Paper presented at the Agricultural Economics Society (AES) 94th Annual Conference, 29-30 March 2021 (Warwick, UK-Hybrid)

Effects of farming practices on the stability of food production and farm income in a variable climate

Caroline Harkness[a, b,], Francisco Areal[c] and Jacob Bishop[a]

[a] School of Agriculture Policy and Development, University of Reading, Earley Gate, Reading RG6 6AH, United Kingdom

[b] Sustainable Agricultural Sciences, Rothamsted Research, West Common, Harpenden, Hertfordshire AL5 2JQ, United Kingdom

[c] Centre for Rural Economy, School of Natural and Environmental Sciences, Newcastle University, Agriculture Building, King's Road, Newcastle upon Tyne NE1 7RU, United Kingdom

Abstract

Climate variability and weather extremes threaten agricultural production and the ability to maintain a stable food supply. Production shocks can also affect the stability of farmers income, representing a significant challenge for farm management and the design of public policies. However, quantitative assessments on agricultural system dynamics at the farm level, and across different farm types, remain rare.

We analyse the relative effects of climate variability, subsidies and farming practices on the temporal stability of food production and farm income. We examine data for 929 farms in England and Wales between 2005 and 2017, and in combination with climatic data we estimate Bayesian multilevel models for cereal, general cropping and mixed farms to provide targeted recommendations for farmers.

Our results show that variability in temperature and rainfall affects both the stability of income and food production, however, the importance of these effects vary between farm type. Agricultural diversity is associated with a relatively large increase in the stability of food production and farm incomes for general cropping and cereal farms. The impact of input intensity is, however, more complex. Spending more on chemical inputs may reduce the variability in calories produced at the farm level, however increasing inputs is associated with more variable income. These results indicate that greater agricultural diversity and more precise and controlled use of chemicals may therefore help to improve stability and the sustainability of farming. Government subsidies are also found to affect the stability of food production and farm income, however the size of these effects are small. Agri-environment schemes may help improve stability of both farm income and food production, for general cropping and mixed farms, whereas cereal farms do not see the same benefits from these schemes.

Our results highlight the importance of considering both farming practices and climate conditions when examining stability of farm performance at the farm level. We also anticipate that recommendations and practices to improve stability vary between farm types, therefore future agricultural policy should be flexible and adaptable to benefit different types of production.

1 Introduction

Agricultural production is highly dependent upon weather conditions and our changing climate is associated with an increase in climatic variability and weather extremes (Rahmstorf and Coumou, 2011; IPCC et al., 2012; Kovats et al., 2015). Climate change poses difficult challenges to agricultural production and consequently is likely to affect farmer's income. Maintaining the stability of food production is vital for future food security, as is the stability of farm income to ensure the sustainability of farm businesses which can continue producing food for a rising population.

Climate variability and extremes (e.g. heat waves, flooding and drought) can severely reduce crop yields (Reyer et al., 2013; Deryng et al., 2014; Trnka et al., 2014; Powell and Reinhard, 2015) and impact livestock systems, influencing both the direct health of the animal, as well as, grassland productivity and the availability of feed (Olesen and Bindi, 2002; Kipling et al., 2016). Farms also suffer economically as a result of production losses from adverse weather; however, subsidies and the global food trade seek to avoid any serious price increases or threats to food security (Battisti and Naylor, 2009).

Farm characteristics and farming practices (e.g. diversity, input intensity and size) and government subsidies have also been found to strongly influence the stability of agriculture, and are important to consider alongside climate change impacts (Reidsma *et al.*, 2009; Harkness *et al.*, 2021). However, quantitative assessments on agricultural system dynamics (i.e. changes over time) remain rare at the farm level (Dardonville *et al.*, 2020). Understanding the effects of farming practices and subsidies alongside, and in comparison to, the influence of climate could help farms in adapting to more variable conditions.

The impacts of climate variability, farming practices and government subsidies on production are most often examined separately at a smaller scale e.g., the field level for individual crops. The stability of agricultural production is usually assessed by examining the variability of yields (e.g. (Reidsma *et al.*, 2009; Ceglar *et al.*, 2016; Iizumi and Ramankutty, 2016)). Reidsma et al. (2009) examined the impact of climate variability, farm characteristics and subsides on the stability of yields at the farm level for five crops. Farm size and output intensity were found to decrease yield variability for most crops, while variability in precipitation and direct payments were found to increase yield variability (Reidsma et al., 2009). However, this European study did not consider the different effects between farm types, which can exhibit very different farm management and characteristics (Harkness *et al.*, 2021). We extend this previous research to also examine the effects of agricultural diversity and input intensity on farm stability. Diversity in crop rotations has been found to enhance the stability and resilience of yields in certain crops, by harnessing favourable conditions and reducing the risk of crop failure (Gaudin *et al.*, 2015; Dardonville *et al.*, 2020). While, increasing fertiliser and pesticides have been found to enhance total yields, however their effect on the variability of yields is unclear (Dardonville et al., 2020).

In this study we examine the stability of all food produced at the farm level, using a common unit of calories. This enables us to examine total production and consider the potential range of responses across different crop and livestock products. Examining factors affecting food production also considers the stability of food production from a global consumer perspective i.e., how many calories are available for consumers and changes over time, which has not been examined previously. Understanding the relative importance of farming practices, subsidies and climate on the stability of all food produced, at the farm level, is important to help farmers adapt and guide future research.

We also examine the stability of farm income to discuss factors affecting the sustainability of farm businesses. Increasing agricultural diversity, reducing input intensity and engaging and government agri-environment schemes, as well as larger farm size have previously been found to increase the stability of income for many farm businesses (El Benni, Finger and Mann, 2012; Enjolras *et al.*, 2014; Pacín and Oesterheld, 2014; Harkness *et al.*, 2021). Maintaining the stability of farm income and reducing domestic price volatility is also a key issue addressed by policy makers within the European Union (EU). However, the ability of direct payments, the main area-based support provided through the Common Agricultural Policy (CAP), to reduce variability of income is mixed (Reidsma *et al.*, 2009; Enjolras *et al.*, 2014; Castañeda-Vera and Garrido, 2017; Harkness *et al.*, 2021). Recent research has, however, indicated farms engaging more in government agri-environment schemes have more stable incomes (Harkness *et al.*, 2021). However, the effect of subsidies on the stability of food produced at the farm level has not been examined previously. Larger farms are also consistently found to have more stable incomes across Europe and a range of different farm types (Reidsma *et al.*, 2009; Harkness *et al.*, 2021).

