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Short communication

Predicting future stability of ecosystem functioning under climate change

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A R T I C L E I N F O

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A B S T R A C T

To maintain food security under global change, we need to consider the stability of ecosystem functioning into the future, particularly in resource production landscapes such as agricultural pasture. With ongoing climate change, extreme climatic events are predicted to become more frequent and severe globally, impacting crop production. The whole process of farming will become more uncertain, from choice of crop and crop productivity to the timing of the windows of opportunity for management decisions. Future agricultural policies, therefore, should not only consider changes in grassland production, but also its future stability. We use a case study of agricultural pastures on the island of Ireland to project different components of ecosystem stability (resistance, recovery time and recovery rate) to 2050 and 2080 under different future climate scenarios: a peak and decline scenario; and a continued emissions scenario. We show that future climate change will have substantial effects on both the future resistance and the recovery of ecosystem functioning following environmental disturbances, but the spatial pattern of effect sizes is not the same for these two measures of stability. National level analyses and agricultural policies, therefore, are likely to ignore regional variation in future change. From this, we encourage the translation of stability-based constructs, as well as maximum yield considerations, into future agricultural policy at the regional level.

1. Introduction

To increase and maintain food security under global environmental change, we need to consider the stability of production in agricultural landscapes. Climate change is already impacting agriculture globally, however, the threats posed by climate change are likely to develop in severity and importance in the future (Lennon, 2015). As well as increases in mean temperatures and variability in precipitation, the frequency and intensity of extreme climatic events, such as droughts and floods, is projected to increase (Beniston et al., 2007; Intergovernmental Panel on Climate Change, 2014; Spinoni et al., 2018). The World Economic Forum has identified extreme climatic events as the most significant risk to humanity (World Economic Forum, 2018). For Ireland, regional climate models predict an increase in mean annual temperatures by 1–1.6 °C by 2050 with increased numbers of heat waves (up to 15 per year) and frost days per year decreasing by up to 58% (Nolan and Flanagan, 2020). The frequency of heavy precipitation events is projected to increase in Ireland by 5–19% by 2050 with substantial increases in extended dry periods as well (Nolan and Flanagan, 2020). These changes in climate conditions will likely impact the stability of ecosystem functions such as productivity, for example, through direct impacts on plant physiology (Yin and Bauerle, 2017) as well as indirectly through impacting local species occurrences, diversity, and asynchrony, which have been shown to promote ecosystem stability (Gilbert et al., 2020).

When we think of food security, management has often focussed on maintaining or increasing agricultural yields. Similarly, research into projected impacts of future climate on agricultural systems have focussed on biomass production (Tubiello et al., 2007). The implications of intensified production as a strategy to deal with the impacts of climate change, however, are unclear (Lennon, 2015). Under a changing environment, food security depends upon the sustained production of

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resources over years, i.e. its stability. We therefore need to know how resistant plant productivity is to climatic events, and its ability to recover, if we are to be able to maintain food production for the growing population. Here, we argue that agricultural policies, such as the EU Common Agricultural Policy (CAP), should not only consider changes in grassland production in terms of their maximum yield, but also its future stability in terms of yield variability and risk of fodder production failure. We present a predictive framework that can be applied across landscapes to identify regions particularly vulnerable to future climate conditions. This moves beyond previous research, which has focused on predicting and promoting increased yields (e.g. Holden and Brereton, 2002; Höglind et al., 2013) and we encourage this framework to be fed into policy development across spatial scales.

The stability of plant productivity has been of particular importance across the island of Ireland, where more than 60% of the land cover is agricultural pasture. This grassland ecosystem is, therefore, vital for food security across the island through supporting livestock for dairy and meat production. The island, however, has suffered multiple 'fodder crises', for example 2012–2013 (DAFM, 2017; Green et al., 2018), where grass production fell substantially because of the combination of a poor growing season followed by a long, cold winter, with serious economic consequences including forage rationing and the need to import international sources of fodder (DAFM, 2019). The island of Ireland, therefore, provides an ideal case study for investigating the stability of future productivity of agricultural grasslands due to their prominence across the landscape, and importance to the economy and food security of the island. Furthermore, the investigation of vulnerability of agricultural grasslands in Ireland to future climate change fits into the proposed actions for the National Adaptation Framework for Agriculture, Forestry and Seafood led by the Department for Agriculture, Food and the Marine (DAFM, 2019).

