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

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12 **Abstract**

13 As has been widely reported, climate change will be felt throughout
14 Europe, though effects are likely to vary dramatically across
15 European regions. While all areas are expected to experience
16 elevated atmospheric CO₂ concentrations (↑C) and higher
17 temperatures (↑T), the north east will get considerably wetter
18 (↑W) while the south much drier (↓W). It is likely that these
19 changes will have an impact on pastures and consequently on
20 grazing livestock. This study aims to evaluate the expected changes
21 to pasture yield and quality caused by ↑C, ↑T, ↑W and ↓W across
22 the different European regions and across different plant functional
23 groups (PFGs). Data was collected from 143 studies giving a total of
24 998 observations. Mixed models were used to estimate expected

25 changes in above ground dry weight (AGDW) and nitrogen (N)
26 concentrations and were implemented using Markov Chain Monte
27 Carlo simulations. The results showed an increase in AGDW under
28 $\uparrow C$, particularly for shrubs (+71.6%), though this is likely to be
29 accompanied by a reduction in N concentrations (-4.8%). $\uparrow T$ will
30 increase yields in Alpine and northern areas (+82.6%), though other
31 regions will experience little change or else decreases. $\uparrow T$ will also
32 reduce N concentrations, especially for shrubs (-13.6%) and forbs (-
33 18.5%). $\downarrow W$ will decrease AGDW for all regions and PFGs, though
34 will increase N concentrations (+11.7%). Under $\uparrow W$ there was a
35 33.8% increase in AGDW. While there is a need for further research
36 to get a more complete picture of future pasture conditions, this
37 analysis provides a general overview of expected changes and thus
38 can help European farmers prepare to adapt their systems to meet
39 the challenges presented by a changing climate.

40 **Key words:** Climate change, meta-analysis, pastures, above ground
41 dry weight

42 **1. Introduction**

43 Depending on global emissions, global average atmospheric CO₂
44 concentrations are expected to rise to between 421 and 936 ppm by
45 2100 (IPCC, 2013). Under a mid-range emissions scenario (IPCC
46 representative concentration pathway (RCP) 4.5), Europe can expect
47 average annual temperature increases of between 1 and 4.5°C, with
48 the greatest warming in the south in summer and in the north-east
49 in winter (EEA, 2017). Annual precipitation is predicted to increase

50 for northern and large parts of continental Europe (up to 25%
51 increase under RCP4.5), while decreasing in southern Europe (up to
52 25% reduction under RCP4.5) (Jacob et al., 2014). Extreme events
53 (heat-waves, heavy precipitation events and droughts) will all
54 become more common across the continent (Kovats et al., 2014).

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

62 Elevated atmospheric CO₂ levels (↑C) generally increase plant
63 yields, though results are conflicting when considering the relative
64 responses of different plant functional groups (PFGs) (Ainsworth and
65 Long, 2004; Nowak et al., 2004; Wang et al., 2012). In terms of plant
66 quality, Dumont et al. (2015) found that ↑C decreases forage
67 nitrogen (N) content, though to varying extents for different
68 geographic areas.

69 The effect of increasing air temperatures (↑T) on plant growth is
70 closely related to water availability. In mid to high latitudes and in
71 mountainous regions, it is predicted that ↑T will increase plant
72 production (Dumont et al., 2015; Hopkins and Del Prado, 2007;
73 Watson et al., 1997); this is partly due to the longer growing season
74 (Kipling et al., 2016; Trnka et al., 2011). However, Alpine regions

75 have been observed to be vulnerable to droughts (Schmid et al.,
76 2011), which would have a negative effect on growth, making it hard
77 to know what the overall impact will be. Northern Europe will
78 experience increased water availability ($\uparrow W$), which promotes plant
79 growth and has a positive effect on plant quality (Matías et al., 2011;
80 Sardans and Peñuelas, 2013).

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

91 Given the expected geographic variation in the effects of climate
92 change on pastures, it is useful to consider these effects on a
93 regional basis. It is also helpful to consider the effects on different
94 PFGs, as these could lead to changes in pasture composition. In this
95 study we use a meta-analysis to quantify the effects of $\uparrow C$, $\uparrow T$,
96 $\uparrow W$ and $\downarrow W$ on both the yield and quality of pasture and forage
97 species across five European regions. We also investigate the
98 impacts on yield and quality for different PFGs and consider the
99 effects of multiple simultaneous climatic changes.

100 **2. Methods**

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

- 110 • Conducted in Europe, or else in controlled laboratory
111 conditions;
- 112 • Includes at least one desirable forage species commonly
113 found in Europe;
- 114 • Assesses the effect of $\uparrow C$, $\uparrow T$, $\uparrow W$ or $\downarrow W$ on plant life;
- 115 • Provides quantitative data on changes in plant yield or
116 quality, including mean, standard deviation (SD) (or
117 equivalent) and sample size.

118 Where plants were sampled several times over a period, only data
119 from the final sampling was used. Several studies compared
120 different cultivars or genotypes of the same species; these were
121 taken as replicates. For the purposes of the present study, plants
122 were grouped into shrubs, forbs, legumes and graminoids. The vast
123 majority of plant species included in the analysis were perennial
124 types with a C3 photosynthetic pathway. Some studies did not

125 report the precise mix of plant species used so it is possible that
126 some C4 species were present; these were treated as 'mixed
127 species' experiments. Each study was assigned to one of five
128 geographical regions: Alpine, Atlantic, continental, northern and
129 southern (see figure 1). Laboratory studies were assigned a region
130 based on the climatic conditions applied and the plant species used.

