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Combining qualitative and quantitative methodology to assess prospects for novel crops in a warming climate

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ABSTRACT

Context: Climate change will alter the global distribution of climatically suitable space for many species, including agricultural crops. In some locations, warmer temperatures may offer opportunities to grow novel, high value crops, but non-climatic factors also inform agricultural decision-making. These non-climatic factors can be difficult to quantify and incorporate into suitability assessments, particularly for uncertain futures.
Objective: To demonstrate how qualitative and quantitative techniques can be combined to assess crop suitability with consideration for climatic and non-climatic factors.
Methods: We carried out a horizon scanning exercise that used Delphi methodology to identify possible novel crops for a region in south-west England. We show how the results of the expert panel assessment could be combined with a crop suitability model that only considered climate to identify the best crops to grow in the region.
Results and conclusions: Whilst improving climate and crop models will enhance the ability to identify environmental constraints to growing novel crops, we propose horizon scanning as a useful tool to understand constraints on crop suitability that are beyond the parameterisation of these models and that may affect agricultural decisions.
Significance: A similar combination of qualitative and quantitative approaches to assessing crop suitability could be used to identify potential novel crops in other regions and to support more holistic assessments of crop suitability in a changing world.

1. Introduction

Climate influences plant growth and development, primarily through the effects of temperature and water availability on physiological processes (Woodward, 1987). For crops, the associated implications for productivity mean that their geographic distribution worldwide is governed largely by environmental conditions (Hatfield et al., 2011). The pace of recent climate change is thus a significant consideration for modern-day farmers; agricultural production globally is likely to be affected (World Bank, 2009) and the places where some of the world's most important crops can be cultivated may shift (Lane and Jarvis, 2007).

In many areas, the impacts of climate change are likely to be negative, as conditions become too hot or dry, and the weather patterns become too extreme for the crops suited to and grown under the current climate conditions. In a meta-analysis of maize, wheat and rice, for example, Challinor et al. (2014) estimate average yield losses globally of 4.90% per 1 C of warming (global surface temperature change of at least 1.5 C is likely by the end of the 21st Century; Collins et al., 2013), but with tropical areas impacted most negatively. In other locations, however, such as in northern Europe, rising mean temperatures and increases in CO_2 and rainfall due to climate change could not only improve yields of existing crops (Olesen et al., 2007; Richter and Semenov, 2005) but also allow new, more exotic crops restricted previously to lower latitudes to be grown (Audsley et al., 2006). Modelling the potential distribution of bioenergy crops under future climate change, for example, Tuck et al. (2006) predict an increase in the area suitable for oilseeds, cereals, starch crops and solid biofuels in northern Europe but a decrease in southern Europe due to increasing temperatures. The recent expansion and success of viticulture in the UK has been considered one example of a climate-driven shift in agricultural practice (Spellman and Field, 2002).

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1.1. Climate models to assess suitability for novel crops

For farmers to take advantage of emerging opportunities to grow novel crops requires them to know what crop types and varieties might grow well on their land. This information can be provided through assessments of climatic suitability, which consider the environmental requirements of different species and determine the locations where these are likely to be met. Climate suitability models have been used to identify opportunities to expand cultivation of high value cropping systems under possible future climate change scenarios. Parker and Abatzoglou (2018), for example, mapped thermal suitability for almond cultivation from 1979 to 2069 across the western United States and identified areas of increasing suitability where the crop is currently limited by insufficient heat accumulation.

As rates of warming, when examined at fine spatial resolution, can vary significantly across a landscape (Maclean et al., 2017), the development of new techniques to downscale climate data to the microscale from the mesoscale for both present and possible future climates (Lembrechts and Lenoir, 2020) could help to identify the best locations to trial or commit to growing novel crops at the farm and field level. High resolution current climate data have been used previously, for example, to identify newly suitable microclimates to grow wine grapes in areas with regional temperatures that remain borderline 'too cool' (Dunn et al., 2019). Accordingly, vineyards at higher latitudes are often located on equatorward-facing slopes to take advantage of the higher growing season temperatures, resulting from higher solar radiation and the reduced risk of frost due to lower cold-air pooling (Mosedale et al., 2016).

Despite the dominant influence of climate on crop suitability, whether opportunities to grow novel crops are realised is likely to depend on both climatic and non-climatic factors. If we consider again the case of wine grapes, a strong interaction between climatic and economic concerns is known to affect the viability of viticultural systems and their vulnerability and resilience to climate change (Lereboullet et al., 2013). Other authors have highlighted how the financial costs associated with growing a novel crop, such as those incurred to translocate a crop to a new area, to purchase new or specialised equipment, or to transport a harvest to processing plants if locally unavailable, may be considerable (e.g. Luedeling et al., 2011) and farmers are unlikely to make these investments if they make the crop commercially unviable. Culturally and socially, there may be pressure on farmers from family or the farming community to grow certain crops, particularly if the crop has a long history of cultivation in the area. Equally, cultivation of a crop may result from industry promotion. Factors such as the perceived risk associated with trialling a new cropping system will also govern farming decisions (Parker and Abatzoglou, 2018) and may reinforce resistance to change. These risks might include instability of markets as well as risks due to inadequate research and development of new technologies (Knox et al., 2010). Crop suitability is thus a complex concept and to capture in aggregate the climatic, economic, social, and cultural environment that may inform whether a new crop is grown in an area is challenging. Furthermore, incorporating socioeconomics into models can be resource intensive and feedback mechanisms make it difficult to make long-term predictions (Fischer et al., 2005).

1.2. Horizon scanning to assess crop suitability

Horizon scanning employs systematic methods and processes to consider possible futures (Sutherland and Woodroof, 2009) and has been used to support and shape decision-making and to identify risks and opportunities in the context of climate change (e.g. Sutherland et al., 2020). It has been applied to consider both broad and global issues (e.g. Sutherland et al., 2020) and to examine more specific problems in detail (e.g. Gallardo et al., 2016). Horizon scanning is not limited by one approach to data collection and may incorporate formal interviews or expert workshops to gather a wide knowledge base on the issue of interest (Sutherland and Woodroof, 2009). This can be useful when considering complex issues that may be difficult to quantify scientifically, such as the social and economic landscape of an area, as expert knowledge is often the only source of this information, particularly in the context of possible future scenarios (Linstone and Turoff, 1975; Rounsevell and Reay, 2009). Horizon scanning has been used to identify important questions for the future of global agriculture (e.g. Pretty et al., 2010), but we are not aware of its previous application to assess prospects for novel crops. However, assessing crop suitability using a qualitative approach and combining these results with the outputs of a climate suitability model might change, or better inform, agricultural decisions through more complete understanding of the best crops to grow, both now and in the future.