2. Measuring large-scale stability

Ecosystem stability consists of multiple dimensions (Donohue et al., 2013). These include: variability (temporal variance in ecosystem functioning); resistance (the magnitude of the immediate change in functioning following a disturbance event); recovery time (the length of time following a disturbance that it takes for ecosystem functioning to reach a pre-disturbance level or equilibrium state); and recovery rate (the rate of recovery following a disturbance event i.e. the recovery time divided by the magnitude of the immediate change in ecosystem functioning following a disturbance event). These follow the definitions of Hillebrand et al. (2017), Hodgson et al. (2015) and White et al. (2020).

Remote sensing data, such as that provided by satellites, provides continuous monitoring of multiple properties of Earth, lending itself to the calculation of different stability measures. One such property is the Enhanced Vegetation Index (EVI), which captures the greenness of vegetation in an area and can be used to assess primary productivity (Shi et al., 2017). EVI is particularly useful in areas of high productivity, such as agricultural grasslands, as it does not saturate as quickly as other vegetation indices (such as the Normalised Difference Vegetation Index) when biomass is high (Huete et al., 2002). Using a time series of EVI anomalies (i.e. how much does the observed EVI in an area deviate from an established baseline of EVI in that area within a particular month), we can calculate the measures of stability outlined above at a broad spatial scale. Details of the calculation of these stability measures from remotely sensed data can be found in White et al. (2020).

3. Predicting future stability

Future climate projections have been developed for a series of different carbon concentration trajectory pathways (Representative Concentration Pathways - RCPs) using coarse scale Global Circulation Models (GCMs) as well as finer scale Regional Climate Models (RCMs) calibrated using GCMs. Due to the expected impact of climate on stability (Stuart-Haëntjens et al., 2018; Gilbert et al., 2020), we can project ecosystem stability into the future under different climate scenarios. Based on the outputs of these models we can produce national risk maps of changes in ecosystem stability. We used data from two RCMs (RCA4 and HIRHAM5) for the European domain of the Coordinated Downscaling Experiment (EURO-CORDEX; euro-cordex.net), calibrated using HadGEM2-ES as the GCM driver model. We found that the two models predicted similar spatial patterns of future stability measures in Ireland (Table 1). We used generalised least squares models with a spatial error term to predict future stability of plant productivity. Explanatory variables included in the model were variance in temperature, variance in precipitation, a fat tail measure of climatic extremes in temperature, and the same measure for extremes in precipitation, for the 50 years preceding our prediction period. This matched the period of climate data available prior to the start of the EVI time series from the E-OBS version 17.0 gridded data product (1950–1999; Haylock et al., 2008). Using climate data immediately preceding the period of stability being modelled or predicted focuses on climatic history rather than contemporary climate. This is based on the hypothesis that climatic history plays a role in the stability of plant productivity (Gao et al., 2016) both positively, through acclimation to extreme events (e.g. Walter et al., 2013), and negatively, through continued response to climate fluctuations outweighing other ecological effects such as biodiversity (e.g. García-Palacios et al., 2018). We projected resistance, recovery time and recovery rate of plant productivity to 2050 and 2080 under two RCPs as laid out by the Intergovernmental Panel on Climate Change in their Fifth Assessment Report (IPCC, 2014): a peak and decline scenario (RCP 4.5); and a continued emissions scenario (RCP 8.5). Detailed methods can be found in Appendix A and all R code for data preparation and analysis can be found at https://github.com/HannahWhite/FutureStabilityScenarios.

