and vegetable supply requires 550 million cubic meters of freshwater each year, the majority (76%) of which comes from the production of these foods overseas. Much of this is from areas which are already water stressed and are expected to see increased water scarcity in the future (e.g. Spain, Egypt and Morocco).[95,96] Imports from the Netherlands are also significant (14% for veg and 4% of fruit) and the Netherlands has a similar water profile to the UK.

Given that relatively less water scarcity is anticipated for the UK than for other regions, increasing domestic horticultural production could be an important strategy for improving food security. This would also reduce carbon footprints in cases where fruits are air-freighted to the UK. However, careful water management—through mulches, intercrops, water harvesting, improved irrigation, etc.—would also be needed to prevent depletion of groundwater stores. Even farms in the highest rainfall areas of the UK such as Tyddyn Teg have needed to invest in more in irrigation systems in recent years.

In Wales, production of cauliflower, and broccoli could be negatively affected by warm winters (i.e. affecting curd initiation), wet winters (blindness can occur if soils are waterlogged) and hotter summers (i.e. drought can cause blindness and heat stress can cause buttoning).[90,97] Again, these crops might be better suited further north.

The production of salad and other leafy crops is likely to improve in spring and early summer. However, higher heat later in summer and extreme heat events could result in lower yields due to increased bolting. Water availability is again, a concern.[90]

Fruit cultivation is experiencing somewhat of a revival in Wales. Fruit production has been in steep decline over the past century in the UK, including in Wales, but from 2010 to 2015, the amount of land used for orchards and small fruits increased by 16% in Wales. In some areas of Wales, however, warmer winters may affect apple production. It might be possible, however, to produce more apricots, nectarines, plums and grapes. However, the unpredictability of frosts and storms could affect these. For shrub fruits such as currants, it is unclear whether milder winter temperatures will negatively affect them,[24,25] but in any case will require good management of water and soil. There could also be more scope for utilising hedgerow fruits such as rosehips, hawthorn berries and blackberries, all of which are sources of vitamin C.

In short, the production of some vegetables and fruits may be negatively affected by climate change but others might benefit. There is scope for increasing domestic production of fruit and veg, particularly as supplies from overseas may be disrupted due to water scarcities.

Crop	Climate Impacts	Adaption Measures
Vegetables		
Brussels Sprouts	• Expected to be negatively affected by warm, wet winters and hot summers	• Shift production north and reorient to other vegetables in the south
Broccoli	• Expected to be negatively affected by warm winters, wet winters and hot summers • Water shortages may jeopardise supplies from Spain and other arid areas	• Reorient to other vegetable options
Cabbage	• Could be negatively affected by different pests and warmer wetter winters	• Intercrop for reduced pest loads • Utilise better water management to avoid waterlogging
Cauliflower	• Can be easily damaged from hail • Reduced risk of damage from frost • Curd initiation can be affected by changing temperatures, particularly for winter cauliflower[98,99]	• Consider different varieties for addressing curd development
Green bean	• Temperature changes increase risk of powdery mildew • Some risk of Bruchid pea beetle extending to Wales from France Negatively affected by drought	• Increase / foster landscape diversity to protect from pests • Consider mulching and/or intercropping • Use a diversity of varieties
Kale	• Some varieties could be negatively affected by hotter summers / autumns	• Incorporate greater diversity of varieties
Leafy greens & salads	• Production could improve in spring and early summer with warmer temperatures • High heat later in summers and extreme heat events could cause bolting • Water shortages may jeopardise supplies from Spain and other arid areas	• Increase domestic production • Improve efficiency of irrigation • Utilise mulches to reduce evapotranspiration losses
Leeks	• Bare soil between crops can result in soil erosion and runoff • Occasional dry springs can reduce yields • Yields can be reduced by higher winter temperatures	• Consider intercropping and mulching to reduce soil erosion and runoff in winters and conserve water in spring • Improve on-farm water management • Consider different and more diverse varieties
Peas	• Temperature changes increase risk of powdery mildew • Some risk of Bruchid pea beetle extending to Wales from France • Negatively affected by drought	• Increase / foster landscape diversity to protect from pests • Consider mulching and/or intercropping • Use a diversity of varieties

Squash	• Some varieties could become more viable with climate changes (e.g. butternut) • Can be damaged by hail	• Consider intercropping to improve soils and diversity • Increase varietal diversity • Consider cold storage in warm winters
Tomato	• Water shortage may jeopardise supplies from Spain and other arid areas • Pests such as spider mites could become more prevalent	• Increase domestic production but keep it seasonal • Improve biodiversity to mitigate pest problems