131 In total, 143 studies were used in this meta-analysis (see
132 Supplementary Material B and C for full details), providing 998
133 observations (one observation is counted as a value under climate
134 change conditions together with the associated control value).

135 Eighty-two studies investigated the effects of $\uparrow C$, with an average
136 increase of 284 ± 79 ppm (mean \pm SD) (number of observations $n =$
137 476) over an average period of 475 days; 45 studies looked at the
138 effects of $\uparrow T$, with an average increase of $3.2 \pm 1.7^\circ C$ ($n = 301$) over
139 an average of 418 days; 59 studies looked at the effects of reduced
140 water availability ($\downarrow W$), with an average water reduction of $79 \pm$
141 26% compared with control treatments ($n = 357$) over an average of
142 70 days (mainly in summer); 9 studies considered the impact of
143 increased water availability ($\uparrow W$), with an average water increase
144 of $117 \pm 96\%$ ($n = 48$) over an average of 189 days (around half
145 during summer, with others during winter and spring). Of these
146 studies, 32 considered the effects of multiple simultaneous climatic
147 changes (162 observations). This CO_2 increase was in the middle of
148 the predicted range for 2100 atmospheric concentrations and the
149 temperature increase also falls within the expected range. The $\uparrow W$
150 and $\downarrow W$ treatments were both quite extreme but are over much

151 shorter time periods than the ↑C and ↑T treatments; they could be
152 seen to represent a particularly wet or dry season.

153 The natural logarithm of the response ratio (L) was used to estimate
154 the effect of the different climate treatments, where $L_i =$
155 $\ln(\bar{X}_{Ti}/\bar{X}_{Ci})$ (\bar{X}_{Ti} and \bar{X}_{Ci} are the mean outcomes for experiment i
156 under test and control conditions respectively). Assuming \bar{X}_{Ti} and
157 \bar{X}_{Ci} are normally distributed, the variance of L_i (S_i) can be
158 approximated as:

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

159 (Hedges et al., 1999)

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

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

172 The model can be described as follows:

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

173 with

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

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

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

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

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

182 WinBUGS fits Bayesian models using Markov Chain Monte Carlo
183 (MCMC) simulations. Non-informative priors were used and all
184 observations were weighted according to their variance. The model
185 was run with three chains to check sensitivity to different initial
186 conditions. Fifty-thousand iterations were sufficient to ensure
187 convergence for all models, with the first 1,000 discarded as burn-in.
188 Bias and homogeneity of the studies was assessed by means of
189 funnel plots. The goodness-of-fit of the models was assessed using
190 posterior predictive p-values (Meng, 1994) and by comparing the

191 cumulative frequency distributions of predicted and observed data
192 (Ntzoufras, 2009).

193 Analyses were performed looking at the effects of $\uparrow C$, $\uparrow T$, $\downarrow W$ and
194 $\uparrow W$ on plant above ground dry weight (AGDW) and on above
195 ground N concentration for different plant functional groups (PFGs)
196 across the five European regions. Studies which looked at multiple
197 simultaneous climatic treatments were used to assess the effects of
198 the different combinations. Where region or PFG was not a
199 significant factor (or when there were only a small number of
200 observations available), then their results are grouped. Analyses
201 were only run when data from at least five different studies was
202 available. This had the effect that the only plant quality measure
203 used was N concentration.

204 **3. Results**

205 *3.1 Bias and sensitivity analysis*

206 In all cases, the models were found to have an acceptable fit. The
207 observed cumulative frequency distribution fell within the 95%
208 credible interval of the predicted cumulative frequency distribution
209 in almost all cases. For some models (N concentration under $\downarrow W$
210 and both AGDW and N concentration for different combinations of
211 treatments), a few points were just outside the interval at the upper
212 end of the distribution, suggesting that these models slightly over-
213 predict results at the upper extreme. Posterior predictive p-values
214 ranged from 0.487 to 0.537 across all models.

215 Funnel plots were made for each analysis (examples in figure 2). The
216 plots shown here are representative of all plots, with those for
217 AGDW generally not showing signs of bias but indicating
218 considerable heterogeneity between studies. Exceptions were plots
219 for forbs under ↓W conditions and the continental region under
220 ↑T, where higher standard errors of measurement were associated
221 with greater negative response to the climatic change. Funnel plots
222 for N concentration generally revealed bias and also high levels of
223 heterogeneity. The plot for N concentration under ↑C was biased
224 towards a greater negative response. For ↓W the overall effect was
225 positive though the bias was towards a reduced or even negative
226 response. For all PFGs except legumes under ↑T the effect was
227 negative and the bias was towards a reduced or positive response;
228 for legumes the bias was towards a more negative response.

