Growing at the Margins: Adaptation to Severe Weather in the Marginal Lands of the British Isles

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ABSTRACT

With the problem of severe weather events having significant impacts on harvests in Britain, this study has looked at how small-scale food producers use agroecology to adapt to adverse weather conditions; 23 sites growing food using agroecology across the British Isles in areas severely disadvantaged to agriculture were investigated. Because the climate in these areas is generally hostile to horticulture (often in combination with other factors such as land quality), all the participants have to adapt to the prevailing weather conditions and frequent severe weather events. Through detailed interviews, a range of adaptations to specific weather hazards, and their impacts, has been recorded. The adaptations have been grouped into nine different responses types and then analyzed. Results show that the biggest driver for a change in adaptation responses has been drought, and the most consistent adaptation response has been to problems associated with heavy rainfall. With participants showing a varying level of adaptation to severe weather hazards, this study indicates that growers' experience and ingenuity are factors influencing adaptation and consequently resilience to severe weather. The study acts as a useful scoping study for the potential of the various methods collected in a knowledge base to be reviewed by stakeholders for scaling up for wider adoption by farmers willing to adapt to climate variability.

1. Introduction

This paper starts by looking at the context of adapting to severe weather by analyzing the recent impacts from extreme weather, which has affected agriculture in the British Isles. This is followed by a literature review into how farmers have responded to adverse weather, and the triggers to behavioral change, with a focus on the British context and the role of agroecology, including certain limitations on adaptability affected by governmental policy.

The concept of the Marginal Lands Project is explored, looking at how adaptations to adverse weather have been used by growers dealing with environments that demand frequent adaptation. The adaptations are described in terms of responses to various weather hazards. The gathering of such techniques into a knowledge base (an illustrated electronic inventory) has allowed an analysis of the participants' level of adaptability as well as of the main drivers to adaptation as well as an outline of some of the constraints. In conclusion, the implications of this research are explored in terms of policy and further adoption by other farms.

a. Extreme weather and the impacts on agriculture in Britain

In Britain farmers reported over £1 billion loss to agriculture in 2012 as a result of extreme weather (Jowitt 2012); a drought in 2011 was followed by widespread flooding during the summer of 2012. The losses were exacerbated when a cold spring with heavy snow occurred in late March 2013, all of which combined to have major impacts on all agricultural sectors in Britain. The costs were increased when the national-scale weather events over Britain coincided with droughts in the U.S. and Russian grain belts; this exerted a knock-on effect on the prices of global agricultural commodities, affecting livestock farmers in the United Kingdom. In 2012, the summer rainfall for England overall was 181% of the norm; the Met Office puts the magnitude of this event in context: June 2012 was the wettest June in the England and Wales rainfall series from 1766. The total summer rainfall in 2012 for all the United Kingdom had only been recorded to have been exceeded in the summer of 1912 (Met Office 2013). The impacts on

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horticulture were particularly acute in England. Horticultural farm incomes in 2012 dropped overall in England by 36% from the previous year and by 72% in the east of England region [data from Rural Business Research (2016)]. The issue of food security for the United Kingdom has become prominent; what became apparent was that the shocks caused by episodes of extreme weather exert the greatest impacts of climate change on agriculture (Benton et al. 2012; Knox et al. 2010). The type of extreme weather and its timing and scale determine the level of impact on agriculture and on which sectors.

Horticulture can bear the brunt of flooding brought about by extreme rainfall occurring in the growing season. In the summer of 2007, flooding affected several areas of Yorkshire and Humber and the southern West Midlands in England. Between May and July, rainfall for May to July in southern Britain was 223% of the (1961–90) average (Marsh 2008). Posthumus et al. (2009) found that horticultural produce such as vegetable and salad crops suffered the greatest losses on a field scale; horticultural farms had relatively higher costs associated with repairs needed to damaged irrigation equipment. For all farms, crops were affected both in terms of yield and in quality. Additional costs were the result of the need to add agrochemicals to maintain crop performance after flooding. There were additional harvesting costs and land reinstatement costs. A major impact was the problem of soils remaining waterlogged for a prolonged period, up until the following spring in some cases.

A report looking at the impact of extreme weather on agriculture in England (ADAS/University of Leeds 2013) investigated the potential future impacts by looking at different combinations of weather events, and their impacts on agriculture, through weather scenarios for the year 2050. This was done by combining analog events and Environment Agency (2016) guidelines for upper-end estimates for peak rainfall and heat events 5 times the standard deviation ($+5\sigma$) from the mean (1981–2010). The latter is in accord with Hansen et al.'s (2012) findings that $+5\sigma$ would be more common with a business as usual emissions scenario. The scenarios were selected by a workshop gathering of expert stakeholders including representatives from U.K. government Department for Environment, Food and Rural Affairs, and economic impacts were estimated through surveys and expert judgement.

A scenario of widespread summer flooding would have the greatest impact per hectare; in this case, the weather scenario was limited to three regions (East and West Midlands and eastern England). This scenario replicates what occurred during 1912, exactly 100 years before the 2011–12 drought and flood. Summer rainfall levels would reach 200% of the mean,[1] with widespread areas in the east of England receiving over 150 mm in 24 h. The next scenario in terms of impact was two consecutive wet autumns and winters (200% of the mean) over northern England. However, the impacts overall in England would be worse if all of England were subject to several consecutive episodes of unseasonal weather involving an early winter followed by a mild spell midwinter; a warm, dry, early spring; and cold, wet summer with flooding. These implications for U.K. farming are immediate. The scenarios were designed to be plausible; their risk has not been specified because models have not accurately predicted the frequency of recent extreme precipitation events [Global Food Security (2015), after Min et al. (2011)].[2]

b. *Farmers' adaptations and resilience to extreme weather*

With significant impacts on agriculture, adapting to extreme weather by farmers is critical. A study in New Zealand (White et al. 2009) looked at the responses by farmers to adverse weather events. Horticulturalists focused on long-term strategic measures such as raising the height of shelter belts, which were seen as part of good practice. However, despite two adverse weather events in one season, they found that the majority of farmers did not make any long-term adaptive investment, as they felt that the frequency of adverse weather did not justify the outlay. In England, those farmers badly affected by flooding in summer 2007 were considering permanent changes to land use on the floodplain as well as improved drainage (Posthumus et al. 2009).

Mardero et al. (2015) investigated smallholders using rain-fed agriculture and their attitudes to drought; they list the agricultural adaptations to droughts as well as means of diversifying income. In a study of U.K. farmers' response to heat waves and droughts since the 1970s, Wreford and Adger (2010) conjecture that a certain amount of adaptation to droughts has been made by U.K. farmers, most likely through increased irrigation, but that further irrigation may no longer be possible because of economic limits (or limits on extraction). Moreover, repeated dry years could "force farmers to make irrigation priorities" perhaps for high-value crops (Subak 1997, p. 50), which implicitly means an abandonment of some crops.

[1] Mean values based on baseline period 1981–2010, that is, the most recent 30-yr climate period.

[2] Since this study, recent Met Office research has found that there is a one in three chance of a new monthly rainfall record in at least one region of England and Wales in winter (http://www.metoffice.gov.uk/news/releases/2017/high-risk-of-unprecedented-rainfall).

Resilience as a concept has developed from ecological resilience described by Holling (1973), as the ability of a system to maintain its characteristics when disturbed. In the context of the weather and climate resilience of a farm system, resilience is understood in social terms, as explored by Fraser et al. (2003). When defining social resilience, they find that social resilience is a function of ingenuity or resources (material and cultural factors). As a result, a farm's response, if seen as a system, would be its ''capacity to adapt or even transform in response to socio-environmental changes such as climate change'' Sharmina et al. (2016, p. 76). Therefore, the growers' ability to adapt to disruptive weather events would be an indicator of resilience, resulting from their innovation or resources at their disposal.