Crop	Climate Impacts	Adaption Measures
Fruits		
Apples	• Warmer winters may affect budding	• Consider varieties which require less winter chilling • Train branches more horizontally for better budding • Consider shifting production further north
Apricots	• Increased temperatures could improve viability • Vulnerable to hail and late frosts	• Consider introducing but be aware of risks
Black currants	• Warmer winters may affect budding though this is not certain	• Consider varieties which require less winter chilling • Consider shifting production further north
Grapes	• Increased temperatures could improve viability • Late spring and heavy rainfall in summer can damage growth	• As with apricots, above
Hedgerow Fruits	• Rosehips, hawthorn berries, blackberries, etc. are nutrient rich and could be utilised more	• Consider increasing use of hedgerow fruits, but ensure harvesting levels are sustainable.
Nectarines	• As with apricots, above	• As with apricots, above
Pears	• Warmer winters may affect budding	• Consider varieties which require less winter chilling • Train branches more horizontally for better budding • Consider shifting production further north

v. Oil Seeds and Nuts

The main sources of fat in the UK diet come from meat, dairy, fish, and culinary oils. Discretionary foods such as cakes, crisps and highly processed foods are also significant contributors. The main types of culinary oils consumed globally are palm, soya, rapeseed and sunflower seed oil. Oil palm is considered to have a strong impact on climate change due to associated deforestation of tropical areas. Climate change could in turn affect the production of palm oil through for example, the spread of fungal diseases.[100,101] Global oil palm production is highly geographically concentrated (in Malaysia and Indonesia), and is thus vulnerable to climate changes. However, expansion of oil palm to other areas poses a risk of deforestation, exacerbating climate change and other ecological damage.[102] It is unlikely that a reliance on palm oil is sustainable or resilient. Soya production is also characterised by unsustainable practices (i.e. high usage of herbicides, pesticides, inorganic fertilisers and monocultures) and is associated with deforestation. The soya value chain is highly concentrated, with agrichemical companies controlling production and a small number of traders (e.g. ADM, Budge, Cargill, Louis Dreyfus) controlling purchasing and distribution between farmgate and retailers.[103] While there are attempts to increase soya production in Europe, levels are still low. The majority (80%) of soya is used for animal feed.

In the UK, at present, the only oilseed crops produced and processed are oilseed rape, hempseed and linseed, though their production is not focused primarily on human consumption. Sunflower production in Southern Europe is likely to be affected by drought, but future climate change scenarios indicate that sunflower production will become increasingly viable in England and Wales. In addition, the consumption of nuts from hazels, sweet chestnuts and walnuts could provide an additional source of dietary fats.

Crop	Climate Impacts	Adaption Measures
Linseed and Hemp	• Good sources of essential fatty acids (Omega-3 and -6) and protein • May be negatively affected by summer droughts and extreme rainfall events • Production currently oriented towards their fibres and animal feed[104]	• Reorient production towards human consumption and/or consider increasing production • Utilise intercropping, mulching and better water management to conserve soil moisture and reduce erosion
Nuts	• Hazels, sweet chestnuts and walnuts could become more commercially viable in Wales in future climate scenarios • Nut trees require several years to begin fruiting, so planting must be future oriented	• Consider increasing the planting of nut trees • Consider integrating nut trees into agroforestry systems
Oilseed rape	• Warmer winters could increase the spread of phoma stem canker, reducing yields[105,106] • Production largely oriented towards biodiesel[107] and animal feed	• Reorient towards human consumption • Consider shifting production to northern England and Scotland, where yields may increase
Palm	• Supplies are currently unsustainable and likely to be disrupted	• Switch to other sources of fats
Soya	• As with palm, above	• As with palm, above
Sunflower	• Production in southern Europe likely to be negatively impacted by drought[108] but could become viable in parts of Wales and in southern England[109] • As with oilseed rape, much of its production is oriented to biodiesel	• Reorient towards human consumption • Utilise intercropping, mulching and better water management to conserve soil moisture and reduce erosion

5. Economic challenges and local alternatives

Many of the techniques, approaches and varieties which could allow for better adaptation to climate change require additional investment in labour, equipment or other costs. In addition, practices which can increase resilience may decrease yields per hectare for certain crops such as grains. Further, while these adaptive practices could play an important role in improving food security in the face of climatic changes and shocks in the future, they cannot be implemented overnight. Investments are needed today to safeguard the future of food and farming tomorrow. This section considers some of the economic considerations of adapting the food system and suggests a few ways in which the economic challenges of transitioning could be overcome at local levels.

1. Economics

Orienting farming and horticulture towards food security requires a departure from allowing markets to determine production and access based on 'supply and demand.' Extra support is needed to allow farmers to produce what is needed by society, which may not necessarily be what offers the best rate of economic return. Similarly, support is also needed to ensure that all of us have access to nutritious foods, and not just those who can pay.

"Climate change is a long-term issue, and some of the production practices which have greater ecological viability in the long term may come with greater economic costs."

Climate change is a long-term issue, and some of the production practices which have greater ecological viability in the long term may come with greater economic costs. Production systems which require low levels of inputs such as pesticides and inorganic fertilisers tend to require higher levels of labour.[110] This might include manually plucking off pests instead of spraying and spreading mulches and manures rather than spraying slurries or fertilisers. However, in economic terms, high labour requirements drive up the monetary cost of food production. **Additional support to producers to allow them to utilise more people per hectare could increase the feasibility of applying some ecologically sustainable practices.** It could also help with rural employment levels.

