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A meta-analysis on the effects of climate change on the yield and quality of European pastures

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ABSTRACT

As has been widely reported, climate change will be felt throughout Europe, though effects are likely to vary dramatically across European regions. While all areas are expected to experience elevated atmospheric CO_2 concentrations (↑C) and higher temperatures (↑T), the north east will get considerably wetter (↑W) while the south much drier (↓W). It is likely that these changes will have an impact on pastures and consequently on grazing livestock. This study aims to evaluate the expected changes to pasture yield and quality caused by ↑C, ↑T, ↑W and ↓W across the different European regions and across different plant functional groups (PFGs). Data was collected from 143 studies giving a total of 998 observations. Mixed models were used to estimate expected changes in above ground dry weight (AGDW) and nitrogen (N) concentrations and were implemented using Markov Chain Monte Carlo simulations. The results showed an increase in AGDW under ↑C, particularly for shrubs (+71.6%), though this is likely to be accompanied by a reduction in N concentrations (−4.8%). ↑T will increase yields in Alpine and northern areas (+82.6%), though other regions will experience little change or else decreases. ↑T will also reduce N concentrations, especially for shrubs (−13.6%) and forbs (−18.5%). ↓W will decrease AGDW for all regions and PFGs, though will increase N concentrations (+11.7%). Under ↑W there was a 33.8% increase in AGDW. While there is a need for further research to get a more complete picture of future pasture conditions, this analysis provides a general overview of expected changes and thus can help European farmers prepare to adapt their systems to meet the challenges presented by a changing climate.

1. Introduction

Depending on global emissions, global average atmospheric CO_2 concentrations are expected to rise to between 421 and 936 ppm by 2100 (IPCC, 2013). Under a mid-range emissions scenario (IPCC representative concentration pathway (RCP) 4.5), Europe can expect average annual temperature increases of between 1 and 4.5 °C, with the greatest warming in the south in summer and in the north-east in winter (EEA, 2017). Annual precipitation is predicted to increase for northern and large parts of continental Europe (up to 25% increase under RCP4.5), while decreasing in southern Europe (up to 25% reduction under RCP4.5) (Jacob et al., 2014). Extreme events (heat-waves, heavy precipitation events and droughts) will all become more common across the continent (Kovats et al., 2014).

A great deal is already known about how specific plant species respond to specific climatic changes in specific ecosystems. However, it is useful to generalise this knowledge to a wider scale in order to make appropriate management and policy decisions. Changes in pasture yield and quality will have knock-on effects on the livestock production sector and it is important for farmers, policy makers and researchers to know what to expect.

Elevated atmospheric CO_2 levels (↑C) generally increase plant yields, though results are conflicting when considering the relative responses of different plant functional groups (PFGs) (Ainsworth and Long, 2004; Nowak et al., 2004; Wang et al., 2012). In terms of plant quality, Dumont et al. (2015) found that ↑C decreases forage nitrogen (N) content, though to varying extents for different geographic areas.

The effect of increasing air temperatures (↑T) on plant growth is closely related to water availability. In mid to high latitudes and in mountainous regions, it is predicted that ↑T will increase plant production (Dumont et al., 2015; Hopkins and Del Prado, 2007; Watson et al., 1997); this is partly due to the longer growing season (Kipling et al., 2016; Trnka et al., 2011). However, Alpine regions have been observed to be vulnerable to droughts (Schmid et al., 2011), which would have a negative effect on growth, making it hard to know what the overall impact will be. Northern Europe will experience increased water availability (↑W), which promotes plant growth and has a positive effect on plant quality (Matías et al., 2011; Sardans and Peñuelas,

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2013).

Southern Europe, by contrast, is expected to experience decreased forage production when climate change impacts alone are considered (up to 30% reduction by 2050 in Portugal and southern France) due to a combination of drought and very high temperatures (Dumont et al., 2015; Rötter and Höhn, 2015), although it is not clear what the net result will be when combined with the fertilisation effect of ↑C. Meta-analyses have shown that warming and drought tend to reduce nutrient availability in plants, particularly in terms of N content, though again there is regional variation (Lee et al., 2017; Dumont et al., 2015).

Given the expected geographic variation in the effects of climate change on pastures, it is useful to consider these effects on a regional basis. It is also helpful to consider the effects on different PFGs, as these could lead to changes in pasture composition. In this study we use a meta-analysis to quantify the effects of ↑C, ↑T, ↑W and ↓W on both the yield and quality of pasture and forage species across five European regions. We also investigate the impacts on yield and quality for different PFGs and consider the effects of multiple simultaneous climatic changes.

2. Methods

The search for studies for this meta-analysis was conducted in January 2017 using the Web of Science database. Additional studies were taken from grey literature, previous meta-analyses on a similar topic, bibliographies of key review articles, expert consultation and internet searches (see Supplementary Material A for full details of the search terms used). Only studies written in English were used due to limitations on resources; no limits were set on the publication date. To be included, a study had to meet the following criteria:

- Conducted in Europe, or else in controlled laboratory conditions;
- Includes at least one desirable forage species commonly found in Europe;
- Assesses the effect of ↑C, ↑T, ↑W or ↓W on plant life;
- Provides quantitative data on changes in plant yield or quality, including mean, standard deviation (SD) (or equivalent) and sample size.