229 *3.2 Above ground dry weight*

230 Shrubs exhibit a considerably higher growth increase than other
231 PFGs under ↑C (+71.6% growth increase), with forbs, legumes and
232 graminoids being more similar in their responses (figure 3).
233 Graminoids are less likely to experience elevated growth under ↑C
234 than legumes or forbs (with the chances of increased growth being
235 55.7%, 94.6% and 96.9% respectively, calculated from the posterior
236 distribution) and generally exhibit less growth than legumes, which
237 in turn exhibit less growth than forbs (mean increases of +0.6%,
238 +8.5% and +13.0% for graminoids, legumes and forbs respectively).

239 Shrubs and legumes both experience significant yield reductions
240 under ↓W (-33.8% and -31.8% respectively). Forbs, and graminoids
241 are both likely to have decreased yields (84.8% and 91.5%
242 likelihoods respectively), with mean decreases of -10.7% and -
243 11.9%. There were no significant differences between PFGs under
244 ↑T and insufficient data for ↑W.

245 Changes in AGDW for different European regions under ↑T and
246 ↓W are shown in figure 4. The southern region is missing for ↑T
247 due to a lack of available data and the northern region is missing for
248 ↓W as this is not an expected consequence of climate change. ↑T
249 increases growth in Alpine and northern areas (+82.6%) and reduces
250 it in the continental region (-32.6%). There is negligible effect on
251 plant yield in the Atlantic region. Under ↓W, there is a significant
252 decrease in AGDW in the continental region (-42.2%) and likely
253 decreases everywhere else, (the likelihoods of a reduction are
254 87.4%, 95.9% and 84.9% for the Alpine, Atlantic and southern
255 regions respectively). For ↑W, all the data came from the Alpine,
256 continental and northern regions, which are all areas which are
257 predicted to receive increased rainfall under climate change, at least
258 for part of the year. AGDW increases under ↑W (+57.1%), though
259 with a large credible interval (17.2 – 110.4%), possibly due to the
260 small dataset and the wide regional variation; unfortunately there
261 was insufficient data for a regional division under ↑W. There were
262 no significant regional differences for ↑C.

263 So far only single climatic changes have been considered (though
264 data from experiments with multiple treatments was used, with the
265 additional treatments included in the models as a fixed effect). The
266 expected changes in AGDW under different combinations of climatic
267 treatments are shown in figure 5. $\uparrow C + \uparrow T$ increases plant growth
268 (+32.8%), while $\uparrow T + \downarrow W$ and $\uparrow C + \uparrow T + \downarrow W$ are likely to lead to
269 reductions. For $\uparrow C + \downarrow W$, the two effects seem to cancel each other
270 out, producing very little change in AGDW. Combining $\uparrow W$ with $\uparrow T$
271 is likely to increase growth (80.3% chance of an increase), though
272 the credible interval is very large, which is likely a result of the small
273 amount of data available for $\uparrow W + \uparrow T$.

274 *3.3 Nitrogen concentration*

275 The expected changes in N concentration under $\uparrow T$ for different
276 PFGs are shown in figure 6. Shrubs and forbs both display significant
277 reductions in N concentration (-13.6% and -18.5% reductions
278 respectively), while N concentration in graminoids is likely to
279 decrease (average reduction of -5.6% with a 94.3% chance of a
280 decrease).

281 Neither PFG nor region had a significant effect for the other climatic
282 changes and so overall average changes are shown (figure 7). Under
283 $\downarrow W$ there was a significant increase in N concentration (+11.7%),
284 while it is likely to decrease under $\uparrow C$ (-4.8% with a 84.8% chance of
285 a decrease).

286 It is interesting to note, when comparing how N concentration
287 changes for different combinations of climate treatments (figure 8),

288 that ↓W produces little change in N concentration when considered
289 alone, while in the previous analysis (figure 7) it produced an
290 increase. This is because all treatments involving ↓W were included
291 in figure 7, including e.g. ↑C+↓W, ↑T+↓W, etc. It appears that
292 ↑C+↓W decreases N concentration (-12.8%) and ↑W increases it
293 (11.8%), but other combinations produce a slight but non-significant
294 reduction.

295 **4. Discussion**

296 The present study set out to quantify the effects of ↑C, ↑T, ↑W
297 and ↓W on pasture yield and quality across Europe. The impacts of
298 these changes on yield and quality for different PFGs were also
299 assessed. The results presented above address these objectives.

300 *4.1 Bias and sensitivity analysis*

301 For all funnel plots there was a large degree of heterogeneity. This is
302 to be expected given the differing methodologies, plant species,
303 locations and soil types across the studies. At least some of this
304 variability is accounted for in the analysis through the fixed and
305 random effects. There are several possible explanations for the bias
306 that was recorded. It may be that some categories (plant species,
307 locations, etc.) are over-represented, there may be publication bias,
308 or it may be that due to the small number of observations for some
309 PFGS and regions that it is not possible to make an accurate
310 estimate. For shrubs in particular there were only a small number of
311 studies available and these results should be treated with caution.

312 Due to the bias found it may be that the results for N concentration
313 under $\downarrow W$ and $\uparrow T$ should show a greater negative response and
314 that those under $\uparrow C$ should have a smaller response. The more
315 extreme observations which have a large standard error should not
316 have too great an influence as the observations were weighted
317 according to their variance.