However, U.K. agricultural policy acts as a limiter for smallholder farms wishing to take a longer-term view of land management. Sharmina et al. find that the focus of agricultural policy in the United Kingdom pays insufficient attention to catchment management and that in the medium to long term, shortcomings in terms of land-use policy ''is likely to jeopardise the resilience of the United Kingdom to climate change impacts'' (Sharmina et al. 2016, p. 81). Resources tend to be limited for small farms and smallholdings. With agricultural payments to farmers slanted in favor of larger landowners, they are at a further disadvantage; 80% of EU agricultural payments are received by just 20% of U.K. farmers, and although most are eligible for payments, many receive insignificant sums and as a result are discouraged from applying because of the level of administration required (Jambor and Harvey 2010). Agricultural payments in the United Kingdom have historically been aimed at intensifying production and therefore have elevated the risk of runoff through increased drainage, hydrological connectivity, and soil compaction (Posthumus et al. 2008). Moreover, in England, financial instruments to encourage farmers to reduce runoff (e.g., through pond construction or tree planting) seem to be lacking (ibid). Monbiot (2014) asserts that because of the way EU agricultural payments have been managed, there is no incentive to increase vegetative cover in the uplands; pastures containing more than 50 trees are not eligible for agricultural subsidy, and, by the time of writing, no EU environmental payments had been made available for upland tree planting in Wales. At higher altitudes, traditional moorland management practices, that is, grazing and/or burning to maintain an open landscape for grazing or shooting, are linked with increasing runoff (Holden 2009; Dadson et al. 2017). To put this in context, England has extremely low tree cover in the uplands: only 9.6% of English uplands have tree cover, with only 3% of the total area being native or mixed woodland (Natural England 2009).

This paper looks at the role of agroecology in increasing the adaptability of food growers to extreme weather. Agroecology is essentially the harnessing of ecological principles with agriculture. Agroecology often builds on many forms of traditional agriculture, such as in Nigeria where strategies are used to deal with unfavorable weather, such as water storage, mulching, intercropping, or the use of tree food crops as an insurance crop (Adejuwon et al. 2008). For the purposes of this study, agroecology encompasses the practices of organic, permaculture, and agroforestry methods. Permaculture is a form of agroecology that combines an ethical framework with an understanding of nature and a design approach (Permaculture Association 2016). Agroforestry is ''the growing of both trees and agricultural/horticultural crops on the same piece of land'' (Agroforestry Research Trust 2016). Certain forms of agroecology have been associated with greater resilience to extreme weather events than conventional farms (Altieri et al. 2015; Borron 2006), though Holt-Giménez (2002) found limits to that resilience in steeper terrain and if a hurricane's rainfall exceeded 300 mm. There is less evidence in the literature of agroecology and climate resilience in temperate climate zones according to Kazakova-Mateva and Radeva-Decheva [2015; after Petersen and Weigel (2015)].

However, there is evidence in Britain of the positive influence of trees and hedges toward modifying the microclimate and therefore moderating exposure to severe and extreme weather. Shelter belts can increase yields through modification of the microclimate through increases in soil temperature and humidity, so reducing the risk of late frosts and the impacts of drying winds (Caborn 1955) and reduction of wind speeds (Gloyne 1954). In the open pastures of mid-Wales, sheep farmers themselves have increased tree cover with the result that the trees improved rates of soil water moisture retention by up to 60 times; shelter belts can reduce river peak flows by up to 40% (Keenleyside 2013). Even conifer plantations have been associated with smoother river discharge flows than bare pasture or moorland in mid-Wales (Archer 2007), and older broadleaf woodland has shown the potential to mitigate flooding in the Scottish Borders (Archer et al. 2013). Trees and hedgerows have reduced runoff and erosion in arable farmland that was suffering increased problems of soil erosion in Norfolk in eastern England (Evans 2006). By utilizing tree cover and soil conservation the above evidence points toward the benefits of agroecology in buffering the effects of adverse weather and harnessing those benefits for adaptation.

c. *Marginal lands in Britain: Adverse climates for agriculture*

The uplands and the north and west of the British Isles are marginal to agriculture; these are land areas experiencing generally a cooler, wetter climate and more severe weather than more favorable agricultural regions in the south and east. The Marginal Lands Project[3] investigated adaptation to severe and extreme weather by those exposed to a more severe climatic regime and who use agroecology methods to either adapt passively or to create microclimates. The term marginal lands, used here, incorporates the EU less-favored areas for agriculture, which are the English, Scottish, and Welsh governmental classifications of disadvantaged areas and severely disadvantaged areas. These designations for disadvantaged areas (which have formed the basis for EU subsidies) are the most vulnerable environments, where geology in combination with an inhospitable climate to agriculture make it more difficult for farmers to compete; they are illustrated in Fig. 1. These areas are characterized as hill farming, where the management of these areas is predominantly through sheep and cattle grazing [Department for Environment Food and Rural Affairs (DEFRA) 2010]. Altitude plays an extremely important role in limiting agriculture by reducing the growing season; Gloyne (1973) finds that for every 100 m rise in altitude in northern Britain, the growing season is reduced by 14 days. The level of solar radiation, summer temperature, and wind are all important factors. The Atlantic-facing coasts and hills of northern Britain are disadvantaged compared to higher-latitude locations such as inland Scandinavia in the summer. For example, the mean maximum July temperature in Oslo, Norway (at 60°N), is 21.6°C, and at Lerwick, Shetland Islands (also at 60°N), it is 14.3°C.[4] Anyone engaged in agriculture in the marginal land areas of Britain has to respond to a challenging climate, particularly those engaged in horticulture.

Horticulture in these marginal land areas is clearly marginal, though there are marked contrasts between the countries of Great Britain. In England for commercial holdings, just 0.8% of the total horticultural land and 6% of horticultural land in Scotland are in less-favored areas. In contrast, in Wales, 30% of horticultural land occupy less-favored land [data collated from DEFRA (2010), Scottish Government (2016), and Welsh Government (2015)].[5] This reflects the much larger area of land devoted to horticulture in England, which has 87% of the horticultural land of the three countries [data from Welsh Government (2015)].[6]

2. Agroecology in the marginal lands—Potential for resilience?

a. *Rationale for the Marginal Lands Project*

With the literature highlighting indications of greater resilience to severe weather offered by agroecology, this article looks at the methods of adapting to severe weather by agroecology practitioners participating in the Marginal Lands Project. The project was a pilot study that investigated the range of adaptation methods in varying geographical and economic contexts and varying sizes of operation. The aim of the Marginal Lands Project was to find out if lessons could be learned by those practicing agroecology in marginal lands, usually (but not exclusively) at a smallholder level, with the potential of transfer to the wider farming community.

This study, however, is limited to providing an indication of Marginal Lands Project participants' resilience by investigating the breadth and level of their adaptations in response to the local climate and episodes of adverse weather. In addition, this article considers how the adaptive responses have been altered by the experience of recent extreme weather events. Those growing food in marginal areas using agroecology have to use innovation to keep their holding viable. This study ascertains the responses to each weather threat and particular weather triggers, leading to an alteration in adaptation strategy. Therefore, adaptations and changes in strategy in response to specific hazards are an indicator of their resilience.

By gathering responses from the marginal lands participants, a knowledge base has been compiled to act as both an inventory and a vehicle for experience sharing. The marginal lands knowledge base gives a nonjudgmental choice of methods in adapting to severe weather. It does not attempt to evaluate the efficacy of each method because of the wide variation in environments, exposure, and local economic contexts that they operate in. While for some, experiments that lead to the partial success of exotic crops would be seen as a success, in others operating in a highly commercial environment, the same outcome could be seen as irrelevant (or even harmful) to their operation.

The knowledge base is a solutions-based approach. The various problems associated with growing in climates

[3] Further information may be found on the Marginal Lands Project website (www.marginallands.org.uk).

[4] Although Gloyne gives contemporary data for these sites, the temperature data quoted is from 1981 to 2010. Data from Met Office (http://www.metoffice.gov.uk/public/weather/climate/gfxnj5fx4) for Lerwick and for Oslo Met Office data from Climatic Data from "Weather" September 2016 (Royal Meteorological Society 2016).

[5] Data from 2013 for England, 2015 from Wales and Scotland.

[6] Data from 2014 for all countries.