In this study, we consider how horizon scanning could provide an important complement to climate suitability model outputs in crop suitability assessments (e.g. Jaime et al., 2018). We use horizon-scanning and Delphi-based techniques to identify possible novel crops (qualitative assessment) for a region in south-west England (Fig. 1a) and then run a climate suitability model for those that scored highly (quantitative assessment). We discuss how combining the results and knowledge gained from the horizon scan with the climate suitability model outputs allows consideration of the socioeconomic environment alongside climate-only constraints on suitability and can provide a more holistic evaluation of crop suitability. We highlight some of the most important non-climatic factors that experts involved in the horizon scan understood to influence whether a crop would be commercially viable.

Cornwall and the Isles of Scilly in south-west England is our case study region. Climatically, annual temperature ranges are low and frosts are rare (Fig. 1b and c), and this means that it could become one of the first places in the UK to benefit from climate change and realise opportunities to grow new crops, as their potential ranges expand northwards from more subtropical regions. Furthermore, 80% of Cornwall's land area is farmed (Cornwall Council, 2016) and 11.3% of the population work in the core agri-food sector (Lobley et al., 2011). The significance of the food and drinks sector is twice that of the rest of Great Britain and so the sustainability of the Cornish economy is highly likely to be dependent on the continued success of agriculture. Non-climatic factors are expected to influence the crops grown in the region. Cornish provenance is used as a marketing tool on products sold nationally and on smaller scales by local producers (Lobley et al., 2011) and there has been ongoing interest and transition in the south-west of the UK towards the production of small-scale, high value niche crops. Alongside the anticipated rapid transformation of the UK agri-economy as a result of leaving the European Union, it is therefore both highly relevant and timely to consider options for agricultural diversification and prospects for novel crops in this area. The results of our study will direct further research on potential novel crops for Cornwall and the Isles of Scilly, but the combination of qualitative and quantitative methods used here to assess crop suitability could be applied elsewhere and is shown to be a resource-efficient way to identify agricultural opportunities for the future.

2. Materials and methods

In the first part of our study, we follow a horizon scanning approach based on the Delphi method (Sutherland et al., 2020) to identify qualitatively, fifteen potential novel crops for the study region. We then run a climate suitability model for these crops as a quantitative assessment of crop suitability. We compare the results from both assessments and discuss how knowledge of the socioeconomic environment can be combined with spatial information on climatic suitability to inform farming decisions. Below, we provide a brief overview of the study region (2.1), and then describe the horizon scan (2.2) and the climate suitability model (2.3) methodologies and how the results of these assessments were combined (2.4).

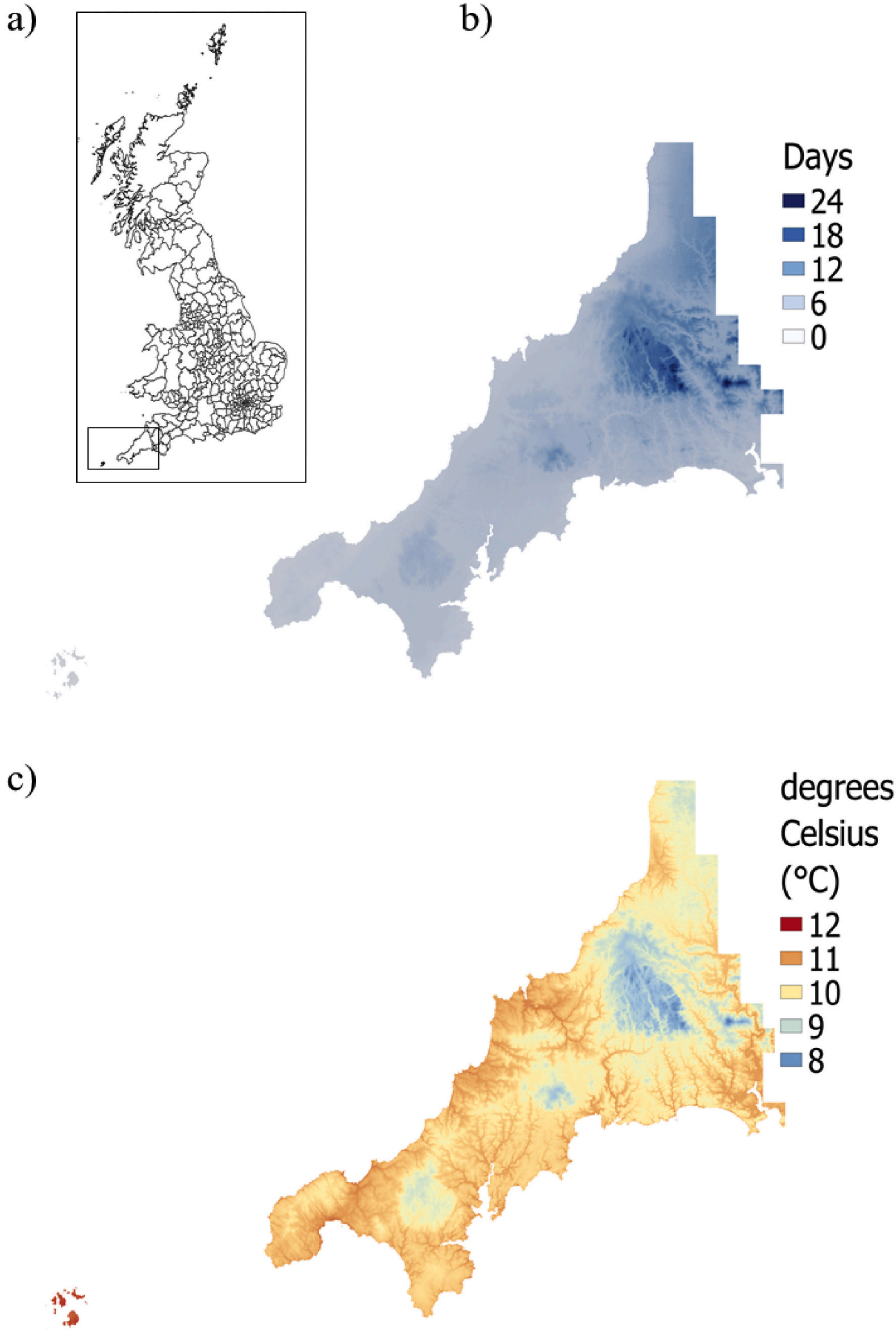

Fig. 1. Location of the study area in the United Kingdom (a); mean annual temperature (average 1983–2017) (b); total days in the year with frost (air temperature below 0 C) (average 1983–2017) (c).