318 *4.2 Above ground dry weight*

319 Looking at the change in AGDW under $\uparrow C$ (figure 3), the results
320 show that shrubs exhibit a larger degree of growth than other PFGs.
321 In this analysis, the average CO_2 increase for experiments involving
322 shrubs was 184 ppm, whereas it was 290 ppm for all other PFGs,
323 making this result particularly surprising. Ainsworth and Long (2004)
324 had a similar finding for trees, but other studies (Nowak et al., 2004;
325 Wang et al., 2012) found contrasting results. This is an area that
326 would benefit from further independent studies.

327 When looking at $\downarrow W$, there was a greater reduction in AGDW for
328 shrubs and legumes than for forbs and graminoids. Elst et al. (2017)
329 suggest that grasses may be more resistant to drought than legumes
330 due to their generally deeper rooting depth, giving them greater
331 access to the limited water resources. The large reduction in shrub
332 yield compared to graminoids could be attributed to competition
333 effects, as proposed by Kreyling et al. (2008).

334 For $\uparrow T$ the effect across functional groups was very similar, there
335 being a slight increase in AGDW, although it should be noted that

336 there were comparatively few studies looking at $\uparrow T$ for southern
337 Europe where high temperatures are expected to have especially
338 negative effects, which could have skewed the results.

339 In general, it seems that in areas which are not water-limited, all
340 functional groups will benefit to some extent, though particularly
341 shrubs. An increase in shrub encroachment could have variable
342 effects on pastures, some positive and some negative (Eldridge et
343 al., 2011; Rivest et al., 2011). In water-limited areas it is harder to
344 predict which functional groups will benefit the most when all
345 climate change effects are considered, however given the variation
346 in responses between groups it seems likely that there will be
347 changes in pasture composition.

348 Looking at change in AGDW by region (figure 4), the increase in
349 growth for the Alpine and northern regions under $\uparrow T$ is unsurprising
350 since these are areas which are often temperature-limited and
351 which will benefit from longer growing seasons. The increased
352 growth under $\uparrow W$ conditions is also to be expected as it reduces
353 the chance of growth being limited by lack of water, though water-
354 logging may become an issue if the $\uparrow W$ becomes too extreme. The
355 results show a great deal of uncertainty about how large the growth
356 might be; comparatively few studies were found which dealt with
357 the effects of $\uparrow W$, making more precise estimates practically
358 impossible. Given that annual precipitation is predicted to increase
359 over a large part of northern and continental Europe, this is certainly
360 an area worthy of further investigation. Under $\downarrow W$ conditions it is

361 interesting to note that a greater decrease in AGDW is predicted for
362 the continental region than the southern, where droughts are
363 expected to be more of a problem. This may be because plants in
364 the southern region are already partially adapted to $\downarrow W$ conditions
365 (Pugnaire et al., 1999; Volaire et al., 2009).

366 When comparing the different combinations of climatic treatments
367 (figure 5), the most interesting results are for $\uparrow C + \uparrow T$ and
368 $\uparrow C + \uparrow T + \downarrow W$, since these combinations most accurately represent
369 future conditions (EEA, 2017). While $\uparrow C + \uparrow T$ will cause yields to go
370 up, adding in the effect of $\downarrow W$ negates the positive growth
371 response. It may be that irrigating pastures, particularly in southern
372 and continental Europe, will become increasingly necessary as
373 conditions become drier, though this will put an increased strain on
374 diminishing water resources (EEA, 2017). It is unfortunate that no
375 studies could be found looking at the effects of $\uparrow C + \uparrow T + \uparrow W$, since
376 this would be useful for predicting future plant growth in northern
377 Europe; however, given that both the $\uparrow C$ and $\uparrow T + \uparrow W$ results show
378 a positive response in AGDW, it seems safe to assume that yields
379 will increase in this region.

380 *4.3 Nitrogen concentration*

381 Looking at N concentration under $\uparrow T$, the general decreasing trend
382 can be explained as a natural consequence of increased growth: as
383 plants get bigger their N concentration becomes more diluted. The
384 relatively minor reduction in legumes is likely due to an
385 enhancement of N fixing caused by warming (Sardans et al., 2008;

386 Zavalloni et al., 2012). Different PFGs have also been found to
387 allocate N in different ways as a response to warming, which could
388 be having an effect here (Sardans et al., 2008). There may also be
389 competition effects at play (most of these experiments were
390 conducted on multi-species swards), as suggested by Andresen et al.
391 (2009). With some PFGs showing higher growth increases and
392 others showing lower reductions in N concentration under $\uparrow T$, it
393 seems that swards containing multiple PFGs are better for livestock
394 than those with only a single PFG, as they enable livestock to benefit
395 from the higher yields while at the same time still having sufficient
396 access to protein.

397 No regional differences were found for N concentration for any of
398 the climatic treatments. The likely reduction under $\uparrow C$ conditions
399 has been widely documented and can be attributed to some
400 combination of increased growth, changes in Rubisco activity
401 (Leakey et al., 2009) and changes in N allocation (Cotrufo et al.,
402 1998). The increase in N concentration under $\downarrow W$ is likely due to
403 the reduced growth and also to changes in allocation (Sardans et al.,
404 2008).