We examine the effects of climate variability, farming practices and government subsidies on the stability of food production and farm income across counties of England and Wales in the period between 2005 and 2017. During this period the UK experienced different adverse weather conditions which affected agricultural production. Including, severe flooding in the summer of 2007 (Posthumus et al., 2009), prolonged drought in 2011, followed by a record rainfall in the spring and summer of 2012 (Kendon et al., 2013; Parry et al., 2013). In addition, the 10 warmest years recorded in the UK have all occurred since 2002 (Kendon *et al.*, 2020). We examine the effect of climate variability, and therefore a range of conditions, on farm stability over time and across counties of England and Wales.

The key aim of our research is to examine the relative effect of climate variability in combination with subsidies and farming practices on the temporal stability of food production and farm income, at the farm level. Examining the relative importance of each of these factors will help to further understand these relationships and how important management and subsidies are in comparison to the effects of climate on the farm business. We also examine where there may be trade-offs between improving the stability of food production and farm income, and where potential adaptation may differ between the farm types considered in this study.

2 Materials and methods

2.1 Data and study area

We examine data from the Farm Business Survey (FBS) between 2005 and 2017, which is a survey conducted in England and Wales, collecting information from approximately 2,500 farm businesses annually (Department for Environment Food and Rural Affairs, 2020). The FBS records farm level data on financial performance and food production, as well as subsidies received and other farm characteristics, including the county (or unitary authority) location of each farm. The county and unitary authority boundaries used to group farms in the Farm Business Survey are shown in Figure 1. Farms are classified in the survey into farm types according to which type of production accounts for more than two-thirds of standard gross margin (SGM). We focus our analysis on cereals, general cropping and mixed farms.

Climate variability, and averages, have been calculated using the HadUK-Grid gridded climate observations produced by the Met Office (Hollis *et al.*, 2019). The HadUK-grid dataset includes a wide set of climate variables, including temperature and precipitation, for daily, monthly, seasonal and annual timescales, as well as long term averages and at different spatial resolutions. We average 5km HadUK-Grid gridded climate observations for each county or unitary authority (shown in Figure 1) to provide an estimate of the climate at each farm.

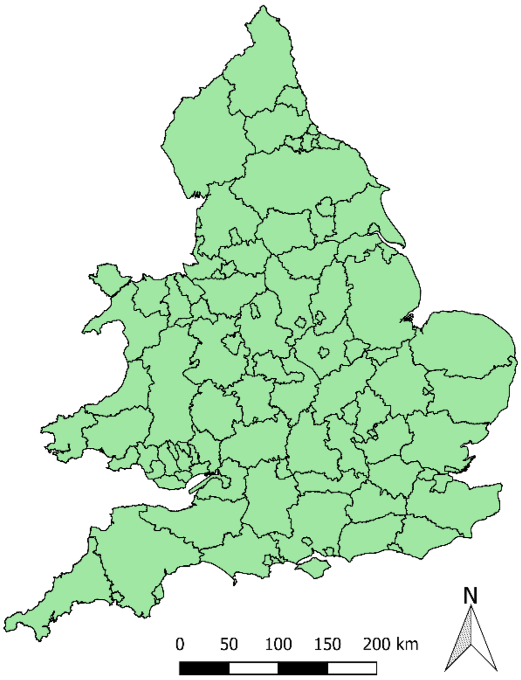

Figure 1 – County and Unitary Authority boundaries of England and Wales in the Farm Business Survey. Source: (Harkness *et al.*, 2021)

2.2 Measuring the stability of food production and farm income

We examine the effect of climate variability in combination with subsidies and farming practices on medium-term stability of food production (calories) and farm income. We calculate medium-term stability using the standard deviation over a 5-year rolling period, as used in previous studies (Barry, Escalante and Bard, 2001; Harkness *et al.*, 2021). This measure indicates the amount of variation or dispersion of farm business income or calories at the individual farm over a 5-year period.

To examine the stability of farm income (changes in income over time), we use farm business income per hectare (£/ha) which is in essence the same as net profit and is the preferred measure of income used by policy makers to examine the impact of policies at the farm level (Department for Environment Food and Rural Affairs *et al.*, 2018).

The FBS data also records annual food production at each farm. To examine the stability of food produced, we calculate the total calories (kcal/ha) available for direct human consumption. Calories represents a common unit of production (analogous to £/ha for income) and therefore no weighting for different products is required. The stability of food production has also been calculated in the same way as for income, using the standard deviation in calories over a 5-year rolling period. To calculate calories we use the FAO Food Balance Sheet (FAO, 2021) which provides country level production, imports, exports and stock variations for 98 food commodities for human consumption and derives calories/energy (kcal), fat and protein per capita. The FAO food balance sheet has been used in previous studies examining food supplies and the resulting adequacy to meet energy requirements (e.g. Macdiarmid et al. (2018) and Smith et al. (2016)). Calories per 100g for each agricultural commodity are derived in the food balance sheet data. We use these factors to convert the units of food produced in the Farm Business Survey (i.e., tonnes (crops), hectolitres (milk), dozen (eggs) and number (livestock)) into calories.

2.3 Factors affecting farm stability

We use the same methods as used in Harkness et al. (2021) to calculate the farming practices examined: farm size, input intensity, agricultural diversification, as well as, direct payments and agri-environment scheme payments per ha, for each farm. The calculations are provided in Table 1. To examine their relative effects on farm stability, these variables are averaged over the same rolling five-year time period used to derive the dependent variables (standard deviation of farm income and calories).

To examine the effect of climate variability on the stability of food production and farm income, we calculate the standard deviation in temperature and rainfall over a rolling 5-year period. This involves firstly calculating the mean temperature and precipitation for the first 6 months of the year (January – June) in each county, to provide an indication of temperature and rainfall in the main growing period, similar to the approach used by Reidsma et al. (2009). These county level climate conditions are then used to calculate the standard deviation in temperature and precipitation over a rolling 5-year period to examine the effect of climate variability at the farm level. The stability of performance may also be influenced by average climate conditions (or base temperatures), as well as variability, therefore we include variables capturing the mean temperature and precipitation for each 5-year period, to reduce the risk of confounding these relationships.

The standard deviation is an absolute measure of dispersion, therefore we also control for the level of income and calories produced by each farm (using total farm business income and calories per hectare), which may also affect the level of stability.