4. Future stability across the island of Ireland

Future climate change will have substantial effects on the future stability of primary productivity in agricultural grasslands. Changes in stability over time, however, are not consistent in space (Fig. 1). Our predictions show that, whilst recovery is likely to slow in the west of Ireland with longer recovery times and slower recovery rates, spatial variation in resistance appears to follow a north-south gradient, with more southerly agricultural pasture likely to show decreased resistance in the future. Some areas may, in fact, increase in stability. Our predictions indicate that resistance may increase, recovery times decrease and recovery rates increase in some regions (Fig. 1). Similar patterns are observed across both emissions scenarios (RCP 4.5 and RCP 8.5) as well as between years (additional results can be found in Appendix B).

Table 1
Spearman rank correlation coefficients between stability measures based on four future climate scenarios (RCPs) from RCA4 and HIRHAM5 Regional Climate Models (RCMs). RCP = Representative Concentration Pathway.

Measure	RCP	Year	Correlation between RCMs	p val
Resistance	RCP 4.5	2050	0.302	<0.01
Resistance	RCP 4.5	2080	0.408	<0.01
Resistance	RCP 8.5	2050	0.788	<0.01
Resistance	RCP 8.5	2080	0.456	<0.01
Recovery time	RCP 4.5	2050	0.843	<0.01
Recovery time	RCP 4.5	2080	0.736	<0.01
Recovery time	RCP 8.5	2050	0.815	<0.01
Recovery time	RCP 8.5	2080	0.629	<0.01
Recovery rate	RCP 4.5	2050	0.806	<0.01
Recovery rate	RCP 4.5	2080	0.602	<0.01
Recovery rate	RCP 8.5	2050	0.778	<0.01
Recovery rate	RCP 8.5	2080	0.599	<0.01