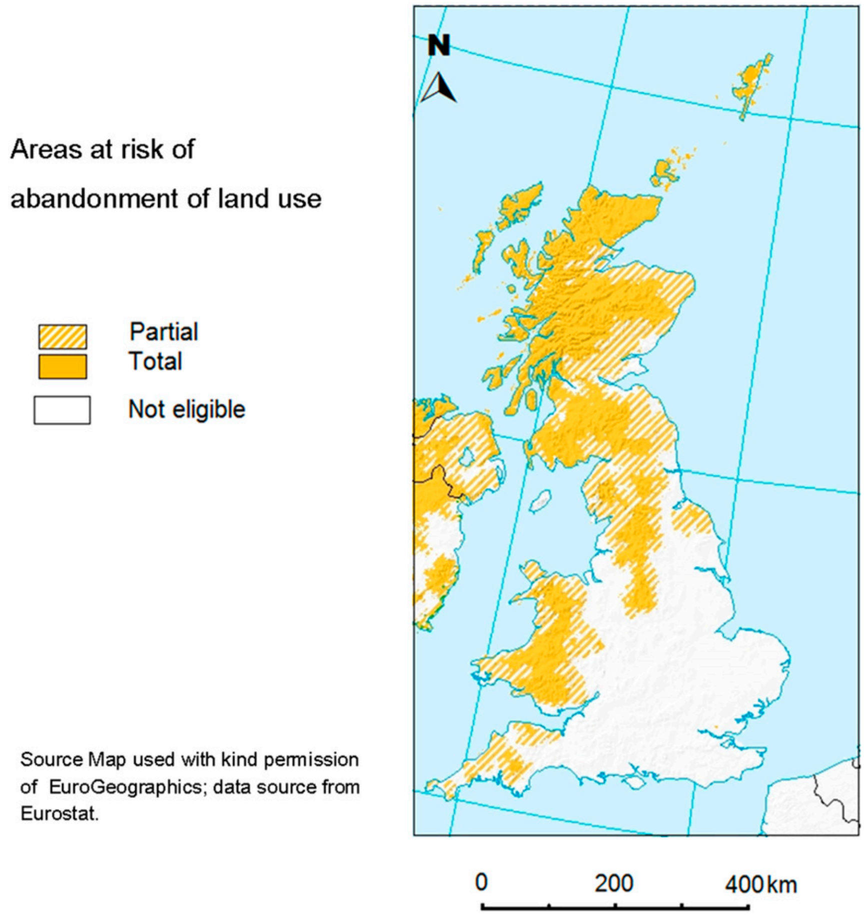

FIG. 1. EU less-favored areas eligible for compensatory allowances in Great Britain.

prone to severe weather inimical to horticulture are listed. From these lists, users can find links to the participants' descriptions of their adaptations, with illustrations and potential problems. In the longer term, the knowledge base will have applications for experience sharing as the subscription to the knowledge base increases outside the Marginal Lands Project areas; at this initial stage of the Marginal Lands Project, the collection of adaptations from varying marginal land environments (albeit in a British context) facilitates an analysis of both the level of adaptation and the popularity of various methods.

The results of this research will indicate the kind of adaptations that can be seen as highly flexible and that potentially merit support through government agricultural and environmental policies.

b. *Method and study area*

To look at adaptability to extreme weather, a series of questions on adaptations were put to 23 smallholders and farms that are all in land classed as less favored or disadvantaged and therefore marginal to fruit and vegetable growing. It was decided to focus on adaptations rather than economic criteria because a focus on economic sustainability might omit ideas with potential for transference, given a different scale or investment than the observed site.

Figure 2 shows the Marginal Lands Project site locations that include some of the Scottish islands (Shetland Islands and Lewis), locations on the British mainland (mostly in the north and west), and one exposed hilltop site in southeast England (which lies outside the disadvantaged areas but had suffered localized problems of drought, erosion, and poor drainage). The length of experience of participants ranges from under 5 to over 30 years. To find out what each holding was doing to respond to weather challenges, each weather challenge was addressed in turn, as well as multiannual responses, in the form of the use of particular crop types or crop varieties.

1) PARTICIPANT SELECTION

The 23 holdings all vary from garden scale to small farm. The size of operation varies widely from garden to

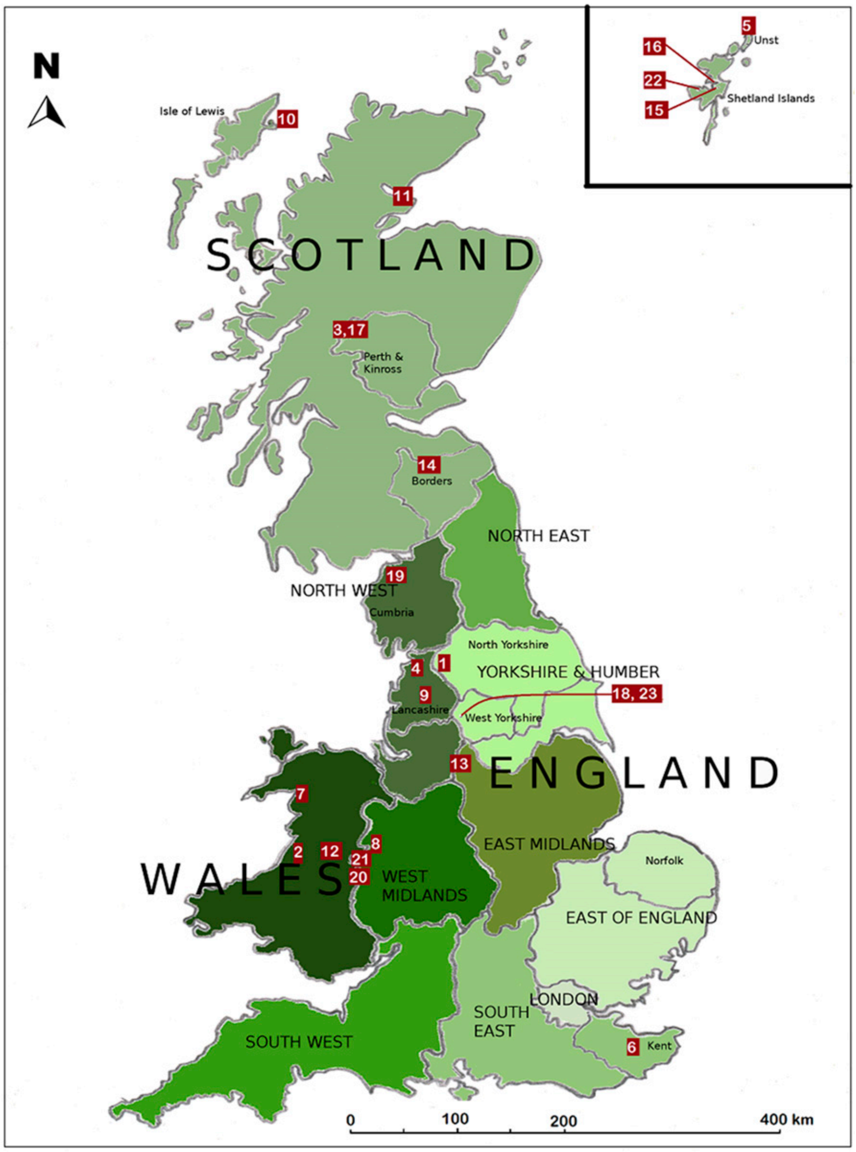

FIG. 2. Marginal Lands Project site locations and locations of countries, English regions, and islands referred to in text.

small farm and have varying types of operating models from communitarian, individual businesses, or educational. All the holdings are surrounded by pasture land or moorland. All are using agroecological methods and have been selected by an invitation via parent organizations, such as the Agroforestry Research Trust or Land Workers' Alliance, or by direct invitation through demonstration sites at the Permaculture Association or individuals linked to Nourish Scotland.

2) Interviews

The participants were asked how they adapted to weather threats. For crop side adaptation to single or multiple weather hazards, participants were asked if they used particular crop types or crop varieties to adapt to the local climate. These responses were elicited through semistructured interviews, where specific weather threats were raised in turn and the participants were asked on how they adapted, either through intervening by altering the microclimate or by mitigating the impacts. Semistructured interviews are a useful method with a relatively small pool of interviewees; the method allows respondents to highlight what was important to them in the context of their operation being for profit, education, or a community role. In the field of climate and weather impacts and adaptation, a study on the impacts of climate extremes on protected grasslands in Hungary used semistructured interviews with stakeholders (Malatinszky 2016), and Berkhout et al. (2006) used this method for analyzing climate change adaptation by business organizations. A semistructured interview allows for further elaboration over a particular topic and eliciting of expertise. The disadvantages of the semistructured interview method are that negative or positive biases may be present, and strict comparison on responses may not be possible. The questions are listed in the appendix.