Independent variable	**Calculation**
Farming practices and subsidies [a]	
Farm size	Area farmed (hectares) = The utilised agricultural area, plus land let in or minus land rented out
Intensity of inputs	The total cost of fertiliser, crop protection and concentrated animal feed (£), per hectare (area farmed) (IRENA indicator 15; European Environment Agency, 2005; Gerrard et al., 2012)
Agricultural specialisation (inverse of diversification)	$Herfindahl\ index\ (S) = \sum_{i=1}^{n} (p_i)^2$ Where *n* is the total number of farming activities, p_i is the proportion of revenue earned from the *i*-th farming activity (revenue from farming activity divided by the total farming revenue). Can also be written as sum of revenue for each farming activity squared, divided by total revenue for agriculture squared: (Wheat^2+ barley^2 + other cereals^2 + oilseed rape^2 + peas and beans^2 + potatoes^2 + sugar beet^2 + horticulture^2 + other crops^2 + by-products and forage^2 + milk^2 + cattle^2 + sheep^2 + pigs^2 + eggs^2 + chickens and other poultry^2 + other livestock^2 + other agriculture^2) /total agricultural gross revenue^2
Direct payments per hectare	Total direct payments (£) (Primarily the single payment scheme or basic payment scheme), per hectare (area farmed)
Agri-environment payments per hectare	Total payments under rural development policy (£; pillar 2), per hectare (area farmed)
Climate variables [b]	
Mean temperature (°C)	Mean temperature (°C) for first half of year (Jan to June)
SD of mean temperature (°C)	SD of mean temperature (°C) for first half of year (Jan to June)
Mean precipitation (mm)	Mean rainfall for first half of year (mm) (Jan to June)

SD of mean precipitation (mm)	SD of mean rainfall (mm) for first half of year (mm) (Jan to June)

[a] Farming practices and subsidies are averaged over the same rolling five-year time period used to derive the dependent variables

[b] Climate variables (standard deviation (SD) and mean temperature and rainfall) are calculated over the same rolling five-year period.

Table 1 - Definition and calculations of farming practices, EU subsidy payments and climate variables analysed in the study

Summary statistics for the variables used in this study are shown in Table 2. The UK Consumer Price Index is used to deflate all monetary variables, including farm business income, to account for the change in the value of money over time (ONS, 2020).

	Mean (2007-2015)				Standard deviation (SD) (2007-2015)			
	All Farms	**Cereals**	**Gen. cropping**	**Mixed**	**All Farms**	**Cereals**	**Gen. cropping**	**Mixed**
Dependent variables								
SD of Farm Business Income (FBI) per ha (£)	219.57	213.77	271.13	183.97	144.05	116.84	192.72	129.06
SD of calories per ha (kcal)	2,537,320	2,864,774	2,736,539	1,668,707	1,557,537	1,340,314	1,655,014	1,562,107
Independent variables								
Farming practices and subsidies								
Specialisation (Herfindahl index) (0-1)	0.41	0.40	0.37	0.49	0.16	0.14	0.14	0.18
Input intensity per ha (£)	413.59	327.26	399.05	607.44	533.25	137.37	243.86	997.30
Direct payments (SPS/BPS) per ha (£)	237.57	244.15	237.49	223.87	62.36	59.95	57.06	69.42
Agri-environment payments per ha (£)	45.70	48.54	39.81	45.22	50.47	56.62	41.19	43.74
Area farmed (hectares)	234.97	233.52	284.21	192.41	246.33	218.59	358.33	144.99
Climate								
Mean temperature (°C)	8.29	8.31	8.40	8.14	0.66	0.66	0.51	0.74
SD of mean temperature (°C)	0.90	0.91	0.91	0.88	0.21	0.21	0.22	0.19
Mean precipitation (mm)	60.07	58.18	55.95	67.84	16.08	13.79	14.72	18.88
SD of mean precipitation (mm)	15.48	15.27	14.42	16.90	4.53	4.35	3.87	5.09
Control variables								
Farm Business Income (FBI) per ha (£)	390.96	387.20	495.80	301.80	393.09	357.27	460.26	373.88
Calories per ha (kcal)	15,929,805	17,651,252	19,406,013	9,115,433	8,110,153	6,608,759	8,087,139	6,968,904
Number of observations	4,529	2,357	1,044	1,128				
Number of farms	929*	512	261	318				
Number of counties/unitary authorities	65	56	38	57				

*Note 162 farms change between farm types during the period, therefore appear in more than one farm type group during the relevant years.

Table 2 - Summary statistics of FBS data (2007-2015); values deflated using UK Consumer Price Index (2015=100; ONS, 2020).

2.4 Multilevel (two-level linear mixed effect) model

We use a multilevel model to examine the relative effects of climate variability, farming practices and subsidies on the stability of food production and farm income. Multilevel models allow us to account for dependencies within the data: Farms belonging to the same county or unitary authority (level 2) have the same estimated climate and may also have more similar environmental conditions (e.g., soils) than farm in different counties. Farms are also surveyed in the data over multiple years (we consider farms in the survey for a minimum of 5 years) therefore the multilevel model controls for the correlation between observations from the same farm (level 1). This type of model can easily accommodate the unbalanced panel data used in this study (Laird and Ware, 1982; Snijders and Bosker, 1999) and has been used previously to examine the influence of management and climate on farm level performance (Reidsma, Ewert and Oude Lansink, 2007; Reidsma *et al.*, 2009; Harkness *et al.*, 2021).

We estimate a varying-intercept Bayesian two-level mixed model with farms nested within counties. The empirical specification of the model is:

$$\begin{aligned} Y_{tjk} &\sim \text{Log-normal}(u_{tjk}, \sigma_e) \\ u_{tjk} &= \alpha + \alpha_{\text{county}[k]} + \alpha_{\text{farm}[jk]} + \sum \beta_p X_{jk} \\ \alpha &\sim \text{Normal}(0, 10) \\ \alpha_{\text{county}} &\sim \text{Normal}(0, \sigma_{\text{county}}) \\ \alpha_{\text{farm}} &\sim \text{Normal}(0, \sigma_{\text{farm}}) \\ \beta_p &\sim \text{Normal}(0, 10) \\ \sigma_{\text{e}} &\sim \text{HalfCauchy}(10) \\ \sigma_{\text{county}} &\sim \text{HalfCauchy}(10) \\ \sigma_{\text{farm}} &\sim \text{HalfCauchy}(10) \end{aligned} \tag{1}$$

We fit a log-normal model to account for the non-normal distribution of the dependent variable, Y_{tjk} (the standard deviation of income and calories), in each model and reduce the impact of outliers. In the linear model, α is the mean intercept across all groups, α_{county} is the county level intercept (level 2), α_{farm} is the farm level intercept (level 1). β_p denotes the coefficients for each predictor variable, X_{jk}, which are listed in Table 1. α and β are given a vague (weakly informative) Gaussian prior centred on 0, and the residual variation (σ_{e}) is given a Half-Cauchy prior (Gelman, 2006; Nalborczyk *et al.*, 2019), thus restricting the range of possible values to positive ones. The same Half-Cauchy prior is specified for the two varying intercepts[1].