405 Looking at combinations of climate treatments (figure 8), $\uparrow C + \downarrow W$
406 shows a clear decrease in N concentration, but other combinations
407 exhibit very little change. This may be due to there being a lot of
408 different factors in play which may be cancelling one another out
409 (for example changes in growth, Rubisco activity, allocation and N
410 uptake). It should also be noted that some of these treatment

411 combinations only featured in a very small number of studies.

412 Further research would provide a clearer picture of the likely

413 outcomes of these combinations of climatic changes.

414 *4.4 Impacts on livestock*

415 Increases in AGDW are a positive result from a livestock perspective.

416 Assuming grazing animals were not already at their maximum intake

417 capacity then there is considerable scope to increase feed intake,

418 leading to increased performance. Of course decreases in yields will

419 have the opposite effect. In terms of forage quality, the general

420 reduction in N concentration indicates decreased protein content,

421 which can have a wide range of negative impacts on livestock

422 (Landau et al., 2000; Schröder et al., 2003). It is likely that farmers

423 will need to make increased use of concentrate feeds to

424 compensate for the drop in protein. Irrigation may also become

425 increasingly necessary (where feasible) to counteract the negative

426 effects of droughts. Where irrigation is not possible, farmers may

427 need to consider using different breeds or species, or else moving to

428 other areas.

429 *4.5 Other factors*

430 Only three of the studies used involved grazing livestock on the

431 study area. To get a realistic idea of the effects of climate change on

432 forage, it would be useful if there was more data available for

433 grazed plant-life, since the presence of livestock would also have an

434 influence. There are also other factors which play a role; our analysis

435 generally shows $\uparrow W$ as having positive effects, but if the $\uparrow W$ is the

436 result of extreme rainfall events then the effect could be
437 deleterious. Increases in ozone concentrations (Fuhrer, 2009; ICP
438 Vegetation, 2011) and changes in the distribution and
439 destructiveness of pests and pathogens (Bale et al., 2002; Jaggard et
440 al., 2010) will also affect forage species. More research is needed to
441 determine how all these different factors will interact in the future.

442 **5. Conclusion**

443 The present study highlights future trends in pasture yield and
444 quality in different European regions. The general results of the
445 meta-analysis can be used to inform farmers and policy makers
446 around future land-use scenarios and animal management options.

447 $\uparrow C$ increases AGDW, particularly for shrubs (+71.6%), though is
448 likely to reduce N concentrations (-4.8%). $\uparrow T$ will increase yields in
449 Alpine and northern areas (+82.6%), though other regions will
450 experience little change or else decreases. $\uparrow T$ will also reduce N
451 concentrations, especially for shrubs (-13.6%) and forbs (-18.5%).
452 $\downarrow W$ will decrease AGDW for all regions and PFGs, though will
453 increase N concentrations (+11.7%). Under $\uparrow W$ there was a 33.8%
454 increase in AGDW.

455 In general, areas which will become warmer and wetter (in
456 particular the northern region and parts of the Alpine and
457 continental regions) can expect higher yields, though this will likely
458 be accompanied by reductions in N concentration. Where conditions
459 become warmer and drier (particularly southern Europe and parts of
460 the continental region), there will be reductions in both yield and

461 probably also N concentration. In areas where predicted climatic
462 changes are less extreme (for example the Atlantic region), changes
463 in pastures will be more moderate, though a reduction in N
464 concentration is likely. How yields will be affected in such areas will
465 largely depend on water availability.

466

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473

474 ***Competing Interests***

475 Conflicts of interest: None

476

477 ***Supplementary material***

478 A: Search terms and sources used to find studies for the meta-
479 analysis

480 B: Studies included in the meta-analysis

481 C: The regions, climatic treatments, yield and quality parameters,
482 plant functional groups and methodologies used in each study

483

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663 **Figures**

- 664 Figure 1: Regional classification (Kovats et al., 2014)
- 665 Figure 2: Funnel plots for (a) above ground dry weight of graminoids
666 under elevated atmospheric CO₂ concentration and (b) N
667 concentration under elevated atmospheric CO₂ concentration. The
668 x-axis shows the natural logarithm of the response ratio of results
669 under climatically altered and control conditions. The dashed lines
670 show pseudo 95% confidence limits and the dotted line indicates
671 the overall effect estimate

672 Figure 3: Mean change in above ground dry weight (AGDW) under
673 (a) elevated atmospheric CO₂ concentration and (b) reduced water
674 availability, grouped by plant functional group. Error bars represent
675 95% credible intervals

676 Figure 4: Mean change in above ground dry weight (AGDW) under
677 (a) elevated air temperature and (b) reduced water availability,
678 grouped by region. Error bars represent 95% credible intervals

679 Figure 5: Mean change in above ground dry weight (AGDW) for
680 different combinations of climate treatments, including elevated
681 atmospheric CO₂ concentration (↑C), elevated air temperature (↑T),
682 reduced water availability (↓W) and elevated water availability
683 (↑W). Error bars represent 95% credible intervals

684 Figure 6: Mean change in N concentration under elevated air
685 temperature, grouped by plant functional group. Error bars
686 represent 95% credible intervals