First, participants were asked how they dealt with persistent heavy rain and associated hazards of waterlogging, soil erosion, or crop damage. Second, they were asked about temperature hazards, such as excessive heat or cold, in the form of cold/warm spells or unseasonal frosts. Third, participants were asked how they mitigated against the wind or protected their site from damaging gales. Fourth, participants were asked how they dealt with the lack of light caused by the predominantly cloudy conditions. Fifth, participants were questioned on how they adapted to drought, where a shortage of a reliable supply of water created vulnerability. Finally, participants were asked about barriers to adapting and whether their methods had been adopted elsewhere.

3) Knowledge base of adaptation and classification of adaptation responses to measure resilience

The responses were compiled to a knowledge base—an inventory of adaptation options. The knowledge base had each adaptive measure listed and commentary by the participants on those measures. This enables a user to explore the context of a measure being used and the advantages or possible pitfalls if they were described by the participant.

Such an inventory with the commentary on many of the measures allows an analysis of the adaptive approaches taken by each of the 23 participants. This analysis summarizes the adaptive approaches taken by the participant for each hazard, and the results can be analyzed in context of the type of holding and its mode of operation (i.e., whether commercial interests may influence a particular decision), by their geographic location, or the type of response to each weather hazard.

Measuring a change in resilience poses a problem for the Marginal Lands Project sites because of the wide variety of weather problems and economic contexts of the various operations. In the Shetland Islands, potential demand for fresh, locally grown produce is high because supply lines are very long, and it is difficult and expensive to maintain freshness in produce. The supermarkets in the capital, Lerwick, are served by overnight ferries from Aberdeen. Access to fresh produce away from the capital, Lerwick, is very limited; on the isle of Unst, a journey to a supermarket involves two ferries. With open terrain, strong winds are the most consistent constraint on growing, with the added problem of salt borne from the nearby Atlantic Ocean or North Sea. There is also a risk of extreme gales damaging infrastructure: wind gusts over 100 mi h^{-1} (mph; 161 km h^{-1}) from intense Atlantic depressions were recorded at low-altitude sites on Shetland in both January 2015 and January 2016. (Met Office 2015, 2016). In contrast, participants in less isolated areas have high levels of competition from a range of suppliers, particularly supermarkets. A farm south of Edinburgh and a market garden near the English–Welsh border have diversified by working with other businesses sharing their site or a shop. The predominant weather risks are different at these inland sites: for example, both have to cope with a risk of late or early frosts.

It is therefore important to measure resilience on the terms of the landholders. Jones and Tanner (2017) measure resilience by utilizing a subjective approach of assessing resilience at a household level. This allows people to self-assess, focusing on factors that are important to them and that may be missed by an expert approach.

The response types, in terms of adapting to adverse weather, have been analyzed and grouped according to the answers supplied by the growers. The strategies for adaptation listed in Table 1 have been coded and assigned a score relating to the level of adaptation. Each adaptation to weather challenges at each site was codified, and this is illustrated in Table 2. The scores assigned to the response strategies (according to the values listed in Table 1) were then totaled for each site. The results of this scoring, together with the type of operation, and their methods are listed in Table 3. In addition, any barriers mentioned in the interview were listed. To give some indication of the varying levels of adaptation, the sites were ranked in terms of the level of adaptation through the weather adaptability score. The levels of adaptation have to be seen in the context of the type of operation and the stated barriers to adaptation.

The choice of categories was based on how participants have reported their initial strategy to the local climate and their reactions to subsequent severe weather events. The categories have been designed to reflect whether adaptability has been affected by external forces or have been of a strategy to gradually adapt (say by planting trees, which over time will modify the microclimate).

TABLE 1. Codes for adverse weather adaptation strategies for individual growers.

Adaptation code	Attitudes toward adaptation responses to severe weather	Score
1	Adaptation strategy currently working	1
2	Adaptation strategy changed by event	1
3	Risk limitation adaptation	0.5
4	Acceptance/partial adaptation	0
5	Incremental change	0.5
6	Experimental strategy: See what works	0.5
7	Adaptation limited by barrier	−0.5
8	No adaptation response, not (yet) exposed	0
9	No adaptation after a hit	−1

These proposed scores were created to give an estimated assessment of the propensity to adapt and are therefore reliant on the participants' assessment of their own strategy. Further refinement of the scoring would be possible with a larger-scale study and more metrics. A higher score of 1 was given to those strategies that appear to be successful or responsive. A score of 0.5 was given for those respondents who sought a balance between adapting fully and lowering risk by reducing their potential yield. A score of zero was for those strategies that had not involved exposure to a hazard or a partial loss was balanced against making some investment into an adaptation. A score of −0.5 was for those finding that their adaptation was limited below what they would ideally like, possibly by external factors such as ownership of the land. The lowest score was for no adaptation: weather-related losses were accepted, but this could be a minor economic loss for a growers' overall operation.

The response types were as follows:

1) Adaptation sufficient—The original strategy is perceived by the participant to be meeting the challenges posed by the weather.
2) Adaptation changed by an event—A single or multiple severe weather episode has been the trigger for a change in response from the original strategy.
3) Risk limitation—The growing period or range of crops is limited (e.g., planting out later than previously or certain crops not attempted).
4) Risk acceptance and partial adaptation—This approach involves adapting up to a certain level (limited by circumstances) and acceptance of losses.
5) Incremental change—This involves a long-term strategy for adaptation over a number of years. There is an implicit acceptance that the mitigating effects will take years to be fully realized (e.g., tree planting).
6) Experimental—This approach is very much one of trial and error to see how particular crop varieties perform or how an innovation might work.
7) Adaptation limited by barrier—This is where a specific barrier has been mentioned such as cost, planning rules, or labor requirements.
8) Unexposed—The adaptation or lack of adaptation has not been met by a weather hazard. While a weather hazard might be potential problem, it is unknown whether there is a vulnerability to the hazard.
9) No adaptation after a loss—After the smallholding has suffered a loss because of the impacts of severe weather, the holder has decided not to change their strategy. This might be due to the losses being insignificant (at least economically, not in yield terms) or due to a perception that despite the loss, nothing could be done in response.

To assess each site's resilience, a weighting score was attached to each response type, and these were added up, and the sites ranked, to give a rough assessment of the adaptability to severe weather.

3. Results and discussion

The responses of the Marginal Lands Project participants are summarized below in the context of the response type, together with popular or notable solutions to particular problems. Before the responses to specific weather and climate hazards, there is a brief synopsis of any multifaceted response by landholders to adverse weather in the form of selections of particular crop types and varieties. The responses to each weather hazard are summarized by the popularity of particular methods and the response type; this is informed by both the knowledge base and the analysis of response types.

a. *Crop varieties*

Most people (13 sites) have a strategy that they perceive as being currently sufficient (adaption type 1). For some, it is selecting varieties that can cope with a shorter season, such as frost hardy salads (mentioned by participants at four sites) or early varieties of crops. This approach could be refined further by selecting local varieties of crops (such as northern English varieties of apples used by four sites) or choosing varieties, not specifically local, that are known to do well in the area and can deal with specific hazards. At site 10 on the isle of Lewis, the holding grows varieties of kale, cabbage, and potatoes that can cope with the windy climate. In the Scottish Highlands, site 17 has tomatoes that can cope with low light levels. At site 14, in the hills of southern Scotland, a half-height variety of kale is grown, which does not break under the weight of snow.

An experimental approach (response type 6) to crop types and varieties was carried out by eight holdings, three of which operate on a commercial basis. A high-altitude

TABLE 2. Coded adaptation strategies for Marginal Lands Project sites against each weather challenge.