In each of the models, predictor variables (listed in Table 1) have been standardised (centred around zero, with a SD of 1) to account for the differences in scale and in order to examine the relative effect size of each independent variable. Year, *t*, is also included as a continuous variable to control for the trend in income stability and calories over time, as well as examine the interaction between time and direct payments per hectare, which was significant for mixed farms. Before fitting the models, we checked for outliers and collinearity using pairwise scatterplots, in addition, correlation coefficients between independent variables were all less than the recommended threshold of 0.7 (Dormann et al. (2013).

We fitted a Bayesian multilevel model in the *brms* package in R (Bürkner, 2017, 2018; R Core Team, 2019). To generate the posterior samples of the parameter estimates *brms* makes use of the computationally efficient Hamiltonian Monte-Carlo (HMC) Sampler (Neal, 2011) and its extension the no-U-turn Sampler by (Hoffman and Gelman, 2014) implemented in the Stan software package (Stan Development Team, 2020). Each model was fitted with 4 chains of 10,000 per chain of which 2,000 were used for the warm-up. Visual model diagnostics showed adequate mixing of chains for each parameter, with the Rhat value (Gelman and Rubin test statistic; Gelman and Rubin, (1992)) less than 1.003, providing strong evidence of convergence.

3 Results

Tables 3 and 4 show the results of the multilevel (two-level linear mixed effect) models, for the stability of farm income and food production respectively and include the posterior means and standard deviation (SD) as well as the 95% credible intervals (CI) for each parameter. Models use the log of the dependent variable, therefore the exponent of the posterior mean, minus 1 multiplied by 100, provides the percentage change in the variability of income (instability) for every increase in the independent variable by one standard

[1] We also ran the models using the default priors set in the *brms* package (weakly informative Student-t distributions), which resulted in little change to the model results.

deviation, holding all other predictors constant. The posterior means (and 95% CIs) indicate the relative effect of farming practices, subsidies and climate conditions on the variability of income and food production by farm type.

3.1.1 Factors affecting the variability of farm income

Model estimates, provided in Table 3, indicate that farming practices are important factors influencing the variability (inverse of stability) of farm business income per hectare. Farms which spend more on chemical inputs (fertiliser, pesticide and concentrated animal feed) have more variable income. Increasing input intensity by 1 standard deviation increases the variability of income between 10 and 21% across the 3 farm types, which represents a large increase relative to other factors examined in the model. More specialised cereal and general cropping farms (i.e. those with less diversity of crop and livestock activities) also have more variable income, however, this was not an important factor for mixed farms. For general cropping farms (which are on average the most diverse; Table 2) specialisation has a large relative effect; increasing specialisation by 1 standard deviation increases the variability of income by 13% (95% CI [7%, 20%]). Larger cereal and mixed farms have more stable incomes. Increasing the area farmed by 1 standard deviation reduces the variability of income by 6% (95% CI [-9%, -3%]) for cereal farms, and for mixed farms the decrease is larger (-11%, (95% CI [-15%, -6%]).

The value of direct payments per ha is found to be an important factor for cereal farms, increasing variability of income by 4% (95% CI [1%, 7%]). While the effect of agri-environment scheme payments differs between farm types; an increase in agri-environment payments per hectare decreases the variability of income for mixed farms by 6% (95% CI [-10%, -3%]), whereas for cereal farms agri-environment payments increase the variability income by 3% (95% CI [0%, 6%]) although the lower bound of the credible interval is close to zero. Government subsidies (direct payments and agri-environment scheme payments) therefore have a smaller relative effect on the variability of income, in comparison to the farming practices examined in this study.

Climatic conditions are also estimated to be an important factor influencing the variability of income. The variability of income for cereal farms are estimated to be particularly sensitive to changes in both the prevailing (mean) temperature and precipitation and its variability. Larger variability of temperature increases the variability of income for cereal farms by 5% on average, while increasing the variability of precipitation also has the same effect (5% increase). Increasing warmth (mean temperatures) and average precipitation has the opposite effect and are both associated with a decrease in the variability of income of 9%, while holding all other factors constant. Changes in precipitation have a larger effect for mixed farms and are found to be more important than changes in temperature. An increase in mean rainfall reduces the variability of income by 11% (95% CI [-16%, -5%]), whereas greater variability in precipitation, over a 5-year period, increases the variability of income by 7% (95% CI [3%, 11%]) for mixed farms.

Generally, the relative effects of climatic factors associated with the variability of income were similar in size to the effects of the farming practices examined. Except for general cropping farms, where the effect of input intensity and specialisation were found to be more important than the climatic conditions examined.

Parameter	Cereals				General Cropping				Mixed			
	Posterior mean	**SD**	**95% CI**		**Posterior mean**	**SD**	**95% CI**		**Posterior mean**	**SD**	**95% CI**	
σ_{county} (county SD)	**0.05***	0.03	0.00	0.13	**0.15***	0.06	0.03	0.26	**0.09***	0.05	0.01	0.19
σ_{farm} (farm SD)	**0.35***	0.02	0.32	0.38	**0.44***	0.03	0.39	0.49	**0.38***	0.02	0.34	0.424
σ_e (SD of residuals)	**0.34***	0.01	0.33	0.35	**0.33***	0.01	0.32	0.35	**0.35***	0.01	0.34	0.372
α (Intercept)	**5.34***	0.04	5.27	5.42	**5.39***	0.06	5.26	5.51	**4.88***	0.06	4.77	4.99
β (Independent variables):												
Input intensity	**0.09***	0.02	0.06	0.12	**0.12***	0.03	0.07	0.17	**0.19***	0.03	0.14	0.24
Specialisation	**0.05***	0.02	0.02	0.08	**0.12***	0.03	0.06	0.18	0.02	0.03	-0.03	0.07
Area Farmed	**-0.06***	0.02	-0.10	-0.03	-0.03	0.04	-0.10	0.04	**-0.12***	0.03	-0.17	-0.06
Direct payments	**0.04***	0.02	0.01	0.07	-0.04	0.03	-0.09	0.01	-0.03	0.03	-0.09	0.04
Direct payments x year									**0.03***	0.01	0.02	0.04
AES payments	**0.03***	0.02	0.00	0.06	-0.03	0.03	-0.08	0.02	**-0.07***	0.02	-0.11	-0.03
SD temperature	**0.05***	0.01	0.02	0.08	-0.02	0.02	-0.07	0.02	0.01	0.02	-0.03	0.05
SD precipitation	**0.05***	0.01	0.02	0.07	0.02	0.02	-0.02	0.06	**0.07***	0.02	0.03	0.11
Mean temperature	**-0.10***	0.02	-0.14	-0.06	-0.02	0.03	-0.07	0.03	-0.02	0.03	-0.07	0.04
Mean precipitation	**-0.09***	0.02	-0.13	-0.05	-0.02	0.04	-0.10	0.06	**-0.11***	0.03	-0.17	-0.05
Total Income per ha	**0.13***	0.02	0.10	0.16	**0.14***	0.03	0.09	0.18	**0.11***	0.03	0.06	0.16
Year (t)	**-0.02***	0.01	-0.04	-0.01	0.00	0.01	-0.02	0.02	**0.04***	0.01	0.02	0.06
Observations (n)	2357				1044				1128			
County (n)	56				38				57			
Farm (n)	512				261				318			