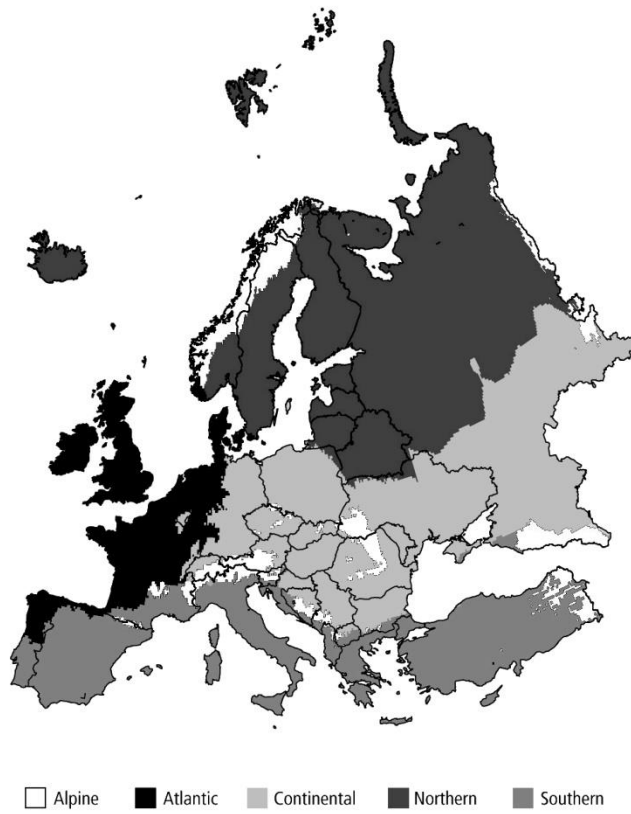
687 Figure 7: Mean change in N concentration under elevated
688 atmospheric CO₂ concentration (↑C) and reduced water availability
689 (↓W). Error bars represent 95% credible intervals

690 Figure 8: Mean change in N concentration for different
691 combinations of climate treatments, including elevated atmospheric
692 CO₂ concentration (↑C), elevated air temperature (↑T), reduced
693 water availability (↓W) and elevated water availability (↑W). Error
694 bars represent 95% credible intervals

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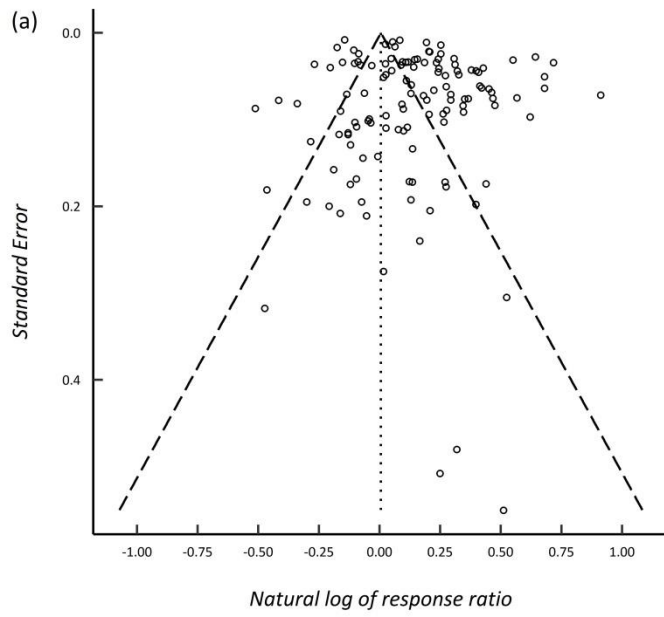
696 **Figures**