			Response to extreme weather challenges									
				Rain				Temperature				
Site	Agroecology methods	Type of holding	Crop Varieties	Waterlogging	Soil compaction	Erosion/ flood	Damp and mold	Cold	Heat	Wind	Light	Drought
1	Permaculture	Livestock farm	1	2	2	7	1	1	1	2	4	1
2	Permaculture	Educational; commercial	1	1	1	1	1	1	4	5	3	2
3	Permaculture	Private garden and commercial	1	6	1	1	4	1	9	7	4	1
4	Permaculture	Livestock farm and educational	6	1	1	5	9	1	2	6	6	4
5	Organic	Commercial market garden	6	4	1	2	1	2	2	2	4	2
6	Permaculture	Livestock farm	8	1	5	2	8	1	5	1	8	1
7	Permaculture	Educational smallholding	6	1	2	1	1	4	4	1	4	2
8	Permaculture	Educational smallholding	1	6	1	2	9	1	1	5	3	2
9	Forest garden	Community garden	1	1	5	1	8	6	8	1	1	1
10	Organic lazy bed crofting	Private garden	3	8	8	8	8	1	8	3	9	9
11	Biodynamic forest garden	Private garden	1	2	1	1	1	1	1	5	1	2
12	Organic no dig	Commercial orchard	6	4	1	1	1	4	9	1	9	2
13	Forest garden	Private garden	6	4	3	4	8	2	4	4	8	4
14	Organic	Educational, commercial, livestock farm	1	2	2	5	4	3	2	5	9	5
15	Permaculture	Commercial/community market garden	6	6	1	1	1	1	4	2	1	8
16	Organic	Private garden	1	1	8	8	1	1	1	1	3	1
17	Permaculture	Commercial, educational, livestock farm	1	7	1	1	8	2	1	3	3	8
18	Organic orchard	Community	1	8	8	1	8	8	8	5	8	1
19	Permaculture	Commercial, educational, livestock farm	6	1	2	8	8	8	8	2	9	5
20	Organic	Commercial market garden	5	1	2	4	3	4	1	2	4	1
21	Forest Garden	Livestock farm and private garden	6	2	1	1	1	9	8	1	9	2
22	Organic No Dig	Private garden and commercial	1	1	1	1	1	1	1	3	1	8
23	Permaculture	Commercial market garden	1	2	1	2	9	2	4	1	3	8

TABLE 3. Adaptation strategies scored, with sites ordered to level of adaptability to weather.

Site No.	Agroecology methods	Type of holding	Barriers to adaptation	Weather adaptability score
11	Forest garden	Private garden	Economic	9.5
22	Organic no dig	Private garden and commercial	(Time for cooling polytunnel)	8.5
2	Permaculture	Educational; commercial	Planning	7.5
5	Organic	Commercial	Economic	7.5
1	Permaculture	Livestock farm	Economic	7
9	Forest garden	Community	Wild animals	7
15	Permaculture	Commercial	Economic; labor	7
16	Organic	Private garden	Economic; availability of land	7
7	Permaculture	Educational	Planning	6.5
8	Permaculture; biodynamic	Educational	Planning; pollution	6.5
20	Organic	Commercial	Economic	6.5
6	Permaculture	Livestock farm	Economic	6
14	Organic	Educational, commercial, livestock farm	Environment; economic	5.5
23	Permaculture/organic no dig	Commercial	Economic	5.5
4	Permaculture	Livestock farm and educational	External	5
17	Permaculture	Commercial, educational, livestock farm	None at small scale	5
3	Permaculture	Private garden and commercial	Livestock	4.5
21	Forest garden	Livestock farm and private garden	Economic, time, labor	4.5
12	Organic no dig	Commercial	None	3.5
18	Organic orchard	Community	Land ownership	3.5
19	Permaculture	Commercial, educational, livestock farm	Economic; time; labor	3
13	Forest garden	Private garden	Planning	2
10	Organic lazy bed	Private garden	Wild animals	0

(350 m) commercial orchard and cider business in mid-Wales, site 12, is trialing around 450 different varieties of apples and 70 varieties of pears to see how well they do in the local conditions.

In contrast, another commercial grower, site 5 on Unst, Shetland Islands, operating on a small scale as a sole trader, does not select particular varieties apart from blight resistant potatoes. A market garden near the Welsh/English border has found their choice of crop is a balance between those that have flavor and those that will perform well on their upland site.

b. *Adaptation to excess rainfall*

Excess rainfall brings about direct problems of waterlogging and erosion and indirect problems of soil compaction and mold from persistent damp conditions. Each problem is dealt with separately.

For waterlogging, 13 sites have improved drainage, seven using field drains and six using swales to disperse rather than remove the water off site. Eight sites use raised beds or terracing, and seven use polytunnels as a barrier to excessive rainfall. Other methods used to intervene in soil moisture conditions include tree planting to absorb excess water and changing the soil composition, either by adding sand and grit or by increasing the organic matter through green manure. There were also more passive ways of coping with wet conditions such as selecting better drained parts of the site for planting, using fruit trees that tolerate boggy conditions, or by using a roof or guttering for strawberries.

In all there were 22 different techniques: 10 out of the 23 sites had kept to their original adaptation strategy. A further five had altered their adaptation plan, and four were trialing new approaches. Many sites had significant losses in the wet summer of 2012, but there were no reports of losses without further adaptation; in other words, the issue of waterlogging was something that was always responded to.

Erosion from flood events were responded to by tree planting and use of raised beds. Other soil management techniques, carried out by single sites, include keyline ploughing[7] and contour fencing (for livestock) in order to manage runoff. In north Wales, at site 7, the creation of a raised marsh through a fascine causeway[8] alleviated erosion and soil washout from an intense storm, when

[7] A keyline plough is used to improve water retention on the land, without turning the soil over; it is used along or just near the contour line.

[8] An ancient Welsh technique using brash to raise the level of a wetland, to filter retain water and act as a path.

over 80 mm of rain fell within 3 h on the surrounding steep terrain in July 2001.

Raised beds were the most popular (12 sites) response to soil compaction. Five respondents have restricted the size of tractors on their land, and one site has introduced horse-drawn equipment to overturn weeds on the fragile soils of Shetland. On the steep hillsides of north Wales, changing the land use from open pasture to a lightly grazed open wood/scrubland was a way of managing the land sustainably for livestock, with the added benefit of berries as a crop.

Again, around half the respondents (11), were content with their original strategy of minimizing losses. Five sites had altered their practice in the aftermath of a flood, two were only able to partially adapt, and another had external circumstances curtailing tree planting.

Persistent damp conditions and mild warm winters can lead to fungal problems, and polytunnels are at risk, so most responses are down to ensuring adequate ventilation and cleaning of the polytunnel. Seven respondents replied that their location, being windy, inhibited the problem of molds. Three respondents reported losses without changing their response, with one losing an entire winter kale harvest. Another response was to grow smaller leaf varieties of salad in winter, which had a lower susceptibility to molds, and to keep crops outside in winter.

In summary, the responses to waterlogging, erosion, and soil compaction are broadly similar in that most sites have an adaptation strategy, and when that has not worked, they have changed it. There was more experimentation carried out to tackle waterlogging. In contrast, for response to the problems of molds there is little change in adaptive responses, and windy sites were repeatedly cited as advantageous.

c. *Adaptation to adverse temperatures*

In response to cold temperatures, respondents listed adaptations they made to deal with the risk of late or early frosts, very low temperatures, prolonged cold, or penetrating icy winds.

Of the solutions, most popular is the use of agricultural fleece (commonly used by conventional farms). The use of a hotbed in the polytunnel or greenhouse revives a historic technique and, with the right timing and scale, can make a dramatic difference where low temperatures are a persistent problem. At site 1, at 380 m up in the hills of the Yorkshire Dales in North Yorkshire in northern England, the risk of frosts and a short growing season was a reduced by building a hotbed using animal manures and straw, which generated heat for six weeks, with temperatures reportedly up to 10°C higher.

To alleviate freezing or generally cold conditions in a polytunnel, water containers were used by six sites, and a further six used either fleece or polythene inside the polytunnel as a protective barrier. At site 14, in the Scottish Borders, the risk of frost can be as late as May and June. Specifically for frosts, in comparison to cold climate conditions, there were fewer adaptations and fewer sites stating that they were making adaptations. With fruit trees vulnerable to frosts and physically difficult to protect, site 9, a forest garden in Lancashire (northwest England) uses an outlet for cold air to drain away using the entrance track through the mature woodland.

In terms of adapting, 11 sites maintained their adaptation strategy, and a further four have changed in response to episodes of severely cold weather; four have experienced some level of loss from a late frost. The two most recently established sites (sites 18 and 19) had not yet experienced exceptionally cold conditions or a frost with an impact.