Table 3 - Multilevel model results examining the effect of farming practices, subsidies and climate on the variability of farm business income, showing the posterior means, standard deviation (SD) and 95% credible intervals (CI) of each parameter. Parameters that do not have 0 in the 95% credible interval are deemed important and marked with an "*"

3.1.2 Factors affecting the variability of food production

We estimate the relative effects of farming practices, subsidies and climate variability on the stability of food produced at the farm level. Model estimates are provided in Table 4. The farming practices examined are found to affect the stability of food produced, as well as incomes, and the relative size of these effects differ between farm types. For general cropping and mixed farms, increasing input intensity is associated with an average decrease in the variability of calories by 4% and 10% respectively. Spending more on chemical inputs (fertiliser, pesticide and concentrated animal feed) therefore helps improve the stability of food production but increases the variability of farmers income. Increasing specialisation of crop and livestock activities is associated with an increase in the variability of calories (and incomes) for general cropping and cereal farms, however, this was not an important factor for mixed farms. The effect of specialisation is relatively large compared to other factors affecting the variability in calories produced and is largest for cereal farms. Increasing specialisation by 1 standard deviation increases the variability of calories by 10% for cereal farms (95% CI [7%, 14%]), and by 5% (95% CI [1%, 10%]), for general cropping farms. Larger farms are associated with less variability in calories produced. Increasing the area farmed by 1 standard deviation reduces the variability in calories between 4% and 9% across the 3 farm types.

The value of direct payments per ha is found to be an important factor for mixed farms, increasing variability of calories by approximately 3% over the period examined, and this effect increases over time. The effect of agri-environment scheme payments on the variability of calories differs between farm types, which is consistent with the effects seen on farm incomes. An increase in agri-environment payments per hectare decreases the variability of calories for mixed farms by 5% (95% CI [-10%, 0%]), whereas for cereal farms agri-environment payments increase the variability calories by 3% (95% CI [0%, 6%]). The relative effects of agri-environment scheme payments are therefore smaller than the farming practices examined in our study, and one bound of the 95% credible interval is close to zero for both cereal and mixed farms.

Climatic conditions are also estimated to be an important factor influencing the variability of calories, however fewer important effects were found compared to those associated with the variability of income. Changes to both the prevailing (mean) temperature, and variability in temperatures over a 5-year period, were important factors affecting the variability of calories produced by cereal farms; Increasing the temperature variability by 1 standard deviation was associated with an increase in the variability of calories of 3% (95% CI [0%, 5%]). While, increasing warmth (mean temperatures) decreased the variability of calories by 4% (95% CI [-7%, 0%]), while holding all other factors constant. An increase in mean rainfall was also associated with a reduction in the variability of calories produced by mixed farms of 11% (95% CI [-17%, -2%]).

In general, the farming practices employed by farms are therefore associated with a larger relative effect on the stability of calories produced, compared to the effects of more variable climate conditions. For general cropping farms in particular, farming practices (area farmed, input intensity and level of specialisation) were more important factors compared to subsidies or climate variability in influencing the variability of calories produced.

Parameter	Cereals				General Cropping				Mixed			
	Posterior mean	**SD**	**95% CI**		**Posterior mean**	**SD**	**95% CI**		**Posterior mean**	**SD**	**95% CI**	
σ_{county} (county SD)	**0.08***	0.03	0.03	0.14	**0.09***	0.05	0.01	0.18	**0.13***	0.06	0.01	0.26
σ_{farm} (farm SD)	**0.31***	0.01	0.28	0.34	**0.31***	0.02	0.27	0.36	**0.56***	0.03	0.50	0.62
σ_e (SD of residuals)	**0.33***	0.01	0.32	0.34	**0.34***	0.01	0.33	0.36	**0.40***	0.01	0.38	0.42
α (Intercept)	**14.65***	0.04	14.58	14.72	**14.66***	0.06	14.54	14.76	**13.80***	0.07	13.67	13.94
β (Independent variables):												
Input intensity	0.01	0.02	-0.02	0.04	**-0.04***	0.02	-0.09	0.00	**-0.11***	0.04	-0.19	-0.03
Specialisation	**0.10***	0.02	0.07	0.13	**0.05***	0.02	0.01	0.10	-0.02	0.03	-0.08	0.05
Area Farmed	**-0.04***	0.02	-0.07	-0.01	**-0.05***	0.03	-0.11	0.00	**-0.10***	0.04	-0.17	-0.03
Direct payments	0.00	0.02	-0.03	0.03	-0.02	0.02	-0.06	0.03	0.02	0.04	-0.06	0.09
Direct payments x year									**0.01***	0.01	0.00	0.03
AES payments	**0.03***	0.02	0.00	0.06	-0.03	0.02	-0.08	0.01	**-0.05***	0.03	-0.10	0.00
SD temperature	**0.03***	0.01	0.00	0.05	-0.01	0.02	-0.05	0.04	-0.01	0.02	-0.06	0.03
SD rainfall	0.02	0.01	-0.01	0.04	0.02	0.02	-0.01	0.06	0.02	0.02	-0.02	0.07
Mean temperature	**-0.04***	0.02	-0.08	0.00	-0.04	0.02	-0.08	0.01	0.02	0.04	-0.05	0.10
Mean rainfall	0.03	0.02	-0.01	0.07	-0.04	0.03	-0.11	0.03	**-0.11***	0.04	-0.19	-0.02
Total Calories per ha	**0.17***	0.02	0.13	0.20	0.28	0.03	0.22	0.33	**0.47***	0.04	0.39	0.55
Year (t)	**0.02***	0.01	0.01	0.03	0.01	0.01	-0.01	0.03	**0.05***	0.01	0.03	0.07
Observations (n)	2357				1044				1128			
County (n)	56				38				57			
Farm (n)	512				261				318			

Table 4 - Multilevel model results examining the effect of farming practices, subsidies and climate on the variability of calories, showing the posterior means, standard deviation (SD) and 95% credible intervals (CI) of each parameter. Parameters that do not have 0 in the 95% credible interval are deemed important and marked with an "*"

4 Discussion

We examine the relative effects of farm characteristics, subsidies and climate variability on the stability of calories produced as well as farm incomes. We consider the stability of food production from a consumer perspective, by examining variability in calories, which has not been explored previously.