Further, many small-scale producers do not produce staples such as potatoes, onions and cabbages because they cannot compete with larger, industrial scale operations which rely on mechanisation. However, smaller scale operations can help to utilise some land more efficiently through allowing productive pockets of land to be cultivated which would otherwise be unsuitable for mechanised production. Mechanised production also precludes some types of practices which could be important for adapting to climate change, such as high levels of diversity, some types of intercropping and in some instances on-contour cultivation. Additionally, some of the practices which could facilitate greater resilience to climate shocks require upfront investments. As seen in Case Study 10 in Totnes, many grains and legumes are produced for animal feed in part because less processing (i.e. drying and cleaning) is required, reducing the costs of their production. **Producers may need financial support to reorient towards the production of dietary staples that may not necessarily be as *economically* valuable but have a great value to society.**

Many of the projections about food security in the context of a changing climate assume that markets will determine access and that price increases will thus threaten food availability for those on low incomes.[111] It does not need to be this way. Local and national action can help to ensure food access for all, regardless of commodity prices.

In sum, competitive markets pressure farmers to produce goods which are not necessarily optimal for food security, and to produce them in ways which are not necessarily ecologically viable in the long term. They can also exclude people with less purchasing power. The next section details some support mechanisms which can help overcome these challenges.

2. Alternative market / distribution mechanisms

Sharing Risks and Rewards through Community Supported Agriculture – In Community Supported Agriculture (CSA), consumers subscribe to, or become a member of, a farm scheme, often for one year at a time. This creates a direct link between producers and consumers, offering farmers higher prices for their produce through eliminating value capture through intermediaries. The scheme also gives farms a degree of certainty about their customer base, thus insulating them from the price fluctuations of commodity markets. Both factors enable CSA farms to use more labour-intensive processes and to produce staple foods which might otherwise be uncompetitive if sold on an open market.

There are two main reasons why people become members of a CSA: to access quality food and/or affordable food. A study of CSAs in England found that while CSA members tend to be middle class on average, 'a handful of initiatives offer discounts to the low waged or accept Healthy Start vouchers.'[112] There are just over 100 CSAs in the UK – each serving an average of 40 households. While this is not insignificant, there is certainly scope for expansion of this model.

A spin off of the CSA approach could be a Climate Adaptive Box (CAB) scheme. This might entail consumers spending a bit more money for their weekly veg box, in order to help support the extra costs to producers of cultivating in different ways (e.g. intercropping) and/or cultivating different foods (e.g. corn[4]), some of which may not become available for some time but would require upfront investments (e.g. apricots). Further market research could explore whether CABs could help in transitioning to more climate adaptive food systems, and in enabling producers to meet the extra costs of these approaches.

Coordinating Fair Food Systems through Community Intermediaries – Not all farms are well positioned to sell directly or start a CSA scheme. In these cases, community interest intermediaries—in the form of cooperatives, community interest companies (CiCs) or other organisations—can play a role in improving farmers' incomes and increasing access to healthy food for all. Community intermediaries can work towards meeting the needs of producers and consumers which might otherwise be marginalised in normal supply chains. This might include coordinating what producers grow (i.e. avoiding duplication and unhealthy competition), reducing intermediary costs to increase prices for producers, and improving access to healthy foods for people normally marginalised in supply chains.

[4] As noted earlier, corn / maize production in England runs risks of severe soil erosion and runoff if not cultivated with the use of intercropping, including undersowing to avoid bare soil over winter.

Tamar Grow Local (TGL) in Plymouth is one example of a community interest organisation which is improving linkages between producers and consumers. With a mark-up of only 18% between the producers and consumers, TGL offers producers fair prices based on the cost of production (i.e. price floors), rather than global commodity market prices. TGL's offerings to producers have been, at times, up to 150-275% higher than average farm gate prices.[113] TGL also creates new marketing outlets for producers through shared label schemes and processing units. TGL's 'Grow Share Cook' scheme buys vegetables from local farmers and distributes them to people living in food poverty who attend cooking classes to learn how to use the produce. The programme has achieved healthier diets for 85% of participants [113].

TGL provides support to 60 local producers, has reached 200 low income households and even more general consumers. They also rent a 12-acre site, which they sub-let to a number of small-scale and new entrant producers. With a required external support of £40k per year from donors, Tamar Grow Local is economically efficient in its support to producers while also generating important social and health outcomes for Plymouth's population [114]. Yet without external funding, the scheme could not exist. TGL has benefitted from both Nesta funding and from council budgets given its orientation towards reducing health inequalities and food poverty.

Improving Market Shares and Pooling Resources through Cooperatives – Cooperatives can enable producers to pool resources, such as processing equipment and storage facilities. They can also aggregate produce for wholesale, again, increasing the prices received by producers by reducing value capture by intermediaries. For example, a co-op of 40 honey producers, co-ordinated by Tamar Grow Local (TGL) in Plymouth, has been able to increase the price received by its producers from £2.30 per pound to £4.40 per pound. Taking into account packaging costs, this represents a 91% increase in price received by the producer, while the price to the consumer stays in the middle of the retail price range. As well as selling wholesale, individual producers can 'buy back' their own honey and sell it themselves. This model is also used for apple juice processing and can apply to other foods as well. As discussed above, in Dorset, Fivepenny Farm hosts a producers' cooperative for sharing processing facilities for cider, dairy and meat, which helps to reduce barriers to entry and costs for producers. In Wales, as in England, there is significant scope for cooperatives to facilitate local production, processing and storing of staple foods, which may help to strengthen food system resilience in the face of climate changes.

Figure 21: The Barn at Fivepenny Farm hosts a cooperative of producers for local processing. Photo: Patrick Whitefield.