697 Figure 1

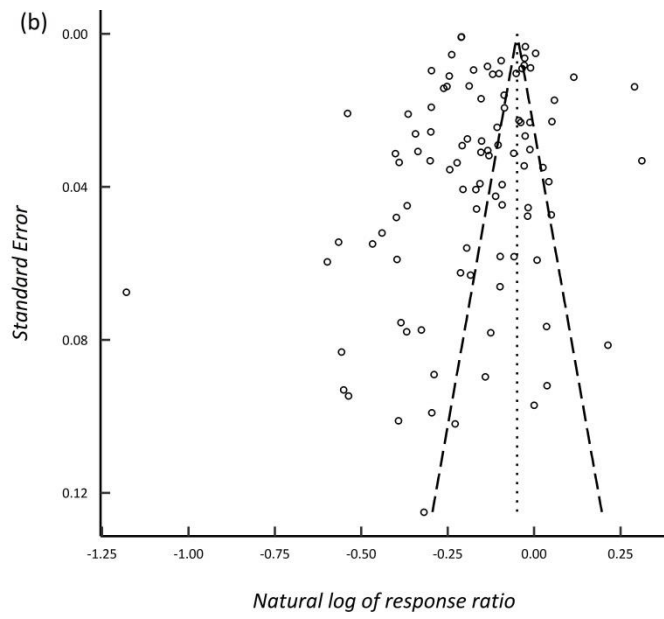


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699 Figure 2

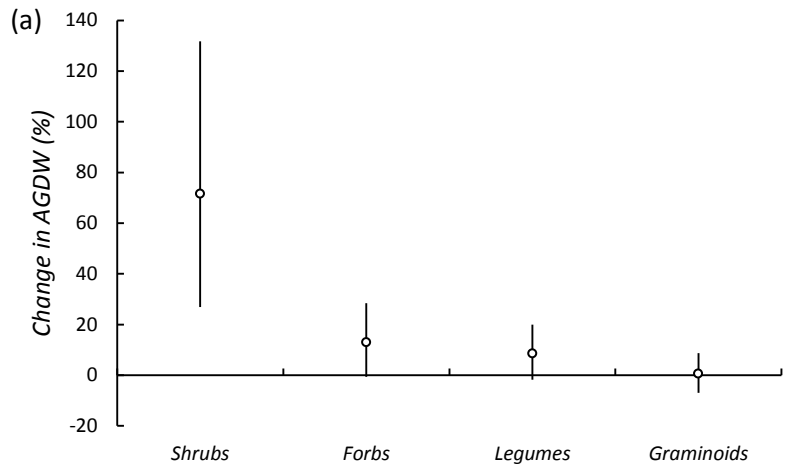


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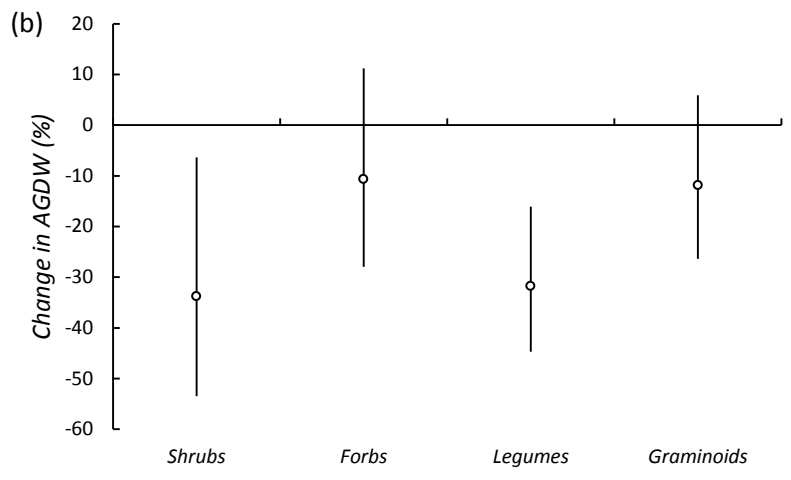


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702 Figure 3



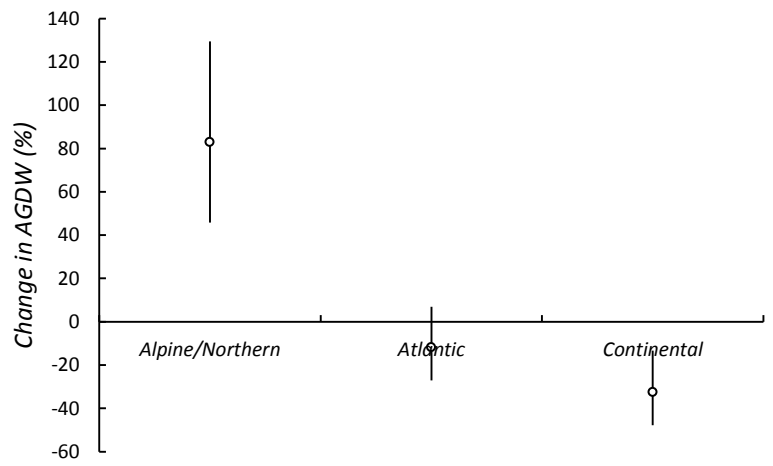
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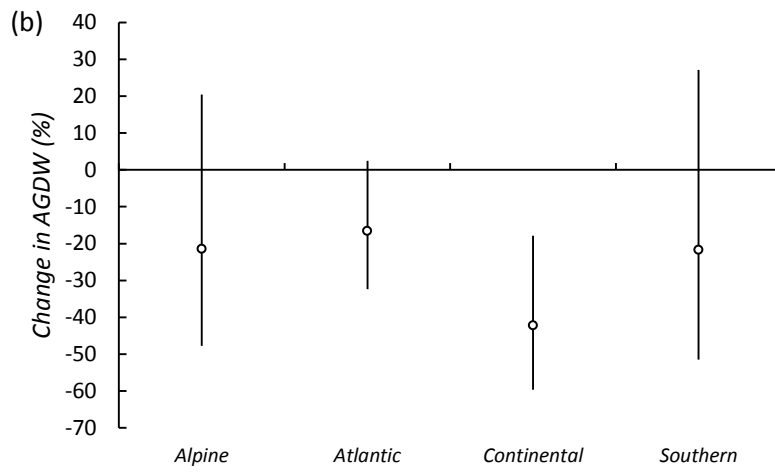
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706 Figure 4