4.1 Diversity benefits both the stability of food production and farm income.

Diversity, in its various forms, is commonly found to affect volatility of the agricultural system (Dardonville *et al.*, 2020). More diverse farm may be more adaptable and resilient to climatic and economic shocks; Diverse crop rotations are associated with greater stability and resilience of yields in certain crops (Gaudin *et al.*, 2015; Dardonville *et al.*, 2020) and farms with more diverse agricultural products are found to have more stable incomes (El Benni, Finger and Mann, 2012; Pacín and Oesterheld, 2014; Harkness *et al.*, 2021). Our results support these previous conclusions on the benefits of diversity. In addition to more stable yields, we also find that greater diversity is associated with greater stability of total calories produced at the farm level. We examine the effect of agricultural diversity (i.e., lower degree of specialisation in different crop and livestock activities) on the stability of calories produced at the farm level, and farm incomes. For cereal and general cropping farms increasing diversity was associated with greater stability of food production and farm incomes. The relative size of these effects, compared to other farming practices and climate conditions, also highlighted the importance of diversity for improving stability. Increasing agricultural diversity is therefore considered a highly important factor for the future sustainability of farming systems and food security.

Farm size was also found to be an important factor affecting stability for farming systems. Larger farms were associated with greater stability of both food production and farm incomes across most farm types, who may be benefitting from greater economies of scale (Marra and Schurle, 1994; El Benni, Finger and Mann, 2012). Larger farms may also benefit from more diverse environments, such as a wider range of landscapes, topography or soils which could also increase the resilience of farms to weather conditions. However, we did not specifically examine landscape diversity.

4.2 Increasing inputs results in a potential trade-off between stability of food production and income

Spending more on increasingly expensive chemical inputs has previously been associated with more variable farm income (Enjolras *et al.*, 2014; Harkness *et al.*, 2021). However, the effect of increasing fertiliser and pesticides on yield variability is less clear (Dardonville et al., 2020). We examine the effect of input intensity (cost of fertiliser, pesticide and concentrated animal feed) on the stability of food production and farm income. Consistent with previous research we find more intensive farms have more variable income. The effect of input intensity on the stability of income is also relatively large compared to other factors, including climate variability, for all farm types examined. However, increasing input intensity is associated with a greater stability of calories produced at the farm level, in general cropping and mixed farms. The effect of input intensity on the stability of food production is largest for mixed farms, who have a higher proportion of income from livestock compared to cereal and general cropping farms. Mixed farms spend more on inputs (Table 2) which includes concentrated animal feed. Concentrates can reduce the reliance on grassland (which can be affected by adverse weather) and therefore may help stabilise livestock production in mixed farms. For general cropping farms higher input intensity may help stabilise calories produced by increasing the ability of these farms to combat pests and disease and adverse weather by applying chemicals. However, our results indicate this may not be economically sustainable for farm businesses with higher input costs increasing the variability of income. This suggests a potential trade-off in the use of chemical inputs between the stability of food production and farm incomes. Greater precision and more controlled use of chemicals may therefore offer an important solution to sufficiently support sustainable food production whilst at the same time reducing inputs costs and increasing income stability.

4.3 The effect of subsidies are relatively small and vary between farm type

The effect of subsidies on the stability of total food production at the farm level has not been examined previously and we find that the value of government subsidies are an important factor, affecting the stability of both food production and farm incomes. However, the relative effects of subsidies on stability are small compared to farming practices (i.e., diversification and input intensity), and vary between farm types. We examine the effects of both direct payments, which are based on the area farmed, as well as, payments from agri-environment schemes. Agri-environment schemes compensate farmers for engaging in practices to benefit the environment or biodiversity and include options to maintain habitats for wildlife as well as soil management practices, which can help enhance ecosystem services and increase the resilience of the farm landscape (Menalled *et al.*, 2003; Kennedy *et al.*, 2013; Blaauw and Isaacs, 2014; Büchi *et al.*, 2018; Ottoy *et al.*, 2018; Degani *et al.*, 2019). Our results showed that mixed farms which received larger agri-environment scheme payments per ha were found to have more stable incomes. In addition, we also found agri-environment scheme payments are associated with greater stability of total food production. The direction of these stabilising effects of agri-environment scheme payments were similar for general cropping farms, however, the upper bound of the posterior distribution slightly overlaps zero, therefore increasing the uncertainty. Farms receiving larger agri-environment payments may therefore be benefitting from their engagement in the schemes by both more stable income, as well as, providing a more stable and in turn sustainable source of calories. Direct payments have the opposite effect for mixed farms increasing the variability of total calories produced.

In contrast with the other farm types examined, payments from agri-environment schemes are found to increase the variability of income and food production for cereal farms, although the size of these effects are relatively small. Agri-environment schemes do not seem to have the same stabilising effect for cereal farms. The options included in these schemes may not provide the same benefits for cereal crops or this could be due to differences in the way these farms are managed and engage with agri-environment schemes. Direct payments are also found to increase the variability of incomes for cereal farms.

Our results firstly indicate that direct payments, based on area alone, are found to increase the variability of income and food production for certain farm types. A guaranteed level of income support from the government may represent a moral hazard to farmers, who may be more inclined to engage in riskier production, leading to greater variability in farm performance (Reidsma *et al.*, 2009; Poon and Weersink, 2011; Enjolras *et al.*, 2014; Harkness *et al.*, 2021).

Secondly, agri-environment schemes may provide opportunities to improve stability of the farm system, both in terms of food production and farm incomes. This is particularly encouraging with the transition from direct payments to a new agricultural policy in the UK focusing on environmental land management, sustainable farming and productivity measures. However, with the different effects observed between farm types, options included in the schemes must be flexible and adapted to different landscapes and production. Additionally, while the effects of EU agri-environment schemes on stability are relatively small compared to other farming practices, greater emphasis could be given to support diversification and more precise chemical application to reduce costs but maintain output and food production.

4.4 The effect of climate variability on farm stability differs between farms types

Climate variability affects both the stability of farm income and food production. However, the importance and relative size of these climate effects vary between the farm types examined. Climate conditions are particularly important for cereal farms; Variability in both temperature and rainfall increase the variability of income, while deviations in temperature are more influential on the variability of food production. For mixed farms changes in precipitation have a larger effect on the stability of income and are found to be more important than changes in temperature. Reidsma *et al.* (2009) also found high variability in precipitation has a large effect on agricultural stability across Europe, however, they did not examine the different effects among type of production. Grass productivity is particularly dependent upon rainfall and limited by more extreme conditions including dry periods in spring and summer (van den Pol-van Dasselaar, Hennessy and Isselstein, 2020). Mixed farms may incur additional costs for feeding livestock during periods of adverse weather, therefore increasing the variability of income.