Facilitating the Transition with Start-Up and Capital Grants – Upfront investments are needed for many of the adaptive practices reviewed in this report, including processing and storage facilities, water management systems and even the purchase of trees. Some of the investment costs for transitioning to more adaptive practices could be covered by grants available under Welsh Government

Rural Affairs, such as the Small Grants – Environment (water) for up to £7,5000), Small Grants – Efficiency (£1,000 to £12,000), and Horticulture Development Scheme (£3,000 to £100,000, existing commercial horticulture producers). It is possible that some producers, including community producers, may not fall within the remit of these schemes (for example, Small Grants Efficiency is for farms over 3ha), or that for bigger types of farms, larger investments are needed. Further, grants only cover 40% of the cost invoiced, and producers must therefore source funds for the remaining 60% of the cost, something that is not always available to all farmers. Yet adapting to climate change is in everybody's interests and the financial burden should not be disproportionately borne by farmers. While pressure for more government funding is needed, private donations and crowd funding could also help support producers with upfront investments to adapt to climate change.

6. Concluding remarks

If production practices and supply chains do not change, then climate change is likely to threaten food security in Wales, where a significant proportion of the population already experiences food scarcity. However, reduced food security does not need to be the outcome of climate changes. As this report highlights, there is enormous scope for producers of all scales to adjust what they produce and how they manage water, soil and biodiversity. Similarly, action by concerned citizens can help to support producers with these transitions and also strengthen the sustainability, fairness and resilience of their food systems. To summarise what each group can do:

Small scale producers:

- Ensure soils are protected through the use of mulches, green manures, intercropping and reduced digging
- Cultivate on contour and consider using swales to divert rainwater where appropriate
- Add in or improve rainwater harvesting (and link to irrigation systems, where appropriate)
- Build diversity through cultivating more varieties, using open-pollinated, heritage and population seeds and creating non-crop habitats
- Consider increasing or improving the use of protective cover, such as caterpillar tunnels and storm resistant polytunnels
- Join, create or strengthen cooperatives and CSAs (and possibly CABs) for processing and retail

Consumer and community groups:

- Become members of local CSAs (and possibly CABs)
- Support local cooperatives
- Support localised storage and processing (e.g. through donations)
- Support funding for adapting more resilient production (e.g. through crowdfunding)
- Explore dietary changes to support climate resilient local food systems (e.g. through consuming different foods and buying local)
- Support the Land Workers' Alliance to establish a training centre

Larger-scale producers:

- Improve water management through swales, bunds, ponds, keylines and cultivating on contour where appropriate
- Improve rainwater harvesting and irrigation to keep crops healthy while preventing pressure on groundwater reserves
- Protect soils through mulching, intercropping, green manures and reduced tillage
- Increase resilience through using intercropping and population varieties
- Reduce pests and improve diversity through creating habitats for beneficial species, including through the integration of more trees and shrubs on farmland
- Reorient production towards nutritious foods for local consumption and consider new crops which are suited to the changing climate
- Join, create or support local processing and storing cooperatives

Home gardeners and allotment growers:

- Ensure soils are protected using mulches, green manures, intercropping and reduced digging
- Add in or improve rainwater harvesting
- Consider growing new types of foods and producing more veg and fruit to share with family, friends and neighbours
- Build diversity through cultivating more varieties, using open-pollinated and heritage seeds and supporting non-crop diversity

If a bold and proactive approach is taken to climate change now, then there is much to gain. However, if producers are not supported and producer-consumer linkages remain left to the market, the threats are numerous. For climate change resilience, the status quo is not an option.

7. Additional resources

Water Management Systems: Jay Abrahams at Biologic Design researches and establishes water management systems. http://www.biologicdesign.co.uk/

Publications by P.A. Yeomans on Keyline systems can be accessed online at https://soilandhealth.org/book/the-keyline-plan/ and https://soilandhealth.org/wp-content/uploads/01aglibrary/010126yeomansII/010126toc.html

Population varieties of wheat: The Organic Research Centre has videos and documents about population varieties of wheat (developed with Martin Wolfe of Wakelyns) http://www.organicresearchcentre.com/?i=articles.php&art_id=783&go=Information%20and%20publications. The population can be purchased for sowing via Walnes Seeds https://www.walnesseeds.com/

Green Manures: The Organic Research Centre has a guide to green manure species selection http://www.organicresearchcentre.com/manage/authincludes/article_uploads/iota/technical-leaflets/green-manures-effects-on-soil-nutrient-management-and-soil-physical-and-biological-properties.pdf

Garden Organic has a guide for green manures https://www.gardenorganic.org.uk/sites/www.gardenorganic.org.uk/files/Sort-Out-Your-Soil-Final.pdf

AHDB has published a briefing on green manures. https://www.soilassociation.org/media/15823/green-manures-factsheet_2018-06-11_web.pdf

Cover crops and their termination: The Soil Association ran a field lab on terminating cover crops without herbicides: https://innovativefarmers.org/field-lab/?id=e05323bd-125e-e611-80ca-005056ad0bd4

Undersowing for horticulture: A market gardening group in Scotland is running a trial on undersowing kale crops with green manures and intercropping with salads. https://innovativefarmers.org/field-lab?id=6f9da1d4-482c-e811-816d-005056ad0bd4

Intercropping in arable systems: Nuffield scholar Andrew Howard produced a comprehensive report on the potentials for intercropping in the UK drawing on other countries: https://nuffieldinternational.org/live/Report/UK/2015/andrew-howard

Pest management through diversity: Specific approaches for arable crops can be found through Sam Cook at Rothamsted Research and for horticulture through Rosemary Collier at University of Warwick.