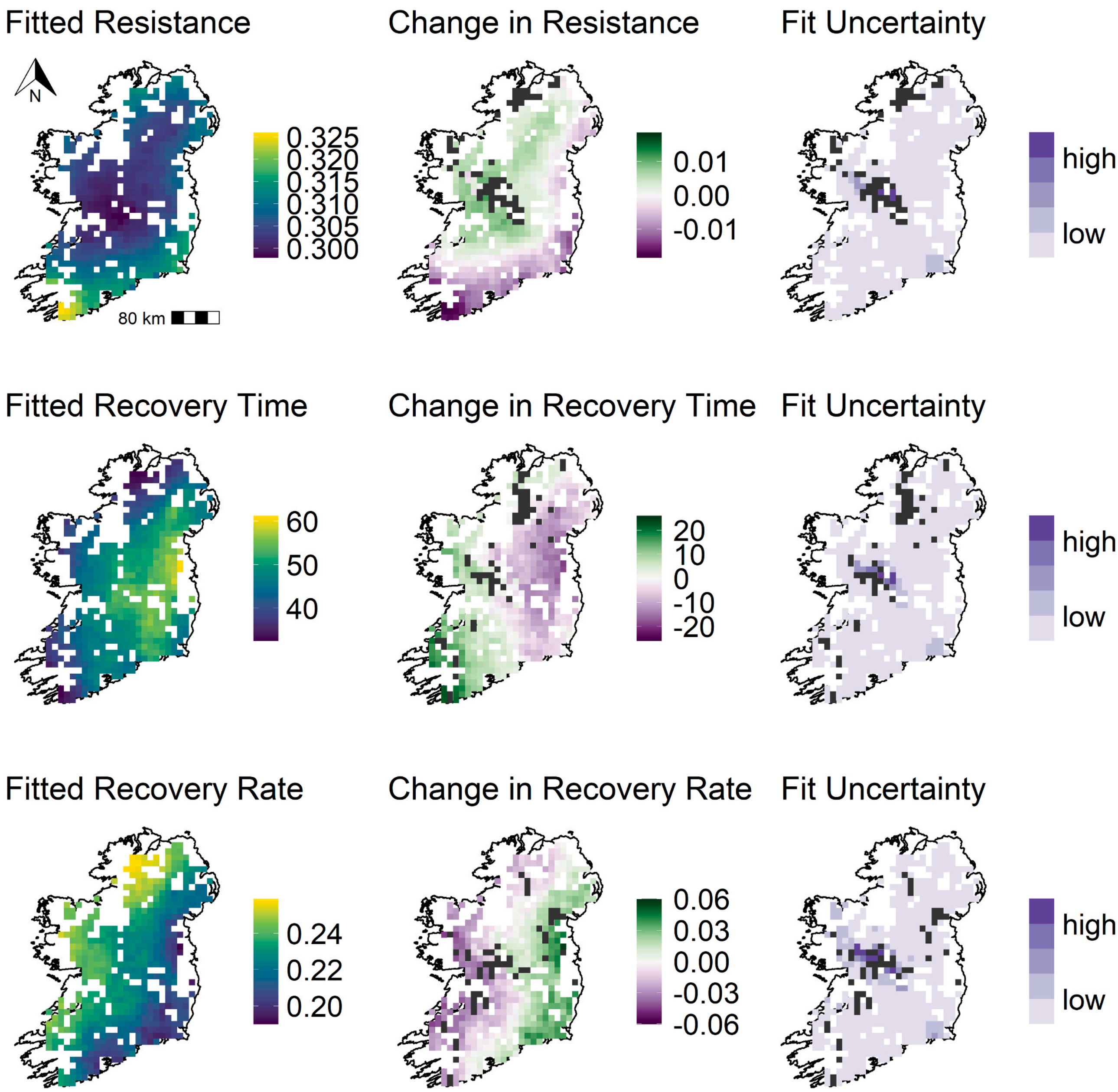

Fig. 1. Spatial variation in current fitted resistance, recovery time and recovery rate (first column), the predicted change in these values in 2050 following a peak and decline scenario in emissions (RCP 45) modelled from climate projections from the RCA4 Regional Climate Model (second column), and standard error around the fit of these models (final column). All fitted and predicted values are from a generalised least squares model at the 10 × 10 km square scale. Only squares which are dominated by pasture are shown. Black squares indicated squares where values fell in the outer 10% of predicted values where the model may be unstable. Resistance is measured as the number of standard deviations below a zero baseline, recovery time is measures as the number of days it takes to return to a zero baseline following a drop in productivity, and recovery rate is the rate of this return.

5. Discussion

The Organisation for Economic Co-operation and Development highlights the innovation and structural change that has contributed to increases in agricultural productivity (Ignaciuk, 2015), however, goals related to climate change and future sustainable productivity remain sparse. Our models are not able to predict the occurrence of severe disruptions to agricultural production or production thresholds, such as fodder crises, which have been shown to arise from a complex mix of conditions (DAFM 20219). They do, however, indicate spatial variation in the stability of primary productivity in agricultural grasslands based on the local climatic history. Farmers in different areas need to be prepared for larger drops in grassland productivity in response to the climatic events associated with climate change, or potentially slower recoveries following these events than they are currently used to managing for. We believe the magnitude of these changes are manageable through adaptation of current management approaches for grazed pastures, as in many cases they often fall within the current island-wide range of variation in the stability measures i.e. their stability capacity has shifted to a level previously observed elsewhere on the island.

National-scale 'one size fits all' management decisions for agricultural practices will not be sufficient to prepare for the challenges that climate change will bring as they hide regional variation in projected outcomes, yet this regional variation is at a meaningful scale for agricultural policy. More regional and local scale adaptations of practices and advice will be necessary to address the spatial variation in impacts on stability of agricultural grasslands, in line with the large spatial variation predicted in future climatic conditions (Dodd et al., 2020). For example, our predictive framework could be used to identify regions particularly vulnerable to climatic extreme events where risk management tools, such as the CAP's insurance premium subsidies and income stabilisation tool, may be particularly advisable (Severini et al., 2019), whilst actively discouraging risk-prone behaviours (Pe'er et al., 2020).