2.1. Study area

We considered potential novel crops for Cornwall and the Isles of Scilly (Fig. 1a). Both annual and seasonal mean and minimum temperatures in the region have increased in the 20th and 21st centuries (Kosanic et al., 2014; Fig. 2a–b) and species composition in some places has shifted in favour of those with higher temperature and lower moisture requirements (Maclean et al., 2015). There is also interest in novel crops and their potential suitability for local commercial production (Michell et al., 2012) and so it is an ideal place to study

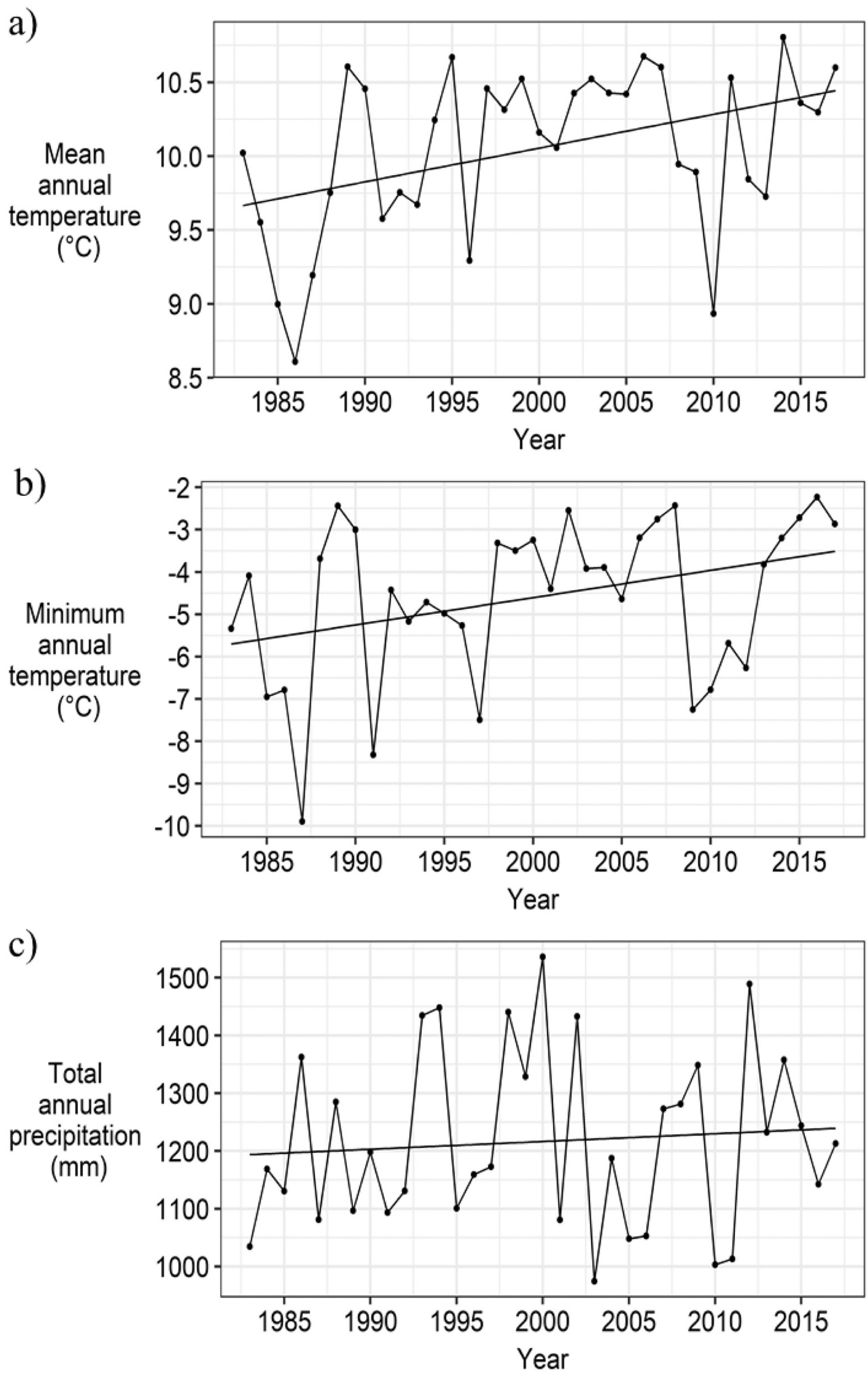

Fig. 2. Mean annual temperature (a), minimum annual temperature (b) and total annual precipitation (c) trends for Cornwall and the Isles of Scilly (1983–2017). In all cases, black, connected dots indicate mean values in each year, solid line represents linear trend.

prospects for novel crops as the climate continues to warm.

2.2. Horizon-scan

To identify novel crops and score their suitability qualitatively, we followed a horizon-scanning approach based on Delphi methodology (e.g. Sutherland et al., 2020). Ultimately, we sought an unbiased and expert-informed shortlist of potential novel crops for the region.

The Delphi technique (Delphi) is a method for gathering expert knowledge through an iterative group communication process (Dalkey and Helmer, 1963). Participants are asked to complete an anonymous questionnaire, responses are collated and shared and then the questionnaire is repeated to reach consensus on an issue (Linstone and Turoff, 1975). The Delphi process is often fully anonymous (Filyushkina et al., 2018), but group discussions may be included. Discussion and debate can help in consensus-building (MacMillan and Marshall, 2006) and has been considered a natural way to provide rationale and improve the methodology of a Delphi study (Mukherjee et al., 2015). We therefore included a workshop component to the horizon scan to add strength to the results (Hutchings and Raine, 2006), and to increase accountability of participant responses (Mukherjee et al., 2015).

The horizon scan was completed by 13 agricultural experts, representing a diversity of stakeholder groups in Cornish agriculture. Experts were affiliated with Cornish farms, governmental, non-governmental, academic, and commercial organisations, as well as special interest and hobbyist groups. Two other organisations contributed to the first stage of the process but could not commit to subsequent rounds.

In the first round, 15 experts were asked to canvass among their organisation and submit suggestions for possible novel crops to grow commercially in Cornwall and the Isles of Scilly. The suggested novel crops were required to meet the following criteria:

1. Considered to be, or have the potential to be, a commercially viable crop
2. Considered to have climatically suitable areas available under current climate that will be sustained or expand in the near future
3. Currently grown on a small scale, or not at all, in Cornwall and the Isles of Scilly
4. Could displace current crops (if grown on current agricultural land)

We allowed invited parties to ‘opt-out’ if they did not feel qualified to make comments on potential novel crops based on these criteria.

Sixty-nine unique crops were suggested in Round 1 (Appendix B, Table B1). In Round 2, the 13 remaining experts scored each of the crops in this long-list for their suitability, on a scale of 0 (not suitable) to 100 (completely suitable). Scores were converted to ranks and the 11 crops with the highest mean rank were retained for further consideration (11 crops were chosen instead of ten as perennial kale (10) and blue lupine (11) received very similar mean ranks (18.3 and 18.8, respectively). Four additional crops that fell outside of the top 11 but that experts felt deserved further discussion were also retained (Table 2).