Incorporating trees into cropping systems: The Agroforestry Research Trust runs courses and publishes guides. https://www.agroforestry.co.uk/

Wakelyns Farm offers agroforestry tours and provides an overview on its website http://wakelyns.co.uk/agroforestry/

The Organic Research Centre also has resources on agroforestry in the UK http://www.organicresearchcentre.com/?go=research%20and%20development&page=Agroforestry

No dig vs dig gardening: Charles Dowding's website and books provide a wealth of information on small scale no dig gardening. https://charlesdowding.co.uk/. As an alternative or counter to this, Iain Tolhurst at Tolhurst Organic runs regular courses on (vegan/stock free) gardening, which incorporates digging approaches and rotations – see https://www.tolhurstorganic.co.uk/.

Community food intermediaries and cooperatives: Tamar Grow Local in Plymouth is a prime example of linking producers and consumers in the interest of community.

Community Support Agriculture: https://communitysupportedagriculture.org.uk/

Heritage Seeds and Grains: The Seed Sovereignty Programme of Gaia Foundation is working on this topic in Wales, see www.seedsovereignty.info. And the Welsh Grain Forum can be found on Facebook, X and Instagram.

Welsh contacts: The Wales Real Food & Farming Conference is a good source of contacts and resources, and publishes email updates. See www.wrffc.wales. Our Food 1200, which is part of the Conservation Farming Trust, is working on farming policies and food security with Welsh Government and in Powys. See www.ourfood1200.wales.

8. References

1 Liu, E. K., He, W. Q. & Yan, C. R. 'White revolution' to 'white pollution'—agricultural plastic film mulch in China. *Environmental Research Letters* **9** (2014).

2 European Commission. Report from the Commission to the European Parliament and the Council on the impact of the use of oxo-degradable, including oxo-degradable plastic carrier bags, on the environment.(European Commission Brussels 2018).

3 Chronic Hazard Advisory Panel on Phthalates and Phthalate Alternatives. Report to the U.S. Consumer Product Safety Commission.(Directorate for Health Sciences, Bethesda, MD, 2014).

4 Bendell, J. (https://jembendell.com/2019/03/28/notes-on-hunger-and-collapse/, 2019).

5 Servigne, P. *Feeding Europe in Times of Crisis (Nourrir l'Europe en temps de crise: Vers des systèmes alimentaires résilients)*. (ACTES SUD, 2017).

6 Jones, A. *et al.* Scoping Potential Routes to UK Civil Unrest via the Food System: Results of a Structured Expert Elicitation. *Sustainability* **15**, (2023).

7 Gaupp, F., Hall, J., Mitchell, D. & Dadson, S. Increasing risks of multiple breadbasket failure under 1.5 and 2 °C global warming. *Agricultural Systems* **175** (2019).