Where plants were sampled several times over a period, only data from the final sampling was used. Several studies compared different cultivars or genotypes of the same species; these were taken as replicates. For the purposes of the present study, plants were grouped into shrubs, forbs, legumes and graminoids. The vast majority of plant species included in the analysis were perennial types with a C3 photosynthetic pathway. Some studies did not report the precise mix of plant species used so it is possible that some C4 species were present; these were treated as 'mixed species' experiments. Each study was assigned to one of five geographical regions: Alpine, Atlantic, continental, northern and southern (see Fig. 1). Laboratory studies were assigned a region based on the climatic conditions applied and the plant species used.

In total, 131 studies were used in this meta-analysis (see Supplementary Material B and C for full details), providing 797 observations (one observation is counted as a value under climate change conditions together with the associated control value). Seventy studies investigated the effects of ↑C, with an average increase of 279 ± 81 ppm (mean ± SD) (number of observations $n = 347$) over an average period of 460 days; 42 studies looked at the effects of ↑T, with an average increase of 3.1 ± 1.7 °C ($n = 3250$) over an average of 445 days; 56 studies looked at the effects of reduced water availability (↓W), with an average water reduction of 81 ± 26% compared with control treatments ($n = 289$) over an average of 74 days (mainly in summer); 9 studies considered the impact of increased water availability (↑W), with an average water increase of 117 ± 96% ($n = 48$) over an average of 189 days (around half during summer, with others during winter and spring). Of these studies, 26 considered the effects of multiple simultaneous climatic changes (97 observations). This CO_2 increase was in the middle of the predicted range for 2100 atmospheric concentrations and the temperature increase also falls within the expected range. The ↑W and ↓W treatments were both quite extreme but are over much shorter time periods than the ↑C and ↑T treatments; they could be seen to represent a particularly wet or dry season.

The natural logarithm of the response ratio (L) was used to estimate the effect of the different climate treatments, where $L_i = ln(\overline{X}_{Ti}/\overline{X}_{Ci})$ ($\overline{X}_{Ti}$ and $\overline{X}_{Ci}$ are the mean outcomes for experiment i under test and control conditions respectively). Assuming $\overline{X}_{Ti}$ and $\overline{X}_{Ci}$ are normally distributed, the variance of $L_i(S_i)$ can be approximated as (Hedges et al., 1999):

$$S_i = \frac{(SD_{Ti})^2}{n_{Ti}\overline{X}_{Ti}^2} + \frac{(SD_{Ci})^2}{n_{Ci}\overline{X}_{Ci}^2}$$

where SD_{Ti} and SD_{Ci} are the standard deviations and n_{Ti} and n_{Ci} are the sample sizes of experiment i under test and control conditions.

Mixed models were used in most cases, with fixed effects relating to plant type, climatic treatment, management practices and experimental methodology and with the individual studies as a random effect. Fixed effects models were used for yield under ↑T and ↑W since in these cases the random effect of the individual studies was found to be insignificant (using a likelihood ratio test). The choice of fixed effects was determined through REML analysis in GenStat 16th Ed. (VSNi, 2013) and the model was implemented in WinBUGS 1.4.3 (MRC, 2007).

The model can be described as follows:

$$L_i \sim N(\theta_i, S_i^2)$$

with

$$\theta_i \sim N(\mu, \tau^2)$$

where θ_i is the true mean of L_i; μ denotes true overall effect across all studies and τ^2 is the between-study variance. To incorporate fixed effects, μ is generalised to a regression function:

$$\mu = \beta_0 + \beta_1 Q_1 + \beta_2 Q_2 + \dots + \beta_p Q_p + \alpha_0 R$$

where $Q_1, \dots, Q_p$ represent p fixed effects (e.g. fertiliser use, treatment time, European region, etc.) and R represents the random effect. Since this models the natural logarithm of the response ratio, the overall effect μ was converted to percentage change using the following equation:

$$\textit{Percentage change} = e^{\mu} - 1$$

WinBUGS fits Bayesian models using Markov Chain Monte Carlo (MCMC) simulations. Non-informative priors were used and all observations were weighted according to their variance. The model was run with three chains to check sensitivity to different initial conditions. Fifty-thousand iterations were sufficient to ensure convergence for all models, with the first 1000 discarded as burn-in. Bias and homogeneity of the studies was assessed by means of funnel plots. The goodness-of-fit of the models was assessed using posterior predictive p-values (Meng, 1994) and by comparing the cumulative frequency distributions of predicted and observed data (Ntzoufras, 2009).

Analyses were performed looking at the effects of ↑C, ↑T, ↓W and ↑W on plant above ground dry weight (AGDW) and on above ground N concentration for different plant functional groups (PFGs) across the five European regions. Studies which looked at multiple simultaneous climatic treatments were used to assess the effects of the different combinations. Where region or PFG was not a significant factor (or when there were only a small number of observations available), then their results are grouped. Analyses were only run when data from at least five different studies was available. This had the effect that the only plant quality measure used was N concentration.