The CAP identifies 'encouraging efficient resource management' as a priority for sustainable primary production in agriculture (European Commission, 2016), identifying the use of digital and other technologies as a key activity to improve environmental performance. Remotely sensed vegetation index data is already being used for short-term alerts of potential drought or food shortages (Becker-Reshef et al., 2010; Kogan et al., 2019). Predictions of future stability of productivity, however, can inform long-term management practices at both the field- and landscape-scale, as we show effect sizes relevant for agricultural production, but at a manageable time scale (for example recovery periods are less than a year) in the context of grazed grasslands. These management decisions include turn-out dates (Green et al., 2018), the amount and type of fodder storage (Petit et al., 2019), or management options which can maximise stability of plant productivity, including changing nutrient input, the diversity of sown species or grazing regimes. These factors are all known to impact plant productivity and its stability (Vogel et al., 2012; Hautier et al., 2014; Ren et al., 2018) and can interact with climate (Li et al., 2018). More investigation is needed with similar predictive models to the ones presented here, for example applied to different grazing levels to determine best practices for livestock management under future climate change. However, we would particularly encourage ecological approaches such as increasing landscape features that promote biodiversity on agricultural land, in line with the strategic priorities of the CAP (European Commission, 2018).

Plant biodiversity has frequently been shown to impact ecosystem stability in grasslands (e.g. Isbell et al., 2009; Craven et al., 2018). As well as promoting non-productive components of the landscape, such as hedgerows, more varied sown seed mixes may also promote stability of plant productivity in agricultural grasslands (Haughey et al., 2018). To mitigate climatic events, such as the extreme cold winters and dry growing seasons that led to the Irish fodder crises in 2013 and 2018 (DAFM 2019), farmers can increase the diversity of their sward to improve its resilience, particularly, for example in the South West of Ireland, where future recovery times based on current plant assemblages are predicted to increase and resistance decrease compared to current stability levels. Therefore, incorporating our work on future stability projections with research on the increased productivity of multi-species swards in grazed grasslands (e.g. Finn et al., 2013) will facilitate the identification of key ecological thresholds for future grassland stability.

There is, of course, a degree of uncertainty to our predictions and other ecological and environmental aspects will also influence ecosystem stability in the future, as will management and other human factors. Our projections assume a direct effect of climate on stability and do not account for additional ecosystem changes that climate change will likely bring about, for example changes in plant ecological communities, land management approaches, and novel pathogens adapted to the new climatic conditions (Lennon, 2015). Range shifts in plant distributions (Kelly and Goulden, 2008; Peters et al., 2014) with climate change may lead to changes in plant communities found within agricultural pasture. This may impact the stability of the system due to biodiversity-stability relationship and could further exacerbate the effect of climate change on the stability of ecosystem functioning. Combining predictive species distribution modelling of plant species under future climate change in conjunction with our stability modelling approach shown here will likely prove fruitful in projecting the impacts of future climate change on grassland production across large spatial scales.

The key message from our Ireland case study is that the stability of agricultural pasture will change in the future to some degree, irrespective of the emissions pathway followed, but that this change will vary in space. Adaptive management by farmers in these grazed grassland systems will, therefore, be crucial to fodder production in the face of climatic variability (Urruty et al., 2016). For example, to mitigate the impacts of weather shocks in grazed systems, Mosnier et al. (2009) demonstrated that purchasing additional feed stocks and maintaining an area of pasture for haymaking are the most effective measures to maintain feed for livestock.

6. Conclusion

Remotely sensed vegetation index data allows us to investigate the future stability of agricultural plant productivity: a vital ecosystem function for food security. Using predictive models based on future climate scenarios, we show substantial variation in changes in resistance, recovery time and recovery rate, which can provide useful data to management across scales from farmers and land managers to regional policy makers and advisors on how to prepare for future global environmental change. The results are also of international relevance, and we believe impact assessment studies of climate change on agricultural systems need to move beyond models of future yield (Tubiello et al., 2007) and shift their focus to yield stability, as do international polices such as CAP to maintain food security under future climate conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107600.

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