8 Trnka, M. *et al.* Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Climate Change* **4** (2014).

9 Sen, A. *Poverty and Famines*. (Oxford University Press, 1986).

10 Wisner, B., Weiner, D. & O'Keefe, P. Hunger: A Polemical Review*. *Antipode* **14** (1982).
11 Trust;, I. T. T. Hunger in Wales.(The Trussel Trust, https://www.trusselltrust.org/wp-content/uploads/sites/2/2023/06/2023-Hunger-in-Wales-report.pdf, 2023).
12 DEFRA. United Kingdom Food Security Report 2021: Theme 4: Food Security at Household Level (Updated 5 October 2023).(UK Department for Environment, Food & Rural Affairs, https://www.gov.uk/government/statistics/united-kingdom-food-security-report-2021/united-kingdom-food-security-report-2021-theme-4-food-security-at-household-level, 2023).
13 Hunter, J. *The Making of the Crofting Community*. (John Donald Publishers, 1976).
14 Devine, T. *The Great Highland Famine: Hunger, Emigration and the Scottish Highlands in the Nineteenth Century*. (John DOnald, 1988).
15 Gerbens-Leenes, P. W. & Nonhebel, S. Consumption patterns and their effects on land required for food. *Ecological Economics* **42** (2002).
16 Harvey, M. & Pilgrim, S. The new competition for land: Food, energy, and climate change. *Food Policy* **36** (2011).
17 Wirsenius, S., Azar, C. & Berndes, G. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems* **103** (2010).
18 Wheeler, A. Welsh Fruit and Veg Production, Baseline Study.(Tyfu Cymru, https://www.tyfucymru.co.uk/knowledge-hub/industry-insights/welsh-fruit-and-vegetable-production-baseline-study/, 2020).
19 Knox, J., Morris, J. & Hess, T. Identifying Future Risks to UK Agricultural Crop Production:Putting Climate Change in Context. *Outlook on Agriculture* **39** (2010).
20 Knox, J., Weatherhead, K., Díaz, J. R. & Kay, M. Developing a Strategy to Improve Irrigation Efficiency in a Temperate Climate:A Case Study in England. *Outlook on Agriculture* **38** (2009).
21 Else, M. & Atkinson, C. Climate Change Impacts on UK Top and Soft Fruit Production. *Outlook on Agriculture* **39** (2010).
22 Salmoral, G., Ababio, B. & Holman, I. P. Drought Impacts, Coping Responses and Adaptation in the UK Outdoor Livestock Sector: Insights to Increase Drought Resilience. *Land* **9**, (2020).
23 Wreford, A. & Topp, C. F. E. Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. *Agricultural Systems* **178** (2020).
24 Sønsteby, A. & Heide, O. M. Elevated Autumn temperature promotes growth cessation and flower formation in black currant cultivars (Ribes nigrum L.). *The Journal of Horticultural Science and Biotechnology* **86** (2011).
25 Sønsteby, A., Opstad, N. & Heide, O. M. Effects of summer temperature on growth and flowering in six black currant cultivars (Ribes nigrum L.). *The Journal of Horticultural Science and Biotechnology* **87** (2012).
26 Pimentel, D. Soil Erosion: A Food and Environmental Threat. *Environment, Development and Sustainability* **8** (2006).
27 Graves, A. R. *et al.* The total costs of soil degradation in England and Wales. *Ecological Economics* **119** (2015).
28 Daniel, T. C., Sharpley, A. N. & Lemunyon, J. L. Agricultural Phosphorus and Eutrophication: A Symposium Overview. *Journal of Environmental Quality* **27** (1998).
29 Withers, P. J. A. *et al.* Towards resolving the phosphorus chaos created by food systems. *Ambio* (2019).
30 Withers, P. J. A. & Lord, E. I. Agricultural nutrient inputs to rivers and groundwaters in the UK: policy, environmental management and research needs. *Science of The Total Environment* **282-283** (2002).
31 Davies, D. B. & Sylvester-Bradley, R. The contribution of fertiliser nitrogen to leachable nitrogen in the UK: A review. *Journal of the Science of Food and Agriculture* **68** (1995).
32 Keay, C. Sea Level Rise & Agricultural Land Loss underUKCP18.(DEERA, 2020).
33 Evans, N., Baierl, A., Semenov, M. A., Gladders, P. & Fitt, B. D. L. Range and severity of a plant disease increased by global warming. *Journal of The Royal Society Interface* **5** (2008).
34 Peters, K., Breitsameter, L. & Gerowitt, B. Impact of climate change on weeds in agriculture: a review. *Agronomy for Sustainable Development* **34** (2014).
35 Rial-Lovera, K., Davies, W. P. & Cannon, N. D. Implications of climate change predictions for UK cropping and prospects for possible mitigation: a review of challenges and potential responses. *Journal of the Science of Food and Agriculture* **97** (2017).
36 Clements, D. R. & Jones, V. L. Rapid Evolution of Invasive Weeds Under Climate Change: Present Evidence and Future Research Needs. *Frontiers in Agronomy* **3** (2021).
37 Hartwell Allen, L., Baker, J. T. & Boote, K. J. in *Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes* (eds F. Bazzaz & W. Sombroek) (UN Food and Agriculture Organisation, 1996).
38 Dellar, M., Topp, C. F. E., Banos, G. & Wall, E. A meta-analysis on the effects of climate change on the yield and quality of European pastures. *Agriculture, Ecosystems & Environment* **265** (2018).
39 AbdElgawad, H. *et al.* Climate Extreme Effects on the Chemical Composition of Temperate Grassland Species under Ambient and Elevated CO2: A Comparison of Fructan and Non-Fructan Accumulators. *PLoS One* **9** (2014).
40 Williams, A. G., Audsley, E. & Sandars, D. L. Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. *The International Journal of Life Cycle Assessment* **15** (2010).
41 O'Mara, F. P. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Animal Feed Science and Technology* **166-167** (2011).
42 Poux, X. & Aubert, P. M. Une Europe agroecologique en 2050: une agriculture multifonctionnelle pour une alimentation saine.(IDDRI, 2018).
43 Freibauer, A., Rounsevell, M. D. A., Smith, P. & Verhagen, J. Carbon sequestration in the agricultural soils of Europe. *Geoderma* **122** (2004).
44 Loisel, J. & Gallego-Sala, A. Ecological resilience of restored peatlands to climate change. *Communications Earth & Environment* **3** (2022).
45 Sommer, R. & Bossio, D. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management* **144** (2014).
46 Hutchinson, J. J., Campbell, C. A. & Desjardins, R. L. Some perspectives on carbon sequestration in agriculture. *Agricultural and Forest Meteorology* **142** (2007).
47 Udawatta, R. P. & Jose, S. Agroforestry strategies to sequester carbon in temperate North America. *Agroforestry Systems* **86** (2012).
48 Hernández-Morcillo, M., Burgess, P., Mirck, J., Pantera, A. & Plieninger, T. Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science & Policy* **80** (2018).
49 Holt-Giménez, E. Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agriculture, Ecosystems & Environment* **93** (2002).
50 Yeomans, P. A. *The Keyline Plan*. (1954).
51 Stevens, C. J. *et al.* The effects of minimal tillage, contour cultivation and in-field vegetative barriers on soil erosion and phosphorus loss. *Soil and Tillage Research* **106** (2009).
52 FAO. Soil Tillage in Africa: Needs and Challenges (1993).
53 Liu, R., Zhang, P., Wang, X., Chen, Y. & Shen, Z. Assessment of effects of best management practices on agricultural non-point source pollution in Xiangxi River watershed. *Agricultural Water Management* **117** (2013).
54 Ricci, G. F., Jeong, J., De Girolamo, A. M. & Gentile, F. Effectiveness and feasibility of different management practices to reduce soil erosion in an agricultural watershed. *Land Use Policy* **90** (2020).
55 Defra. Controlling soil erosion: A manual for the assessment and management of agricultural land at risk of water erosion in lowland England.(Department for Environment, Food and Rural Affairs, London, 2005).