To complete the horizon scan, the 13 experts met in a workshop environment facilitated by the authors and discussed in turn the suitability of the 15 shortlisted crops. All experts were actively encouraged to participate in the discussion and to share their opinions on the suitability of the crops to avoid problems of dominance (Mukherjee et al., 2015). Each crop was discussed for ten minutes. The main issues considered to influence crop suitability by the panel fell broadly into six themes: marketability; familiarity; set-up costs; running costs; climate risk; and government policy (Table 1). After the discussion, experts were asked to re-score independently and anonymously the 15 crops according to perceived suitability, again from 1 (not unsuitable) to 100 (completely suitable). From these scores we calculated final suitability ranks for each crop. This gave us a list of fifteen ‘top crops’, with reasons for and against their suitability for cultivation in the region (section 3.1), and scores to reflect how this affected overall expert opinion on their suitability (Table 2).

Table 1
Major considerations for novel crops as identified by the expert panel during workshop discussions

Consideration	Influencing factors
Marketability	Market price and required economies of scale Consumer demand, either local or otherwise – is there a niche market available? Is this market large enough to be profitable? Contract issues with purchasers Consumer perception of the product (e.g. hemp’s association with marijuana)
Familiarity	Little or no knowledge of the crop and where or how to grow it (e.g. Chinese mahogany) Lack of experience (e.g. licence acquisition for hemp)
Set-up costs	Licence requirements Licence renewals Seed acquisition (dependence on imports) Price of specialist machinery
Running costs	Resource-intensive harvest methods e.g. sea buckthorn Access to machinery Processing costs, including any cost of transport to processing plants Cost of transport to market Input requirements (e.g. fertilisers/pesticides)
Environmental risk	Are crop failures or poor harvests likely due to marginal climate conditions or otherwise poor environmental suitability? Limited time-window for harvesting e.g. flax
Government policy	Licence requirements Difficulties acquiring seed or dependence on imports

Expert participation in the study was voluntary and it was possible to withdraw at any point or for any reason. Full informed consent to participate in the study was obtained from all experts. In our initial email inviting participation we provided information on the purpose of the research and compliance with the General Data Protection Regulation (GDPR); GDPR legally protects the privacy and personal data of all citizens in the United Kingdom. Consent was obtained for secure storage and access to data arising from the study by the authors for a period of five years, after which the data will be destroyed. We stated that results would be written as a scientific paper with intention for publication in peer-reviewed literature. Anonymity of scoring was maintained in all rounds. Ethical approval of methods was also obtained from the University of Exeter’s ethics committee prior to commencing the study (Ethics committee approval: eCORN002005 v2.1).

We provide further details on the horizon scan in the supplementary material (Appendix A).

2.3. Climate suitability model

We assessed the climatic suitability of crops shortlisted during Round 2 of the horizon scan using the crop suitability model ‘Ecocrop’, as implemented through the R package *dismo* (Hijmans et al., 2017). Ecocrop is a mechanistic crop suitability model that estimates climate suitability for a crop based on comparison of user-inputted monthly mean and minimum temperature and total monthly precipitation data with crop-specific environmental tolerances (see Appendix A, Table A1 for a list of these parameters). The *dismo* package contains environmental tolerance data for over 1500 crops.

Ecocrop returns a climate suitability score that ranges from 0 (unsuitable) to 1 (optimally suitable). A score of 0 means that climate conditions are beyond the crop’s absolute tolerance thresholds and a score of 1 means that climate conditions match exactly the crop’s optimal requirements. Here, we consider any score above 0.5 to indicate climate suitability (Ramirez-Villegas et al., 2013). Despite its simplicity, Ecocrop has been shown to estimate climate suitability well (Ramirez-Villegas et al., 2013), and can provide a useful first approximation of climate suitability (Manners and van Etten, 2018). It has been applied previously to estimate climate change impacts on suitability for staple crops and to suggest options for agricultural adaptation (e.g. Jarvis et al., 2012). Appendix A provides a more detailed description of the

Table 2
Results of Round 1 and Round 2 crop scoring by the expert panel showing crop ranks and rank standard deviation. Average total area of suitable land (km^2, 2002–2017) for shortlisted crop species.

Crop name	Mean expert rank (Round 1)	Expert rank standard deviation (Round 1)	Mean expert rank (Round 2)	Expert rank standard deviation (Round 2)	Area of land with climate suitability >0.5 (km^2)
Blue lupine	18.8	16.6	7.23	4.78	3792
Borage	12.4	17.9	2.77	2.17	2784
Flax	17.9	18.9	12.08	2.87	3763
Hemp	10.4	15.7	4.38	4.01	3533
Perennial kale	18.3	20.3	10.31	3.66	3284
Rosemary	14.8	14.8	7.85	4.36	0
Sea buckthorn	23.3	18.5	6.50	4.30	1682
Sea kale	13.6	12.9	5.00	2.74	3600
Soybean	25.7	20.4	4.25	3.57	0
Sunflower	16.8	17.3	6.54	3.36	3711
Sweet potato	21.8	14.5	5.23	3.66	0
Thyme	16.9	15.2	10.77	2.68	3068
Vines	17.2	11.8	7.54	4.62	0
Chinese mahogany	36.8	18.9	7.17	3.60	
Samphire	10.4	14.6	8.58	3.53	

Ecocrop model.

We ran Ecocrop for 13 out of the 15 crops shortlisted in Round 2 (for two crops, Chinese mahogany and samphire, crop-specific environmental tolerance data required to run Ecocrop were unavailable). Crop suitability was modelled across Cornwall and the Isles of Scilly for years 2002–2017 using monthly precipitation, minimum temperature, and mean temperature climate data at 100m spatial resolution. For each crop, model outputs were averaged, and we calculated the area of land (km^2) with a suitability score >0.5. We also produced maps of average climate suitability scores (2002–2017) for each crop to show how suitability varied across the study region.

Climate data were sourced from coarse resolution datasets including those from the Met Office (2018); the National Weather Surface National Centres for Environmental Prediction (NOAA-NCEP; Kalnay et al., 1996); the EUMETSAT Satellite Application Facility on Climate Monitoring (CMSAF; Posselt, Müller, Trentmann, Stockli, and Liniger, 2014); and the National Oceanic and Atmospheric Administration (NOAA; Reynolds et al., 2007) (please see Appendix A for further details). We extracted data for Cornwall and the Isles of Scilly and used functions in the R package *microclima* (Maclean et al., 2019) to derive hourly temperature estimates at 100m spatial resolution and at 1m above the ground. The microclimate model has been well-validated using field observations, details of which are provided in Maclean et al. (2017, 2019) and Maclean (2020).