Both heat waves and mild winters bring problems, and overheating in polytunnels was mentioned as a risk in several sites in Shetland, despite the cool summer temperatures; the mean maximum temperature in July is 15°C at Baltasound on Unst.[9] Widely, ventilation was cited as the simplest response for heat in polytunnels or cooling with water. Site 14 (in southern Scotland) had introduced a Keder house, which encourages a more even internal temperature because of its cladding material. Another method was the mulching of the soil to protect the ground from heat, which was used by four sites.

The heat hazard triggers a different adaptive response. Seven sites accept some impacts from heat, with some or no mitigating action (i.e., response types 4 and 9). Another seven sites were using their original strategy, with just two altering after a heat wave. On the southernmost site, site 6, in Kent, shade for livestock is encouraged through tree planting along swales in parallel lines.

This different response toward heat could be explained by the fact that out of the 23 sites, 6 have not been exposed to heat waves as a hazard, indicating for many of the sites heat waves are rare, and the risk is perceived as lower than for excess rain.

d. *Adaptation to high winds*

All mainland (i.e., on the island of Great Britain itself) sites used either trees (13 in total) and/or hedges (12 in total) as windbreaks. Most of the island-based sites did not, instead using mesh or fishing nets to break up the

[9] http://www.metoffice.gov.uk/public/weather/climate/gcw7y8w53.

wind; mesh was also used by four inland sites. Four sites also used raised earth banks to divert the wind away from crops. Where possible, in smaller cultivated areas, buildings or a fence were used to shelter from prevailing winds. Where there were larger fields, such as at site 20, a more windproof mulch for the soil was used.

While there are problems for sites with a windy climate, there is a need for adaptation to the strongest wind storms, which cause physical damage to crops, buildings, or infrastructure. Apart from securing polytunnels or staking of crops, other solutions include shorter varieties of crops or the use of layers of shelter belts. The orchard at site 12 used a forestry notch planting system[10] for young apple and pear trees to prevent damage by gales.

In terms of response to the wind hazard, five sites had taken a long-term incremental (response type 5) approach, that is, using growing shelter belts. Another seven have kept to their original strategy. Two are hampered by implementing optimal solutions to high winds; at site 3 in Highland Perth and Kinross, double fencing to protect a hedge from livestock cannot be installed on one side because of the land belonging to a neighbor. At site 5, financial circumstances prevented the purchase of a reinforced polytunnel, a polycrub, which can withstand winds of over 160 km h^{-1} (100 mph); however, the polytunnel has since been rebuilt to a more robust specification.

In summary, the main focus on adaptation to wind is through trees or hedges; where this is more difficult, mesh or netting is used to break up the wind.

e. Adapting to low light

The lack of light from very cloudy conditions has brought about the least number of strategies that have been regarded as sufficient by landholders—just five. For most sites on the British mainland, the unusually wet year of 2012 also brought dark, cloudy conditions, with the whole of the United Kingdom recording just 80% of summer sunshine hours compared to the 1990–2010 average [data from Met Office (2012)]. Four sites met the highest weather hazard with response type 9 (a loss with no further adaptation) and a further five of response type 4, who feel that they can only partially adapt to the lack of light. Significantly, it is the only hazard where there was no change in adaptation in response (response type 2).

Nevertheless, there were responses to low light conditions, and this involved increasing light by improving light conditions on site by siting plants selectively by the design of the site or by removing shade. Just two sites used artificial lighting, and a further two used reflective surfaces on a wall to increase light levels. Another approach is to reduce the risk of poor light by growing low light demanding plants and accepting the limitations of low light levels outside of summer (response type 3). At sites 11 and 17 in the highlands of Scotland, the landholders do not try to grow during the dormant season.

f. Adaptation to drought

Drought triggered the biggest number of sites making a change in strategy (adaptation type 2) in response to a drought event: 7 sites out of 23, with just six keeping their original strategy and a further two with a long-term incremental plan.

Increasing the water storage capacity on site was the most frequent response, from introducing large tanks (nine sites), rainwater harvesting from buildings (seven sites), and the creation of ponds (six sites). On the island of Unst in Shetland, site 5 has no access to mains water, and water is supplied from a ditch with a very limited catchment. The owner of the market garden has adapted by collecting water through the autumn, winter, and spring, using solar-charged batteries to power a bilge pump to fill 13 intermediate bulk containers (IBCs)[11] (13 000-L capacity), but even this supply was down to the last 250 L after a prolonged dry spell.

Another important adaptation by eight sites was a long-term adaptation measure by mulching of soil, adding an organic cover to the soil to reduce evapotranspiration. Site 4 was also starting to use biochar, a form of charcoal, as a means of increasing the soil's water retention capacity. Other individual innovations included the recycling of heating water and the storing of water in ditches or a small pit.

Despite most sites being in areas of high rainfall, the responses from the landholders show that all but four have experienced drought, and this has been the biggest trigger to change strategy, more so than the other weather hazards. There were seven instances of changing strategy after a drought (response type 2) compared to just two after heat waves; six had not been exposed to heat waves (response type 8), while only four had not been exposed to drought.

The analysis of adaptation strategy is summarized in Table 3. Although these are ranked, this is meant as a preliminary analysis, as it based on subjective responses and does not take into account the yields or economic circumstances of each operation.

[10] The forestry notch system is a means of planting a tree in a T-shaped cut in the ground to maximize root stability and obviates the need for staking a tree against high winds.

[11] Each IBC has a capacity of 1000 L.

Taking these factors into account it appears that the most adaptive sites (those scoring over 7) include a forest garden, a private garden and a smallholding, a livestock farm, and a community garden. Those scoring least may well be fortunate in having less exposure to weather hazards. Site 10 on Lewis managed by growing traditional island crofter's crops. Other sites have less experience or have a relatively resilient site for their particular activity; site 18 is an orchard on a slope that has withstood recent flooding and has not yet been exposed to a prolonged drought.

There is no common factor in terms of the type of activity or geographical location, which indicates that adaptability to severe weather is very much based on individual responses. The sites with the three highest scores are relatively well established (1995, 2000, and 2008) compared to those at the lower end of adaptability.

4. Conclusions

The focus on adaptions appears to be aimed at the main climatic limitations of British marginal lands, such as high levels of rainfall and wind. The results show that there is a high level of response to heavy rainfall and associated problems of waterlogging and soil issues such as erosion and compaction. More problematic was responding to molds from damp, still conditions, and only windy sites had an advantage. The exceptionally prolonged wet weather during the summer growing season, which occurred in 2012, also brought the greatest challenge to many of the sites. Those less affected were growing under cover or had salads, but most importantly, all had adaptations in place and had intentions of further adaptation.

The main problem from cold conditions came from late or early frosts, as many sites had adaptions in place to deal with more prolonged cold conditions. Heat waves appeared to be a rarer phenomenon, as many of the sample sites are located on islands, have a strong maritime influence, or are at high-altitude locations. However, drought had forced nearly one-third of sites to alter their strategy. Most (21 of 23; the exceptions being sites 6 and 11 with rainfall below the U.K. average[12]) are disadvantaged land sites associated with high rainfall and cooler conditions, so it is clear that the perception of these areas' climate, that is, the main limit being the high rainfall, belies their actual vulnerability to drought.

The analysis by adaptation type can give a more nuanced view of the motivations for action, being much more than a cost–benefit decision, as implied by White et al. (2009) or Posthumus et al. (2009). By looking at marginal lands participants, the study indicates that those with higher weather adaptability scores have adaptation strategies to severe and extreme weather that are constant and sophisticated rather than responsive to individual adverse weather events. This reflects the very different approach to food production, particularly from the practices of permaculture and agroforestry in which a close observation appreciation of the local climate and environment is central to the creation of low input food systems, with the landholding design reflecting the resilience and stability of a natural ecosystem through diversity (King 2008).