56 Abrahams, J. C., Coupe, S. J., Sañudo-Fontaneda, L. A. & Schmutz, U. The Brookside Farm Wetland Ecosystem Treatment (WET) System: A Low-Energy Methodology for Sewage Purification, Biomass Production (Yield), Flood Resilience and Biodiversity Enhancement. *Sustainability* **9** (2017).

57 Jump, A. S., Marchant, R. & Peñuelas, J. Environmental change and the option value of genetic diversity. *Trends in Plant Science* **14** (2009).

58 Lopes, M. S. *et al.* Exploiting genetic diversity from landraces in wheat breeding for adaptation to climate change. *Journal of Experimental Botany* **66** (2015).

59 Mondal, S. *et al.* Harnessing Diversity in Wheat to Enhance Grain Yield, Climate Resilience, Disease and Insect Pest Resistance and Nutrition Through Conventional and Modern Breeding Approaches. *Frontiers in Plant Science* **7** (2016).

60 Almekinders, C. & Louwaars, N. *Farmers' seed production. New approaches and practices*. (IT publications 1999).

61 Wach, E. in *Food Systems Governance: Challenges for justice, equality and human rights* (eds A. Kennedy & J. Liljeblad) (Routledge, 2016).

62 Fernández-Aparicio, M., Amri, M., Kharrat, M. & Rubiales, D. Intercropping reduces Mycosphaerella pinodes severity and delays upward progress on the pea plant. *Crop Protection* **29** (2010).

63 Živanov, D., Jevtić, R., Tančić, S., Vasiljević, S. & Maširević, S. Control of winter forage pea diseases by pea-oat intercropping under field conditions. *Pesticidi i fitomedicina* **29** (2014).

64 Howard, A. The potential for companion cropping and intercropping on UK arable farms.(Nuffield UK, 2016).

65 Brooker, R. W. *et al.* Does crop genetic diversity support positive biodiversity effects under experimental drought? *Basic and Applied Ecology* **56** (2021).

66 Pakeman, R. J. *et al.* Increased crop diversity reduces the functional space available for weeds. *Weed Research* **60** (2020).

67 Kirwan, L. *et al.* Evenness drives consistent diversity effects in intensive grassland systems across 28 European sites. *Journal of Ecology* **95** (2007).

68 Lee, J. M., Clark, A. J. & Roche, J. R. Climate-change effects and adaptation options for temperate pasture-based dairy farming systems: a review. *Grass and Forage Science* **68** (2013).

69 Kindred, D., Berry, P., Burch, O. & Sylvester-Bradley, R. Effects of nitrogen fertiliser use on green house gas emissions and land use change. *Aspects of Applied Biology* **88** (2008).

70 Newbould, P. The use of nitrogen fertiliser in agriculture. Where do we go practically and ecologically? *Plant and Soil* **115** (1989).

71 Greenop, A., Woodcock, B. A., Wilby, A., Cook, S. M. & Pywell, R. F. Functional diversity positively affects prey suppression by invertebrate predators: a meta-analysis. *Ecology* **99** (2018).

72 Lu, Z.-X. *et al.* Mechanisms for flowering plants to benefit arthropod natural enemies of insect pests: Prospects for enhanced use in agriculture. *Insect Science* **21** (2014).

73 Gillespie, M. A. K., Gurr, G. M. & Wratten, S. D. Beyond nectar provision: the other resource requirements of parasitoid biological control agents. *Entomologia Experimentalis et Applicata* **159** (2016).

74 Gladbach, D. J. *et al.* Crop–noncrop spillover: arable fields affect trophic interactions on wild plants in surrounding habitats. *Oecologia* **166** (2011).

75 Thies, C., Steffan-Dewenter, I. & Tscharntke, T. Effects of landscape context on herbivory and parasitism at different spatial scales. *Oikos* **101** (2003).

76 Beduschi, T., Tscharntke, T. & Scherber, C. Using multi-level generalized path analysis to understand herbivore and parasitoid dynamics in changing landscapes. *Landscape Ecology* **30** (2015).

77 Dodds, P. A. A. *Using PRD and RDI to save water, reduce vegetative vigour, and improve fruit quality in strawberry*, Lancaster University and East Malling Research, (2008).

78 Van Bruggen, A. H. C. *et al.* Environmental and health effects of the herbicide glyphosate. *Science of The Total Environment* **616-617** (2018).

79 Powles, S. B. Evolved glyphosate-resistant weeds around the world: lessons to be learnt. *Pest Management Science* **64** (2008).

80 Aura, E. Effects of shallow tillage on physical properties of clay soil and growth of spring cereals in dry and moist summers in southern Finland. *Soil and Tillage Research* **50** (1999).