We used high spatial resolution climate data so that we could model climate suitability at the farm and field scale and determine how climate suitability for each of the crops varies across the landscape. We considered that 100m resolution would identify any localised opportunities to grow a crop in suitable microclimates and would also be the most relevant scale at which to provide information on crop suitability given that crop decisions are made often at these fine spatial scales (Bramer et al., 2018).

Appendix A provides full information on climate data download and processing. The 15-year time period was considered to characterise the current climate of the region and appropriate given our interest in novel crop suitability. Furthermore, the climate of the region has warmed over the last 35 years (Fig. 2a–b) and so examining suitability over a longer period could over-estimate the suitability of cold-climate crops and underestimate the suitability of warm climate crops. Nevertheless, we provide evidence that our results are robust against outliers, for example due to a single anomalously warm year in the last 15 years, in a repeat analysis for a 35-year period, 1983–2017 (Appendix B, Table B2; Figs. B2–B3 and Appendix C, Table C3; Fig. C2).

2.4. *Test of model sensitive parameters*

Although Ecocrop has been used in assessments of crop suitability globally (e.g. Lane and Jarvis, 2007), it is a simple model based on monthly mean temperature data. When climate data are averaged, variability is lost, and so extreme conditions experienced within the month can be obscured and subsequently overlooked by the model. We tested the sensitivity of results to the use of monthly mean temperature data and found that reductions in suitable land area were small for most crops. The full methods and results for this analysis are detailed in Appendix C.

2.5. *Additional biophysical constraints on crop suitability*

We recognise that there are other biophysical constraints on crop suitability that Ecocrop does not capture, but which may affect whether a crop will be grown in an area. This limitation is not unique to the Ecocrop model and, indeed, the inability of climate suitability models to be complete and accurate in their parameterisation is a motivation for this research. However, to account for other environmental factors that could influence crop suitability in the study area, we re-ran the analysis of crop suitability with the exclusion of suitability scores in non-agricultural land and areas where average maximum wind speeds were above 18m/s. The filter for agricultural land excluded any areas not classified as "Arable" by the Centre of Ecology and Hydrology's land use map (Rowland et al., 2017) and so areas where cultivation of novel crops might not be possible given current land use. It was also considered that this filter might exclude areas with poor soil and drainage, as farms would be unlikely to be positioned in these places due to the limitations this would impose on crop growth and productivity. Exposure to high wind speeds can limit crop growth and is relevant given the maritime position of the study area. Slope and aspect, which influence temperature, are captured in the microclimate model (see Appendix A). The results of applying the agricultural land and wind speed filters with the maximum temperature filter are reported in Appendix C. Most crops retained large areas of suitable land. Flax, sunflower and hemp had the largest areas of suitable land remaining but less than 100 km^2 of suitable land remained for blue lupine and borage (Table C2, Fig. C1). We present mapped results in Appendix C, Fig. C1 of the supplementary material to show this.

2.6. *Combining the results of the horizon scan with the results of the climate suitability model*

We combine the results of the horizon scan with the results of the climate suitability model in two ways. First, we compare expert ranks and the total area of climatically suitable land for each crop and discuss the similarities and differences between these two estimates of suitability. Second, we demonstrate and discuss how expert-based knowledge could be used alongside maps derived from crop-climate model outputs, and that show the spatial variation in climatic suitability, to inform agricultural decisions about novel crop cultivation.

We use climate suitability scores without filters because a) our investigation to check model limitations imposed by using temporally averaging data, through the exclusion of suitability scores in areas where the absolute maximum hourly temperatures in the year exceeded crop tolerance thresholds, did not affect significantly the area of suitable land for most crops; b) we did not want to pre-impose restrictions to grow novel crops only on existing agricultural land, because future cultivation of novel crops may be desirable or necessary outside of these areas; and c) it would be possible to reduce wind speeds on farms to protect crops, for example, through hedgerow planting. Fig. A1 in Appendix A of the supplementary material provides a visual description of how we used the horizon scan and climate suitability model to assess overall suitability for each crop.

R version 3.5.2 (R Core Team, 2018) was used to run Ecocrop and for all statistical analyses.

3. Results

3.1. Top five novel crops from the horizon scan

The top five crops considered by experts to have the greatest commercial potential to be grown in Cornwall and the Isles of Scilly were 1) borage; 2) soybean; 3) hemp; 4) sea kale; and 5) sweet potato (Table 2). These crops are discussed below.

3.1.1. Borage (Borago officinalis L.)

Borage was considered a ‘good all-rounder’ by our expert panel. It is known to be suited to the Cornish climate and can be seen growing wild in many places. There is a good UK market for its seed oil, which is often marketed as the more attractively named ‘Starflower oil’ and the crop benefits biodiversity and is highly desirable to some pollinators (e.g. bumblebees; Foster et al., 2017). There is also a small local demand for its flowers, which are used as edible meal decorations by restaurants. Borage has been found to have DNA protective and chemo-preventative properties (Lozano-Baena et al., 2016) and it was felt that the growing public interest and demand for nutraceuticals could increase market opportunities for the fresh plant (leaves).

3.1.2. Soybean (Glycine max L.)

The expert panel discussed how cultivation of soybean in Cornwall could take advantage of a rising market price and high demand for soybean products. Soybean is grown primarily for its oil, but also as a protein source in the manufacture of compound feeds for animals (Heath, 1987). The amount of land climatically favourable for the crop is expected to increase with climate change (Carter et al., 1991) and so it could be an option for the future. It was considered that soybean could be a good break crop, especially due to its nitrogen-fixing abilities. However, the panel also discussed how soybean would not provide the biodiversity benefits that are possible with other crops, such as borage.

3.1.3. Hemp (Cannabis sativa L.)

The panel were enthusiastic about the huge diversity of industrial applications for hemp, which include use as a bioplastic and graphene substitute, but raised the ‘chicken and egg’ problem, similarly highlighted by Fike (2016), that many industries that could and would use hemp products are challenged by lack of supply, yet producers will not invest in growing crops to supply a market that does not yet exist. Hemp is grown mostly for its oil and fibre, but hemp seed protein is also sold as a vegetarian food supplement. Experts discussed that, given the right environment, yields could be very high compared to other crops (Van der Werf et al., 1996) and hemp was also considered environmentally friendly due to little harmful accumulation or emission of chemical inputs (Montford and Small, 1999) and the ability to reduce greenhouse gas emissions by carbon sequestration (Finnan and Styles, 2013). However, it was emphasised that a major drawback to growing hemp is the crop’s association with the use of the illegal narcotic marijuana. This means it can be difficult to acquire seeds and that a licence from the Home Office is required to grow hemp in the UK. The licence lasts only for one growing season and both new licences and licence renewals involve a fee. Licence applications from farms near to ‘sensitive areas’ such as schools or areas of public access are more likely to be rejected.