General cropping farms do not appear as sensitive to changes in temperature and precipitation, and the effect of input intensity and specialisation were found to be more important. General cropping farms are, on average, the most diverse (Table 2), which may provide greater resilience to climate variability compared to other farm types.

Generally, the relative effects of climatic factors associated with the variability of income were similar in size to the effects of the farming practices examined. However, for general cropping farms, the effect of input intensity and specialisation were found to be more important than the climatic conditions examined. For factors explaining the stability of calories produced, the farming practices employed are associated with larger relative effects. Our findings highlight the importance of considering both farming practices and climate conditions when examining stability of farm performance at the farm level.

5 Conclusions

Our study provides knowledge on the relative importance of farming practices, subsidies and climate variability on the temporal stability of food production and farm income, at the farm level. Results highlight the important of agricultural diversity in increasing the stability of agriculture. We find that increasing agricultural diversity was associated with a relatively large increase in the stability of food production and farm incomes for general cropping and cereal farms. Increasing agricultural diversity is therefore a highly important factor for the future sustainability of farming systems and food security.

Our results also show that, for all farm types examined, increasing the amount spent on chemical inputs is associated with a relatively large increase in the variability of income. However, chemical inputs may reduce the variability in calories produced at the farm level, particularly for mixed farms. This indicates a potential trade-off in the use of chemical inputs between the stability of food production and farm incomes. More precise and controlled use of chemicals to reduce costs may therefore help to reduce income variability whilst maintaining outputs and food production.

Subsidies paid to farmers through the EU Common Agricultural Policy have, on average, a relatively small effect on the stability of food production and farm incomes compared to other farming practices. The effects of subsidies also vary between farm types. Direct payments, based on area alone, are found to increase the variability of income and food production for most farm types. Whereas agri-environment schemes may improve stability of both farm income and food production, for general cropping and mixed farms. This is particularly encouraging with the transition from direct payments to a new agricultural policy in the UK focusing on environmental land management. Cereal farms do not appear to benefit from current agri-environment schemes therefore future schemes must be flexible and adapted to different landscapes and production.

Climate conditions are also important factors affecting both the stability of income and food production, at the farm level. However, the relative size of these effects varies between farm type. Variability in both temperature and rainfall increase the variability of income for cereal farms, while deviations in temperature are more influential for food production. For mixed farms changes in precipitation have a larger effect than temperature on the stability of income. For general cropping farms the effect of farming practices were more important than the effects of climate variability.

Our results highlight the importance of considering both farming practices and climate conditions when examining stability of farm performance at the farm level. Our results also suggest that adaptation to improve stability varies between farm types, therefore future agricultural policy should be flexible and able to be tailored to different types of production.

Acknowledgements

Caroline Harkness acknowledges financial support from the University of Reading and Rothamsted Research, who provided joint funding for this research. Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) through Designing Future Wheat [BB/P016855/1] and Achieving Sustainable Agricultural Systems [NE/N018125/1] jointly funded with NERC.

References

Barry, P. J., Escalante, C. L. and Bard, S. K. (2001) 'Economic risk and the structural characteristics of farm businesses', *Agricultural Finance Review*, 61(1), pp. 73–86. doi: 10.1108/00214760180001117.

Battisti, D. S. and Naylor, R. L. (2009) 'Historical Warnings of Future Food Insecurity with Unprecedented Seasonal Heat', *Science*, 323(5911), pp. 240–244. doi: 10.1126/science.1164363.

El Benni, N., Finger, R. and Mann, S. (2012) 'Effects of agricultural policy reforms and farm characteristics on income risk in Swiss agriculture', *Agricultural Finance Review*, 72(3), pp. 301–324. doi: 10.1108/00021461211277204.

Blaauw, B. R. and Isaacs, R. (2014) 'Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop', *Journal of Applied Ecology*, 51(4), pp. 890–898. doi: 10.1111/1365-2664.12257.

Büchi, L. *et al.* (2018) 'Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system', *Agriculture, Ecosystems and Environment*. Elsevier, 256(December 2017), pp. 92–104. doi: 10.1016/j.agee.2018.01.005.

Bürkner, P. C. (2017) 'brms: An R package for Bayesian multilevel models using Stan', *Journal of Statistical Software*, 80(1), pp. 1–28.

Bürkner, P. C. (2018) 'Advanced Bayesian multilevel modeling with the R package brms', *R Journal*, 10(1), pp. 395–411. doi: 10.32614/rj-2018-017.

Castañeda-Vera, A. and Garrido, A. (2017) 'Evaluation of risk management tools for stabilising farm income under CAP 2014-2020', *Economia Agraria y Recursos Naturales*, 17(1), pp. 3–23. doi: 10.7201/earn.2017.01.01.

Ceglar, A. *et al.* (2016) 'Impact of meteorological drivers on regional inter-annual crop yield variability in France', *Agricultural and Forest Meteorology*. Elsevier B.V., 216, pp. 58–67. doi: 10.1016/j.agrformet.2015.10.004.

Dardonville, M. *et al.* (2020) 'Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems', *Agricultural Systems*, 184(November 2019). doi: 10.1016/j.agsy.2020.102913.

Degani, E. *et al.* (2019) 'Crop rotations in a climate change scenario: short-term effects of crop diversity on resilience and ecosystem service provision under drought', *Agriculture,* *Ecosystems and Environment*. Elsevier, 285(August), p. 106625. doi: 10.1016/j.agee.2019.106625.

Department for Environment Food and Rural Affairs *et al.* (2018) *Agriculture in the United Kingdom 2017*, *National Statistics*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/741062/AUK-2017-18sep18.pdf.

Department for Environment Food and Rural Affairs (2020) *Farm Business Survey*. Available at: https://www.gov.uk/government/collections/farm-business-survey (Accessed: 20 March 2020).

Dormann, C. F. *et al.* (2013) ‘Collinearity: A review of methods to deal with it and a simulation study evaluating their performance’, *Ecography*, 36(1), pp. 27–46. doi: 10.1111/j.1600-0587.2012.07348.x.

Enjolras, G. *et al.* (2014) ‘Direct payments, crop insurance and the volatility of farm income. Some evidence in France and in Italy’, *New Medit*, 13(1), pp. 31–40.

European Environment Agency (2005) *Agriculture and environment in EU-15 — the IRENA indicator report*. Copenhagen, Denmark.

FAO (2021) *FAO Food Balance Sheet*, *FAOSTAT*. Available at: http://www.fao.org/faostat/en/#data/FBS (Accessed: 26 February 2021).

Gaudin, A. C. M. *et al.* (2015) ‘Increasing crop diversity mitigates weather variations and improves yield stability’, *PLoS ONE*, 10(2), pp. 1–20. doi: 10.1371/journal.pone.0113261.