Evidence from the Marginal Lands Project, where former rough pasture sites can support horticulture, would suggest agroecology can potentially increase resilience. Agroecology encompasses longer-terms solutions to drought and flooding issues through measures such as tree planting, fascine causeways, or improving the soil's organic content to increase its water retention capacity. These long-term adaptation measures can increase the resilience of a farm if they are applied in a way to maintain its long-term viability. The marginal land growers have to use innovation simply to operate at all, and the results from the knowledge base show a wide range of adaptations. This indicates a high level of ingenuity as a factor of resilience stated by Fraser et al. (2003), coupled with available resources (monetary or nonmonetary). However, the results also indicate that experience with a wide range of severe weather events over time may well be a factor in increasing resilience. The marginal lands knowledge base itself could potentially help to increase resilience as the experience sharing could assist landholders make more informed choices on adaptations. In addition, there are barriers to adaptations mentioned by participants such as the cost of fencing to protect crops and trees from wild or neighboring farm animals, planning permission, and shortage of affordable land. These issues need to be addressed by policymakers as part of assisting more "climate smart" agriculture.[13]

With this evidence, there are opportunities for further research. First, there is the potential of the techniques and crop choice and varieties used by agroecology practitioners in marginal lands to be adopted by conventional farms in similar environments

[12] Site 6 has approximately 800-mm annual rainfall; site 11 has 646 mm. The mean value for the United Kingdom is 1154 mm (1961–90 average). Sources are Met Office (2017a,b) and Kendon et al. (2016).

[13] CSA is defined as way forward for food security in a changing climate. CSA aims to improve food security, help communities adapt to climate change, and contribute to climate change mitigation by adopting appropriate practices, developing enabling policies and institutions, and mobilizing needed finances [Paudel et al. (2017), after FAO (2013)].

and by demonstration sites. How these techniques assist in the resilience of farms during periods of severe weather would need to be examined by agricultural stakeholders, and this has been already been done to assess a pool of techniques for climate smart agriculture (CSA) in Nepal in conjunction with demonstration and testing and to develop climate smart agriculture ''champions'' (Paudel et al. 2017). As a consequence, farms in the agricultural heartlands of Britain could buffer their risk by growing resistant crops alongside their main crop or by using agroforestry techniques to moderate severe weather events.

Resilience can also be looked at in terms of relative yields, inputs, and/or the economic sustainability of agroecology and conventional sites and set against a time series of severe weather events.

Second, the moderation of the microclimate at particular sites could be measured to observe the level of exposure, and therefore change, possible using carbon neutral (e.g., fossil fuels are minimized) agroecological techniques.

With the ADAS/University of Leeds (2013) report indicating the greatest threat to English agriculture was from a combination of severe weather, the range of adaptation options used by the more adaptive marginal land sites, in a variety of geographical and economic situations, suggests that institutional support for experimentation and demonstration of some of these techniques would allow for appropriate adoption by the wider farming community. It implies a more diverse production model, which is a break from the production-oriented agricultural policies of the past. With food security driving a move toward sustainable intensification in food production, there needs to be a debate on the implications of the most appropriate methods to be used on the British landscapes, in view of the potential for more extreme weather in future. Garnett et al. (2013) declare that sustainable intensification ''demands radical rethinking of food production to achieve major reductions in environmental impact. In some areas increases in yield will be compatible with environmental improvements'' (Garnett et al. 2013, p. 33).

Any increase in the threat of climate change–induced extreme weather events means that moving toward a more resilient landscape and means of food production is of paramount importance; the Marginal Lands Project already offers some examples for sustainable adaptation.

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APPENDIX

Questions on Growing Food in Marginal Lands

Can you give a description of your site in terms of location, slope, soils, exposure, and what is grown and for what use.

0. Multi Annual Adaptations

Do you grow any specialized crops to deal with harsher climate, and unpredictable weather, such as late frosts?

1. Rain

How have you coped with excess rainfall?

(a) How have you coped with waterlogging of beds or fields? (I am thinking of events with higher than normal rainfall.)
(b) Any problems with soil compaction?
(c) Any problem with floods/erosion (possibly caused from upstream?)
(d) Any mold problems from excess moisture/mild winters?

2. Temperatures

(a) How have you coped with cold temperatures?
(b) Have you made any adaptations to deal with the risk of late or early frosts?
(c) Very low temperatures, prolonged cold (e.g., <-5°C), or penetrating icy winds?
(d) How have you coped with heat waves, out of season high temperatures?

3. Wind

(a) How have you dealt with general exposure to high winds?
(b) Have you had occurrences of storm winds causing damage?

4. Cloud and Light

How have you coped with low light levels for vegetables and fruit?

5. Drought

How have you coped with drought? (This includes droughts outside of summer.)

6. General

What are the barriers to implementing adaptations? (e.g., cost, regulations, neighbor's opposition?)

Have your innovations/adaptations been copied/ taken on by neighbors and contacts?

7. Anything not covered here?

REFERENCES

ADAS/University of Leeds, 2013: Climate change and extreme weather events; establishing a methodology for estimating economic impacts on agriculture. ADAS and University of Leeds Rep., 106, http://randd.defra.gov.uk/Default.aspx?Menu5Menu&Module5More&Location5None&Completed50&ProjectID518670.

Adejuwon, J. O., T. O. Odekunle, and M. O. Omotayo, 2008: Using seasonal weather forecasts for adapting food production to climate variability and climate change in Nigeria. *Climate Change and Adaptation*, N. Leary et al., Eds., Earthscan, 163–180.

Agroforestry Research Trust, 2016: Agroforestry. Accessed 19 August 2016, https://www.agroforestry.co.uk/about-agroforestry/.

Altieri, M. A., C. I. Nicholls, A. Henao, and M. A. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agron. Sustainable Dev.*, **35**, 869–890, https://doi.org/10.1007/s13593-015-0285-2.

Archer, D. R., 2007: The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales. *J. Hydrol.*, **347**, 487–496, https://doi.org/10.1016/j.jhydrol.2007.09.036.

Archer, N. A. L., M. Bonell, N. Coles, A. M. MacDonald, C. A. Auton, and R. Stevenson, 2013: Soil characteristics and land-cover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local flood management. *J. Hydrol.*, **497**, 208–222, https://doi.org/10.1016/j.jhydrol.2013.05.043.

Benton, T., B. Gallani, C. Jones, K. Lewis, and R. Tiffin, 2012: Severe weather and UK food chain resilience: Detailed appendix to synthesis report. U.K. Government Office for Science Rep., 35 pp.

Berkhout, F., J. Hertin, and D. M. Gann, 2006: Learning to adapt: Organisational adaptation to climate change impacts. *Climatic Change*, **78**, 135–156, https://doi.org/10.1007/s10584-006-9089-3.

Borron, S., 2006: Building resilience for an unpredictable future: How organic agriculture can help farmers adapt to climate change. Food and Agriculture Organization of the United Nations, 25 pp.

Caborn, J. M., 1955: The influence of shelter-belts on microclimate. *Quart. J. Roy. Meteor. Soc.*, **81**, 112–115, https://doi.org/10.1002/qj.49708134727.

Dadson, S. J., and Coauthors, 2017: A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proc. Roy. Soc.*, **A473**, 20160706, https://doi.org/10.1098/rspa.2016.0706.

DEFRA, 2010: Structure of the agricultural industry in England and the UK at June. Accessed 3 June 2016, https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june.

Environment Agency, 2016: Adapting to climate change: Advice for flood and coastal erosion risk management authorities. Accessed 17 May 2017, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/571572/LIT_5707.pdf.

Evans, R., 2006: Curtailing water erosion of cultivated land: An example from north Norfolk, eastern England. *Earth Surf. Processes Landforms*, **31**, 598–605, https://doi.org/10.1002/esp.1354.

FAO, 2013: *Climate-Smart Agriculture Sourcebook*. Food and Agriculture Organization of the United Nations, 557 pp., http://www.fao.org/docrep/018/i3325e/i3325e.pdf.

Fraser, E. D., W. Mabee, and O. Slaymaker, 2003: Mutual vulnerability, mutual dependence: The reflexive relation between human society and the environment. *Global Environ. Change*, **13**, 137–144, https://doi.org/10.1016/S0959-3780(03)00022-0.

Garnett, T., and Coauthors, 2013: Sustainable intensification in agriculture: Premises and policies. *Science*, **341**, 33–34, https://doi.org/10.1126/science.1234485.

Global Food Security, 2015: Extreme weather and resilience of the global food system. Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience, Global Food Security, 17 pp., https://www.foodsecurity.ac.uk/publications/extreme-weather-resilience-global-food-system.pdf.

Gloyne, R. W., 1954: Some effects of shelterbelts upon local and micro climate. *Forestry*, **27**, 85–95, https://doi.org/10.1093/forestry/27.2.85.

——, 1973: Crop production in higher latitude, maritime areas. *Int. J. Bioclimatol. Biometeor.*, **17**, 349–354, https://doi.org/10.1007/BF01554064.