3.1.4. Sea kale (Crambe maritima L.)

One benefit of sea kale is that it can be grown on land unsuitable for other crops, as it is tolerant to salt spray and saline soils (de Vos et al., 2010). It grows well as a wild plant on the south-eastern, southern, and western coasts of the UK, including Cornwall (Sanyal and Decocq, 2015). Experts thought that sea kale could be marketed as a superfood due to its high nutritional value but also, through its maritime association, that clever branding as a speciality Cornish product could promote sales by distinguishing the vegetable from other kale varieties. The main issues for the crop could be establishing this market to ensure economies of scale.

3.1.5. Sweet potato (Ipomoea batatas L.)

It was felt that sweet potato could be an exciting novel crop to grow in Cornwall, as an exotic vegetable grown rarely in the UK. Crop trials in west Cornwall have established that some varieties can be grown successfully in fertile soil and sheltered locations (Michell et al., 2012). There is a good market for sweet potato in the UK, and the rising demand for local or UK-produced food could support the viability of sweet potato as a commercial crop in Cornwall. However, experts felt that the amount of climatically suitable land to grow the crop could be limited and restrict cultivation to small areas of favourable microclimate. More research is needed to identify the best locations for further crop trials, which should also explore the viability of other varieties.

3.2. Crops with largest area of suitable land from the climate suitability model

The five crops with the largest area of climatically suitable land were 1) blue lupine (3792 km^2); 2) flax (3763 km^2); 3) sunflower (3711 km^2); 4) sea kale (3600 km^2); and 5) hemp (3533 km^2) (Table 2, Appendix B, Fig. B1).

3.3. Combining the results of the horizon scan with the results of the climate suitability model

Table 2 shows crop ranks from the horizon scan and area of suitable land as determined from the crop suitability model. Most simply, by comparing expert scores with the results of the climate suitability assessment we can make suggestions about the best novel crops for the region. Borage, for example, could be a good candidate novel crop; it scored highest among the expert panel (mean rank 2.77), and has a reasonably large area of climatically suitable land (2784 km^2). We might also choose to explore options for blue lupine, which received a mean expert rank of 7.23 and had the largest area of suitable land (3792 km^2) across all fifteen crops. Despite having the second largest area of climatically suitable land (3763 km^2), flax may not be a good candidate for reasons highlighted by the panel and as reflected in its low mean expert rank of 12.08, which placed it in fifteenth place (out of fifteen crops) for expert-based suitability. Nevertheless, because it is so highly suited to the climate, we might choose to explore ways that non-climatic limitations might be overcome to allow its successful cultivation. Other crops like rosemary and vines, which did not score highly in either assessment, may not be considered any further.

The combination of results from the horizon scan and climate suitability model can be most powerful when climate suitability scores are considered in a spatial context. Fig. 3, for example, shows a map of the average climatic suitability for borage, flax, sweet potato, and rosemary. It displays spatially how average climate suitability for the different crops varies across Cornwall and the Isles of Scilly and when combined with expert knowledge, this information could aid local farming decisions. We know already, for example, that borage does not have the largest total area of suitable land among all crops considered but was considered a promising crop by the panel. The crop suitability map highlights areas of high suitability, such as in sheltered valleys and along the coast, and farmers in these locations may pursue options to grow borage on their land. For sweet potato, the map shows that the climate is not totally unsuitable, although less than 0.5 (Fig. 3c). As the crop received high expert scores (mean rank 5.23), it may be worth exploring options to reduce climatic constraints (e.g., irrigation if rainfall is limiting, or greenhouse cultivation if minimum temperature is too cold) in the 'best' marginal areas (such as in the north-east of the region). Alternatively, the climate suitability map for rosemary might confirm that this crop is a poor option for farmers and unless overall suitability can be improved, we may not pursue options to grow this crop any further.

4. Discussion

Global agricultural production is tied intimately to environmental conditions and so the risks presented by climate change are numerous. However, warming temperatures may provide new opportunities to grow crops in areas where conditions were previously unfavourable (e.g. Audsley et al., 2006), such as in northern Europe (e.g. Hannah et al., 2013). Identifying where and what these opportunities might be is the first step to realising them.

Here, we used horizon scanning techniques to identify five novel crops considered by an expert panel to have the highest potential for commercial growth in Cornwall and the Isles of Scilly. The group discussions that led to this consensus emphasised how crop suitability is a complex issue and that both climatic and non-climatic factors will influence agricultural decisions. We show how these discussions and results can be combined with the outputs of a climate-only crop suitability model for a more holistic assessment of crop suitability; when non-climatic factors are considered, the crops most appropriate for a region may not be those with the largest areas of suitable climate.

4.1. Using horizon scanning in crop suitability assessments

Although crop production will only be possible within certain climatic ranges, social, economic, and cultural factors have an important role in agricultural decision-making. Studies at the global scale have found that these non-climate factors form major constraints on cultivation and can be used to describe patterns of agricultural land (Ramankutty et al., 2002). Furthermore, recent studies for Europe have shown that, in some locations, non-climatic pressures can be more important drivers of land use than climate (Holman et al., 2005; Rounsevell and Reay, 2009) and suggest the need to include changes in climate and non-climate factors (technological, social and economic) to assess future changes in crop yield and suitability (Schröter et al., 2005).

The horizon scan highlighted socioeconomic issues as having major influence on crop suitability. One recurring theme was the marketability of crops and the top five crops were only those considered to have an established or a good potential market. A crop's market 'niche' was important; perennial kale, for example, was considered too similar to other widely available kale varieties to make it an attractive option, whereas the maritime link between sea kale and Cornwall could present branding opportunities for the vegetable as a high-quality and speciality