Gelman, A. (2006) ‘Prior distributions for variance parameters in hierarchical models’, *Bayesian Analysis*, 1(3), pp. 515–534. Available at: http://projecteuclid.org/euclid.ba/1340371048.

Gelman, A. and Rubin, D. B. (1992) ‘Inference from Iterative Simulation Using Multiple Sequences’, *Statistical Science*, 7(4), pp. 457–472. doi: 10.1214/ss/1177011136.

Gerrard, C. L., Padel, S. and Moakes, S. (2012) ‘The use of Farm Business Survey data to compare the environmental performance of organic and conventional farms’, *International Journal of Agricultural Management*, 2(1), pp. 5–16. doi: 10.5836/ijam/2013-01-02.

Harkness, C. *et al.* (2021) ‘Stability of farm income: The role of agricultural diversity and agri-environment scheme payments’, *Agricultural Systems*. Elsevier Ltd, 187(December 2020), p. 103009. doi: 10.1016/j.agsy.2020.103009.

Hoffman, M. D. and Gelman, A. (2014) ‘The no-U-turn sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo’, *Journal of Machine Learning Research*.

Hollis, D. *et al.* (2019) ‘HadUK-Grid—A new UK dataset of gridded climate observations’, *Geoscience Data Journal*, 6(2), pp. 151–159. doi: 10.1002/gdj3.78.

Iizumi, T. and Ramankutty, N. (2016) ‘Changes in yield variability of major crops for 1981-2010 explained by climate change’, *Environmental Research Letters*. IOP Publishing, 11(3). doi: 10.1088/1748-9326/11/3/034003.

IPCC (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M. L. Parry et al. Cambridge, UK: Cambridge University Press. doi: volume.

IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Edited by C. B. Field et al. Cambridge University Press, Cambridge, UK, and New York, NY, USA. doi: 10.1017/CBO9781139177245.

Kendon, M. *et al.* (2020) ‘State of the UK Climate 2019’, *International Journal of Climatology*, 40(S1), pp. 1–69. doi: 10.1002/joc.6726.

Kennedy, C. M. *et al.* (2013) ‘A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems’, *Ecology Letters*, 16(5), pp. 584–599. doi: 10.1111/ele.12082.

Kipling, R. P. *et al.* (2016) ‘Modeling European ruminant production systems: Facing the challenges of climate change’, *Agricultural Systems*. Elsevier Ltd, 147, pp. 24–37. doi: 10.1016/j.agsy.2016.05.007.

Macdiarmid, J. I. *et al.* (2018) ‘Assessing national nutrition security: The UK reliance on imports to meet population energy and nutrient recommendations’, *PLoS ONE*, 13(2), pp. 1–16. doi: 10.1371/journal.pone.0192649.

Marra, M. C. and Schurle, B. W. (1994) ‘Kansas Wheat Yield Risk Measures and Aggregation: A Meta-Analysis Approach’, *Journal of Agricultural and Resource Economics*, 19(1), pp. 69–77. Available at: https://www.jstor.org/stable/40986829.

Menalled, F. D. *et al.* (2003) ‘Temporal variation in the response of parasitoids to agricultural landscape structure’, *Agriculture, Ecosystems and Environment*, 96(1–3), pp. 29–35. doi: 10.1016/S0167-8809(03)00018-5.

Nalborczyk, L. *et al.* (2019) 'An introduction to bayesian multilevel models using brms: A case study of gender effects on vowel variability in standard Indonesian', *Journal of Speech, Language, and Hearing Research*, 62(5), pp. 1225–1242. doi: 10.1044/2018_JSLHR-S-18-0006.

Neal, R. M. (2011) 'MCMC using hamiltonian dynamics', in *Handbook of Markov Chain Monte Carlo*. doi: 10.1201/b10905-6.

Olesen, J. E. and Bindi, M. (2002) 'Consequences of climate change for European agricultural productivity, land use and policy', *European Journal of Agronomy*. doi: 10.1016/S1161-0301(02)00004-7.

ONS (2020) *Consumer price inflation time series (MM23)*. Available at: https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/d7bt/mm23 (Accessed: 20 March 2020).

Ottoy, S. *et al.* (2018) 'Impacts of selected Ecological Focus Area options in European farmed landscapes on climate regulation and pollination services: A systematic map protocol', *Environmental Evidence*. BioMed Central, 7(1), pp. 1–10. doi: 10.1186/s13750-018-0122-6.

Pacín, F. and Oesterheld, M. (2014) 'In-farm diversity stabilizes return on capital in Argentine agro-ecosystems', *Agricultural Systems*, 124, pp. 51–59. doi: 10.1016/j.agsy.2013.10.008.

van den Pol-van Dasselaar, A., Hennessy, D. and Isselstein, J. (2020) 'Grazing of dairy cows in europe-an in-depth analysis based on the perception of grassland experts', *Sustainability (Switzerland)*, 12(3). doi: 10.3390/su12031098.

Poon, K. and Weersink, A. (2011) 'Factors affecting variability in farm and off-farm income', *Agricultural Finance Review*, 71(3), pp. 379–397. doi: 10.1108/00021461111177639.

R Core Team (2019) *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.r-project.org/.

Rahmstorf, S. and Coumou, D. (2011) 'Increase of extreme events in a warming world', *Proceedings of the National Academy of Sciences*, 108(44), pp. 17905–17909. doi: 10.1073/pnas.1101766108.

Reidsma, P. *et al.* (2009) 'Vulnerability and adaptation of European farmers: A multi-level analysis of yield and income responses to climate variability', *Regional Environmental*

Change, 9(1), pp. 25–40. doi: 10.1007/s10113-008-0059-3.

Reidsma, P., Ewert, F. and Oude Lansink, A. (2007) ‘Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity’, *Climatic Change*, 84(3–4), pp. 403–422. doi: 10.1007/s10584-007-9242-7.

Reyer, C. P. O. *et al.* (2013) ‘A plant’s perspective of extremes: Terrestrial plant responses to changing climatic variability’, *Global Change Biology*, 19(1), pp. 75–89. doi: 10.1111/gcb.12023.

Smith, M. R. *et al.* (2016) ‘Global Expanded Nutrient Supply (GENuS) Model: A New Method for Estimating the Global Dietary Supply of Nutrients’, *PloS one*, 11(1), p. e0146976. doi: 10.1371/journal.pone.0146976.

Stan Development Team (2020) *Stan Reference Manual*. Available at: https://mc-stan.org/.

Trnka, M. *et al.* (2014) ‘Adverse weather conditions for European wheat production will become more frequent with climate change’, *Nature Climate Change*, 4(7), pp. 637–643. doi: 10.1038/nclimate2242.