Hansen, J., M. Sato, and R. Ruedy, 2012: Perception of climate change. *Proc. Natl. Acad. Sci. USA*, **109**, E2415–E2423, https://doi.org/10.1073/pnas.1205276109.

Holden, J., 2009. Upland hydrology. *Drivers of Environmental Changes in Uplands*, A. Bonn et al., Eds., Routledge, 113–134.

Holling, C. S., 1973: Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.*, **4**, 1–23, https://doi.org/10.1146/annurev.es.04.110173.000245.

Holt-Giménez, E., 2002: Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: A case study in participatory, sustainable land management impact monitoring. *Agric. Ecosyst. Environ.*, **93**, 87–105, https://doi.org/10.1016/S0167-8809(02)00006-3.

Jambor, A., and D. Harvey, 2010: Review of the challenges of CAP reform. Centre for Rural Economy Discussion Paper Series 27, University of Newcastle upon Tyne, accessed 5 July 2017, https://www.researchgate.net/profile/Attila_Jambor/publication/228417100_Review_of_the_Challenges_of_CAP_Reform/links/00463518a336e070d2000000.pdf.

Jones, L., and T. Tanner, 2017: 'Subjective resilience': Using perceptions to quantify household resilience to climate extremes and disasters. *Reg. Environ. Change*, **17**, 229–243, https://doi.org/10.1007/s10113-016-0995-2.

Jowitt, J., 2012: Farmers urge minister to provide extreme weather insurance. *Guardian*, 31 December, https://www.theguardian.com/uk/2012/dec/31/farmers-urge-ministers-for-weather-insurance.

Kazakova-Mateva, Y., and D. Radeva-Decheva, 2015: The role of agroecosystems diversity towards sustainability of agricultural systems. *147th EAAE Seminar CAP Impact on Economic Growth and Sustainability of Agriculture and Rural Areas*, Sofia, Bulgaria, European Association of Agricultural Economists, http://ageconsearch.tind.io/record/212250/files/Kazakova.pdf.

Keenleyside, C., 2013: The Pontbren Project: A farmer-led approach to sustainable land management in the uplands. COED CADW/Woodland Trust Research Rep., 36 pp., accessed 16 January 2014, http://www.woodlandtrust.org.uk/mediafile/100263187/rr-wt-71014-pontbren-project-2014.pdf?cb=f98dc76df3c64c31bfce622387d7379a.

Kendon, M., M. McCarthy, S. Jevrejeva, and T. Legg, 2016: State of the UK Climate 2015. Met Office, 64 pp., accessed 5 August 2016, https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/climate/state_of_the_uk_climate_2015.pdf.

King, C. A., 2008: Community resilience and contemporary agri-ecological systems: Reconnecting people and food, and people with people. *Syst. Res.*, **25**, 111–124, https://doi.org/10.1002/sres.854.

Knox, J., J. Morris, and T. Hess, 2010: Identifying future risks to UK agricultural crop production: Putting climate change in context. *Outlook Agric.*, **39**, 249–256, https://doi.org/10.5367/oa.2010.0016.

Malatinszky, Á., 2016: Stakeholder perceptions of climate extremes' effects on management of protected grasslands in a central European area. *Wea. Climate Soc.*, **8**, 209–217, https://doi.org/10.1175/WCAS-D-15-0029.1.

Mardero, S., and Coauthors, 2015: Participants' adaptations to droughts and climatic variability in southeastern Mexico. *Environ. Hazards*, **14**, 271–288, https://doi.org/10.1080/17477891.2015.1058741.

Marsh, T., 2008: A hydrological overview of the summer 2007 floods in England and Wales. *Weather*, **63**, 274–279, https://doi.org/10.1002/wea.305.

Met Office, 2012: UK actual and anomaly maps. Accessed 26 August 2016, http://www.metoffice.gov.uk/climate/uk/summaries/anomacts.

——, 2013: Record rainfall—April to July 2012. Accessed 26 August 2016, https://www.metoffice.gov.uk/climate/uk/interesting/april-july2012.

——, 2015: Climate summaries. Accessed 19 July 2017, https://www.metoffice.gov.uk/climate/uk/summaries/2015/january.

——, 2016: Climate summaries. Accessed 19 July 2017, https://www.metoffice.gov.uk/climate/uk/summaries/2016/january.

——, 2017a: Tain Range climate. Accessed 19 July 2017, https://www.metoffice.gov.uk/public/weather/climate/gfm0vv8h1.

——, 2017b: Faversham climate. Accessed 19 July 2017, https://www.metoffice.gov.uk/public/weather/climate/u10eu40xb.

Min, S.-K., Z. Zhang, F. W. Zwiers, and G. C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470**, 378–381, https://doi.org/10.1038/nature09763.

Monbiot, G., 2014: *Feral*: *Rewilding the Land, the Sea, and Human Life*. University of Chicago Press, 319 pp.

Natural England, 2009: Food, wood and energy. Mapping values: The vital nature of our uplands, Natural England, 6–11, http://publications.naturalengland.org.uk/file/92023.

Paudel, B., R. C. Khanal, A. KC, K. Bhatta, and P. Chaudhary, 2017: Climate-smart agriculture in Nepal. Local Initiatives for Biodiversity, Research Program on Climate Change, Agriculture and Food Security Policy Brief, 10 pp., https://cdkn.org/wp-content/uploads/2017/06/Nepal-agriculture-synthesis-final444.pdf.

Permaculture Association, 2016: The basics: What is permaculture? Permaculture Association, accessed 30 September 2016, https://www.permaculture.org.uk/knowledge-base/basics.

Petersen, U., and H. J. Weigel, 2015: Klimaresilienz durch Agrobiodiversität? Literaturstudie zum Zusammenhang zwischen Elementen der Agrobiodiversität und der Empfindlichkeit von landwirtschaftlichen Produktionssystemen gegenüber dem Klimawandel. Thünen Rep. 25, 136 pp.

Posthumus, H., C. J. M. Hewett, J. Morris, and P. F. Quinn, 2008: Agricultural land use and flood risk management: Engaging with stakeholders in north Yorkshire. *Agric. Water Manage.*, **95**, 787–798, https://doi.org/10.1016/j.agwat.2008.02.001.

——, J. Morris, T. M. Hess, D. Neville, E. Phillips, and A. Baylis, 2009: Impacts of the summer 2007 floods on agriculture in England. *J. Flood Risk Manage.*, **2**, 182–189, https://doi.org/10.1111/j.1753-318X.2009.01031.x.

Royal Meteorological Society, 2016: July 2016 mostly unsettled, but very dry in south. One very hot day, then a day of severe thunderstorms.*Weather*, **71**, i–iv, https://doi.org/10.1002/wea.2632.

Rural Business Research, 2016: Farm business survey. Rural Business Research, U.K. Department for Environment, Food and Rural Affairs, http://www.farmbusinesssurvey.co.uk/index.aspx.

Scottish Government, 2016: Agriculture facts and figures 2016. Accessed 26 August 2016, https://beta.gov.scot/publications/agriculture-facts-figures-2016/.

Sharmina, M., and Coauthors, 2016: A nexus perspective on competing land demands: Wider lessons from a UK policy case study. *Environ. Sci. Policy*, **59**, 74–84, https://doi.org/10.1016/j.envsci.2016.02.008.

Subak, S., 1997: Agriculture. *Economic Impacts of the Hot Summer and Unusually Warm Year of 1995*, J. P. Palutikof, S. Subak, and M. D. Agnew, Eds., University of East Anglia, 45–55.

Welsh Government, 2015: Welsh agricultural statistics 2014. Accessed 26 August 2016, http://gov.wales/docs/statistics/2015/151028-welsh-agricultural-statistics-2014-ency.pdf.

White, T. D., H. G. Moodie, T. A. Payne, M. A. Wedderburn, and N. Botha, 2009: Increasing on-farm resilience to adverse weather events: A Northland case study. *Proc. N. Z. Grassl. Assoc.*, **71**, 21–24.

Wreford, A., and W. N. Adger, 2010: Adaptation in agriculture: Historic effects of heat waves and droughts on UK agriculture. *Int. J. Agric. Sustainability*, **8**, 278–289, https://doi.org/10.3763/ijas.2010.0482.