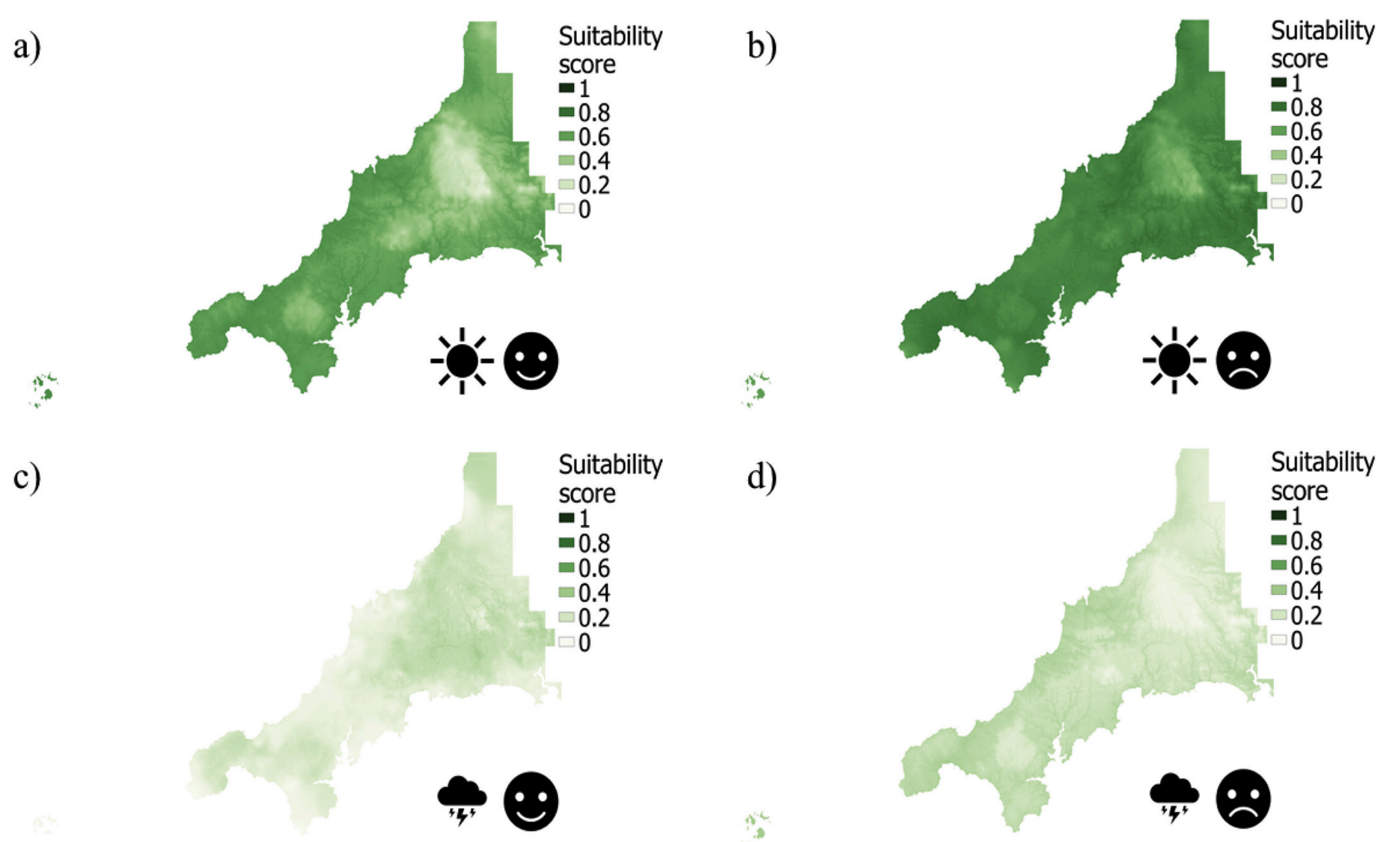

Fig. 3. Ecocrop model output showing average climate suitability (2002–2017) for borage (a); flax (b); sweet potato (c); and rosemary (d). Sun and cloud icons indicate high and low climate suitability, respectively. Happy and sad face icons indicate high and low expert ranking, respectively.

'Cornish' product ('Cornish sea kale'). Similarly, as vines are already grown commercially in Cornwall (although only on a small scale), market opportunities for Cornish wine were considered somewhat saturated, in lieu of increasing consumer demand. Although a market was identified for samphire, which initially scored highly in Round 2, contract issues with local restaurants who were expected to be the main buyers were considered a major risk. Both rosemary and thyme were considered to lack economies of scale. As very niche market crops, they could be a useful 'extra' for farmers, but not viable as a main source of income.

We show how the crop ranks and knowledge gained from the horizon scan can be combined with estimates of climate suitability to determine the best crops for an area. Most simply, we can compare expert scores with the amount of suitable land and choose (or not choose) the crops that receive high (low) scores in both cases. In such an assessment, flax, for example, might be discounted as a possible novel crop; despite large areas of suitable land, it received low expert scores due to a short and labour-intensive harvest window, with no guarantee of product quality. Similarly, the climate model identified blue lupine as a highly suitable crop for Cornwall and the Isles of Scilly, but this crop did not feature in our experts' top five. Experts felt there was little or no market for blue lupine and therefore poor incentive to grow the crop. Being poorly weed tolerant, it could also be expensive to grow if the application of large amounts of herbicide was required. Thus, incorporating socioeconomic considerations into crop suitability assessments may uncover that the best crop climatically is not the most viable option commercially.

A strength of the climate suitability assessment is that it can provide spatially explicit information on where a crop may grow well across an entire landscape to guide farming decisions. For example, the panel ranked borage as the most promising novel crop for Cornwall and the Isles of Scilly. Fig. 3 (a) shows how the most suitable land climatically can be found in sheltered valleys and along the north coast and with this information we might decide that borage is only a good option for farmers in these areas, rather than those inland where the climate is less favourable. In small areas with favourable microclimates, borage could be very successful as a high-value, niche market product with additional biodiversity benefits. It could be grown commercially for its seed oil, which is in demand for medical purposes due to containing high levels of gamma linolenic acid (GLA) (El Hafid et al., 2002). We would only know from the horizon scan the potential market for borage, and the climate suitability model shows where its requirements for moderate summer temperatures and reasonable moisture might be met (Nicholls, 1996).

The horizon scan results and discussions could be combined with the climate suitability assessment in other ways. Hemp, for example, scored highly in both assessments but experts raised that it could be difficult to cultivate commercially due to government policy that restricts access to seeds and requires farmers to obtain a licence to grow the crop. The Home Office may impose restrictions on where hemp is grown and applications from farms near to 'sensitive areas' such as schools or areas of public access may be rejected. Using spatial information from the climate model that indicates areas of suitable climate alongside the information obtained from the horizon scan could help to prevent money being invested in areas where applications are likely to be rejected and/or where yields may be poor (Appendix B, Fig. B1). Thus, the qualitative and quantitative assessments complement each other as they each consider aspects of suitability that the other cannot.

Horizon-scanning exercises could identify research priorities for possible novel crops that might make their commercial cultivation possible. Sweet potato, for example, was ranked highly by experts but did not have large area of suitable climate (Fig. 3c). It could be a promising crop in areas where the microclimate can be made more favourable (Lobley et al., 2011), or if breeding programmes can develop a more cold-tolerant variety. Otherwise, it might be a crop to reconsider in a few years' time, as experts anticipated that its suitability was likely to increase with future climate change. Combining horizon-scanning with climate-only suitability assessments could therefore prevent a crop from being completely disregarded in its potential to be grown commercially. It could stimulate microclimate research to detect areas of increasing suitability and where crop trials might be successful, help to ascertain the best varieties, or inform breeding programmes to produce more tolerant varieties. Indeed, there have been successful trials for sweet potato in West Cornwall (Michell et al., 2012).