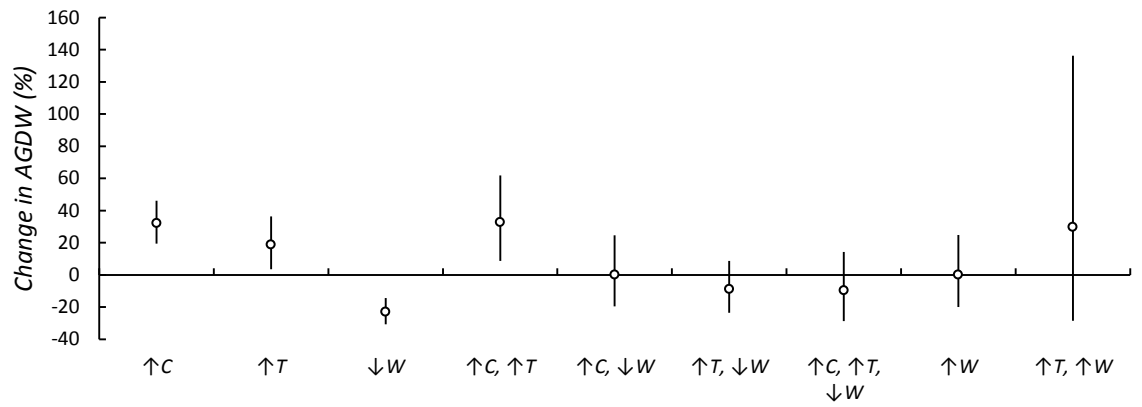
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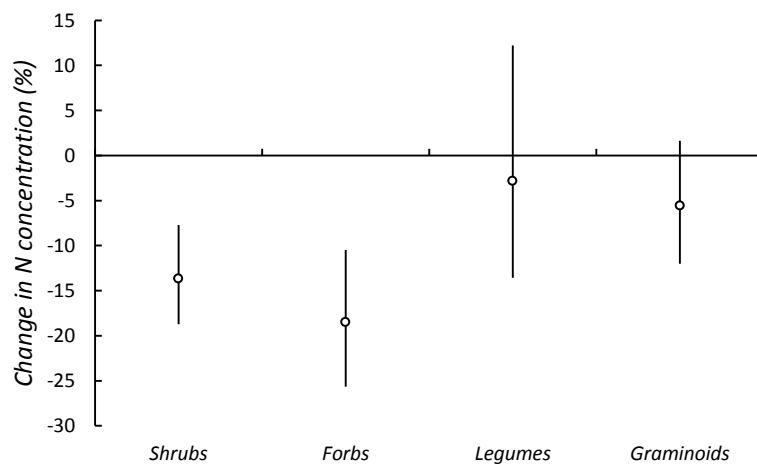
710 Figure 5



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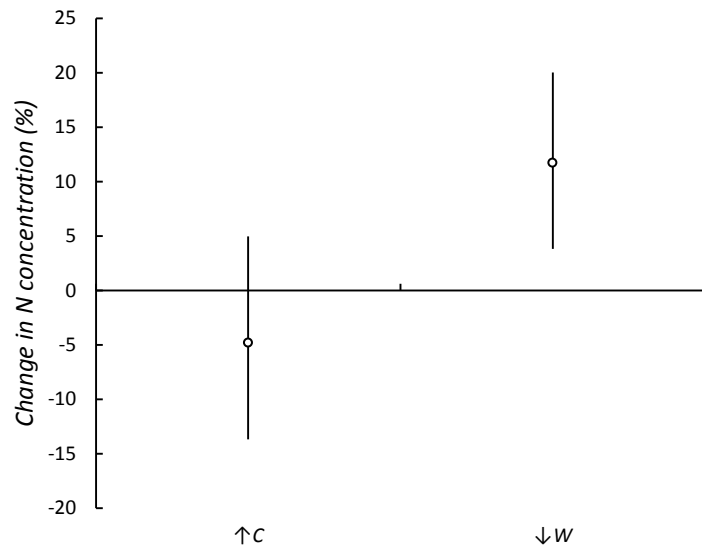
713 Figure 6



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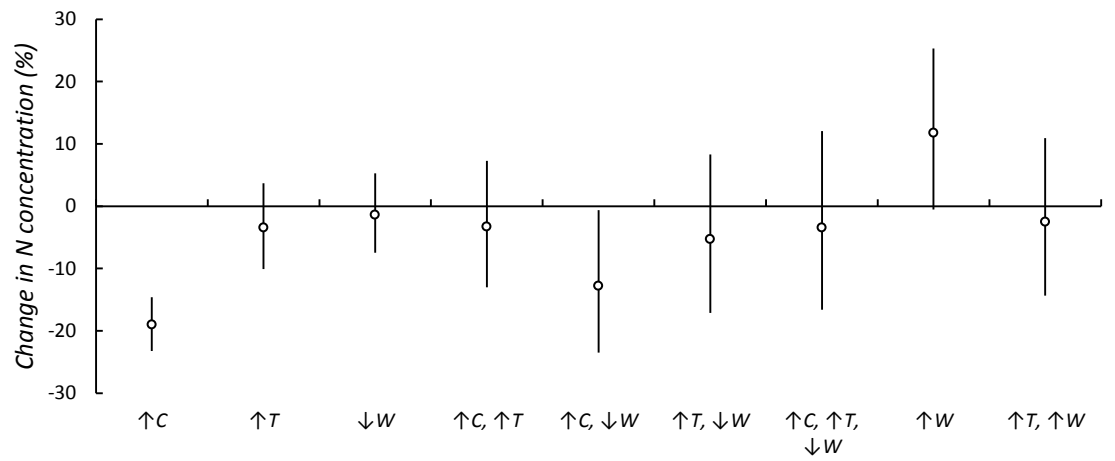
716 Figure 7



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