81 Bai, Z. *et al.* Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agriculture, Ecosystems & Environment* **265** (2018).

82 Warner, D., Tzilivakis, J. & Lewis, K. Sustainability of UK Strawberry Crop.(Defra Agriculture and Environment Research Unit, 2005).

83 Calzadilla, A. *et al.* Climate change impacts on global agriculture. *Climatic Change* **120** (2013).

84 Wheeler, T. & von Braun, J. Climate Change Impacts on Global Food Security. *Science* **341** (2013).

85 Fairlie, S. Can Britain Feed Itself? . *The Land* **Winter 2007-8** (2008).

86 Miglietta, F. *et al.* in *Climate Change and Global Crop Productivity* (eds K.R. Reddy & H.F. Hodges) (CABI Publishing, 2000).

87 Boardman, J. Soil Erosion in Britain: Updating the Record. *Agriculture* **3** (2013).

88 Ruysschaert, G., Poesen, J., Verstraeten, G. & Govers, G. in *Soil Erosion in Europe* (eds J. Boardman & J. Poesen) (2006).

89 Richter, G. M., Qi, A., Semenov, M. A. & Jaggard, K. W. Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. *Soil Use and Management* **22** (2006).

90 Collier, R. H. in *Oxford Real Farming Conference.*

91 AHDB. *UK cereals supply and demand estimates*, 2020).

92 Farnworth, G., Melchett, P. . Runaway Maize: subsidized soil destruction.(Soil Association, Bristol, 2015).

93 Casswell, L. in *Farmers Weekly* (https://www.fwi.co.uk/arable/grow-your-own-quinoa-super-crop, 2018).

94 Defra. Horticulture Statistics 2022.(https://www.gov.uk/government/statistics/latest-horticulture-statistics/horticulture-statistics-2022, Accessed 2024).

95 Bocci, M. & Smaris, T. Assessment of the impacts of climate change on the agriculture sector in the Southern Mediterranean: Forseen developments and policy measures.(Union for the Mediterranean Secretariat, 2019).

96 Schilling, J., Freier, K. P., Hertig, E. & Scheffran, J. Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agriculture, Ecosystems & Environment* **156** (2012).

97 Collier, R. H. & Else, M. in *Climate Change Impact and Adaptation in Agricultural Systems* (eds J. Fuhrer & P. J. Gregory) (CABI Publishing, 2014).

98 Wurr, D. C. E. & Fellows, J. R. Leaf production and curd initiation of winter cauliflower in response to temperature. *The Journal of Horticultural Science and Biotechnology* **73** (1998).

99 Wurr, D. C. E., Fellows, J. R. & Fuller, M. P. Simulated effects of climate change on the production pattern of winter cauliflower in the UK. *Scientia Horticulturae* **101** (2004).

100 Paterson, R. R. M., Kumar, L., Taylor, S. & Lima, N. Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. *Scientific Reports* **5** (2015).

101 Paterson, R. R. M., Sariah, M. & Lima, N. How will climate change affect oil palm fungal diseases? *Crop Protection* **46** (2013).

102 Paterson, R. R. M. & Lima, N. Climate change affecting oil palm agronomy, and oil palm cultivation increasing climate change, require amelioration. *Ecol Evol* **8** (2017).

103 iknowfood. *Soy Governance Research*, 2019).

104 Gibson, K. Hemp in the British Isles. *Journal of Industrial Hemp* **11** (2006).

105 Butterworth, M. H. *et al.* North-South divide: contrasting impacts of climate change on crop yields in Scotland and England. *Journal of The Royal Society Interface* **7** (2010).

106 Evans, N. *et al.* The impact of climate change on disease constraints on production of oilseed rape. *Food Security* **2** (2010).

107 Stephenson, A. L., Dennis, J. S. & Scott, S. A. Improving the sustainability of the production of biodiesel from oilseed rape in the UK. *Process Safety and Environmental Protection* **86** (2008).

108 Debaeke, P., Casadebaig, P., Flenet, F. & Langlade, N. Sunflower crop and climate change: vulnerability, adaptation, and mitigation potential from case-studies in Europe. *OCL* **24** (2017).

109 Bellarby, J., Wattenbach, M., Tuck, G., Glendining, M. J. & Smith, P. The potential distribution of bioenergy crops in the UK under present and future climate. *Biomass and Bioenergy* **34** (2010).
110 Laughton, R. A Matter of Scale: A study of the productivity, financial viability and multifunctional benefits of small farms.(Centre for Agroecology, Water and Resilience (CAWR), Coventry, 2017).
111 Schmidhuber, J. & Tubiello, F. N. Global food security under climate change. *Proceedings of the National Academy of Sciences* **104** (2007).
112 Saltmarsh, N., Meldrum, J. & Longhurst, N. The impact of community supported agriculture.(Soil Association, 2011).
113 Ferguson, C. & Wach, E. Local food strategies: what has led English councils to develop sustainable local food strategies and what have these entailed? .(Institute of Development Studies and Land Workers' Alliance Brighton, UK, 2017).
114 Ferguson, C. & Wach, E. Strategies for markets and finance to support agroecological farming in the UK.(Institute of Development Studies and Land Workers' Alliance Brighton, UK, 2017).