Another benefit of horizon scanning could be that it draws attention to little-known crops and stimulates interest and research into their potential. For example, although a good case was put forward for Chinese mahogany, most participants were unfamiliar with this crop and it received a low rank in the final round of scoring. Despite group discussions, participants perhaps remained uncertain about the crop's suitability and would need further information before considering whether to grow it. Horizon-scanning could help to share knowledge on unfamiliar crops such as this. Otherwise, crop novelty may prove beneficial for farmers if they can demand a high price for a niche product. The group discussed how climate change would likely favour the growth of crops such as sweet potato and soybean, for example, and the novelty of these crops being 'locally grown' could help them to reach a high market price.

4.2. Limitations of the study

Horizon scanning exercises are unique to the expert panel make-up and the individual experiences and opinions of each participant. However, participation by a diverse and independent group of government, non-governmental, hobbyist and commercial stakeholders, attempted to maximise the breadth of expert knowledge and reduce any bias in the initial crop suggestions and scoring. It is possible crops that would grow well in Cornwall were not identified, either because experts were unaware of these crops or because they did not suggest crops that they were unfamiliar with and felt unable to comment on in terms of suitability. We might suppose, however, that if experts were unaware or unfamiliar with a crop, then general market demand for these crops may be low and crops would therefore have received low suitability scores (as observed for Chinese mahogany in this study).

Our climate suitability assessment may be limited by the simple parameterisation of the Ecocrop model, which requires only mean and minimum temperature and precipitation as inputs. This may explain why vines were considered poorly suitable for the Cornish climate, despite knowledge that they grow in some areas (e.g. Camel Valley vineyard, Bodmin). However, this limitation may support the use of horizon-scanning exercises, or other techniques that capture expert and local knowledge in crop suitability assessments if climate-only models may underestimate potential for some crops. Furthermore, Ecocrop is considered a useful model when climate data are limited (Manners and van Etten, 2018) and we suggest that horizon scanning could be particularly beneficial in these cases to gather additional information on crop suitability and to support the results of climate models. Horizon scanning may also help to identify potentially suitable crop varieties, which climate models may represent inadequately (Rötter et al., 2011). Although crop suitability can be assessed in more complex ways, the tools to do this may not be available for all the crops of interest.

Although our conclusions are robust to the use of monthly mean temperature data by the Ecocrop model (Appendix C), this may not hold true in new time periods or in different locations, particularly if these are less temperate and/or with more seasonal or extreme climates. As climate change is expected to increase both the frequency and severity of extreme events (Stocker et al., 2013), the ability of crop models to capture short-term climate variability could become increasingly important in the future. Our method of calculating climate suitability with Ecocrop could therefore be improved by using a mechanistic model that requires at least daily data, such as the WOrld FOod STudies (WOFOST) model (de Wit et al., 2019). Increasing the complexity of the inputs to the suitability model, for example, to incorporate other biophysical constraints such as soil type, or the application of filters to consider climate suitability only in certain areas (such as current agricultural land) could also help to assess suitability more accurately. Nevertheless, even the most highly parametrised suitability model could not hope to capture all the qualitative aspects that our horizon scan identified as important and useful when assessing crop suitability, and for many crop types, the parameters required to drive more complex models are simply not known. We propose, therefore, that horizon scanning could be combined into any crop suitability assessment when non-climatic factors that cannot be quantified might influence crop suitability.

4.3. Wider implications: the benefits of identifying and growing novel crops

Identifying opportunities to grow novel crops might prove beneficial to biodiversity. The conversion of natural habitats to farmland has been a leading cause of global biodiversity decline (e.g. Green et al., 2005) and in the UK intensive management of agricultural land has accounted for more changes in species' populations than has climatic change (Burns et al., 2016). As novel crops have the potential to give high returns (e.g. Parker and Abatzoglou, 2018), their cultivation may support 'land sparing' (e.g. Phalan et al., 2011a, 2011b) and save natural habitat from conversion to agricultural production. Equally, by expanding crop diversity across a landscape (by growing novel crops in some places), we might create agricultural matrices that provide habitats for species important to ecosystem health (Grass et al., 2019). However, as the introduction of a novel crop could be a significant land use change, we stress that the environmental impacts of a novel crop should be considered comprehensively to achieve the most sustainable outcomes for both farmers and wildlife (Haughton et al., 2009).

Novel crops could help to balance our appetite for exotic foods, whilst reducing the environmental impact of our consumption patterns. The UK market for exotic fruit and vegetables has increased exponentially in recent years (Kell et al., 2018). Growing products locally, rather than relying on imports, could help satisfy this demand whilst reducing food miles and the associated emissions of long-distance transport that contribute to climate change. Novel crop cultivation could support climate change solutions in other ways. Sunflowers, for example, emit less greenhouse gases and require lower pesticide use than the cereals or oilseed rape they could replace in northern Europe as climate conditions become more suitable (Debaeke et al., 2017). Hemp, which ranked third in the horizon scan, can sequester large amounts of carbon and has been shown to offer similar benefits (Finnan and Styles, 2013). Novel crops could therefore present opportunities for 'climate smart' agricultural practices and it might prove beneficial to change which crops are grown in an area to deliver maximum yield or profit with minimum losses to the environment (Dungait et al., 2012).

5. Conclusion

Climate change will present exciting opportunities for some farmers to grow novel crops. Whilst climate suitability models provide important information and can determine where a novel crop may grow well, crop suitability assessments need to consider both climatic and non-climatic factors. We show how horizon scanning can be applied to identify promising novel crops, highlight non-climatic barriers to their commercial cultivation and can be combined with the results of climate-only suitability models so that the multiple and often complex issues that influence crop suitability can be assessed together. The methods followed allow suitable microclimates to be identified for some of the most promising novel crops. Although we focus on a single region, the methodology could be applied anywhere on earth and could provide a way to identify novel crops to grow on large scales, to provide future sustenance, or at small scales to take advantage of niche markets. Thus, we demonstrate a time- and resource-efficient way to gather collective, expert knowledge and evaluate more holistically crop suitability in a changing world.

Declaration of Competing Interest

Alexandra Gardner's PhD is part-funded by Cornwall Council and one representative for Cornwall Council was present on the expert panel. However, this expert had no prior involvement with the PhD project and the authors do not consider that their presence on the panel would have led to any conflict of interest, nor influenced the results of the study.

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Appendix A. Supplementary data

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