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Abstract: To optimise trade-offs provided by future changes in grassland management, spatially and temporally explicit estimates of grassland productivity are required at the systems level. Here, we benchmark the potential national availability of grassland biomass, identify optimal strategies for its management, and investigate the relative importance of intensification over reversion (prioritising productivity versus environmental ecosystem services). Process-conservative meta-models for different grasslands were used to calculate the baseline dry matter yields (DMY) at 1 km2 resolution for the whole UK. The effects of climate change, rising atmospheric [CO2] and technological progress on baseline DMYs were used to estimate future grassland productivities (up to 2050) for low and medium CO2 emission scenarios of UKCP09. UK baseline productivities (1970-1980) of 10.5, 7.9 and 2.6 t/ha were extrapolated to benchmark productivities (2010) of 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland, respectively. By 2050, grassland productivities under medium emission scenario is predicted to increase to 15.5 and 9.8 t/ha on temporary and permanent grassland, respectively, but not on rough grassland. Based on surveyed grasslands areas for Great Britain in 2010 the GIS-modelled distributions of grassland productivity and total availability of biomass were shown at 1 km2 grid. Assuming that optimal N application could close existing productivity gaps of ca. 40% there are a range of management options available that could deliver additional biomass availability or spare some grasslands for provision of other ecosystem services.

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Science of the Total Environment

23 November 2017

Submission of Original Research Article

Modelling productivity and resource use efficiency for grassland ecosystems in the UK

Dear Professor Ludwig

On behalf of all authors I would like to submit our article to Science of the Total Environment because we think it fits perfectly its scope in more than one aspect, first quantifying the extent of different grassland ecosystems and, second describing benchmark productivity and how this might change with regard to different land use scenarios. The results can be helpful in terms of environmental management and policy

This paper is a companion paper to an earlier one describing model development and scenario simulations for different grassland ecosystems. Here, we exemplify opportunities for grassland management and documents in great detail statistical and spatial inputs at the whole country level. This paper lays the foundations for a bioenergy/biomass whole systems analysis that includes all production vectors, food, feed and fuel.

Yours faithfully,

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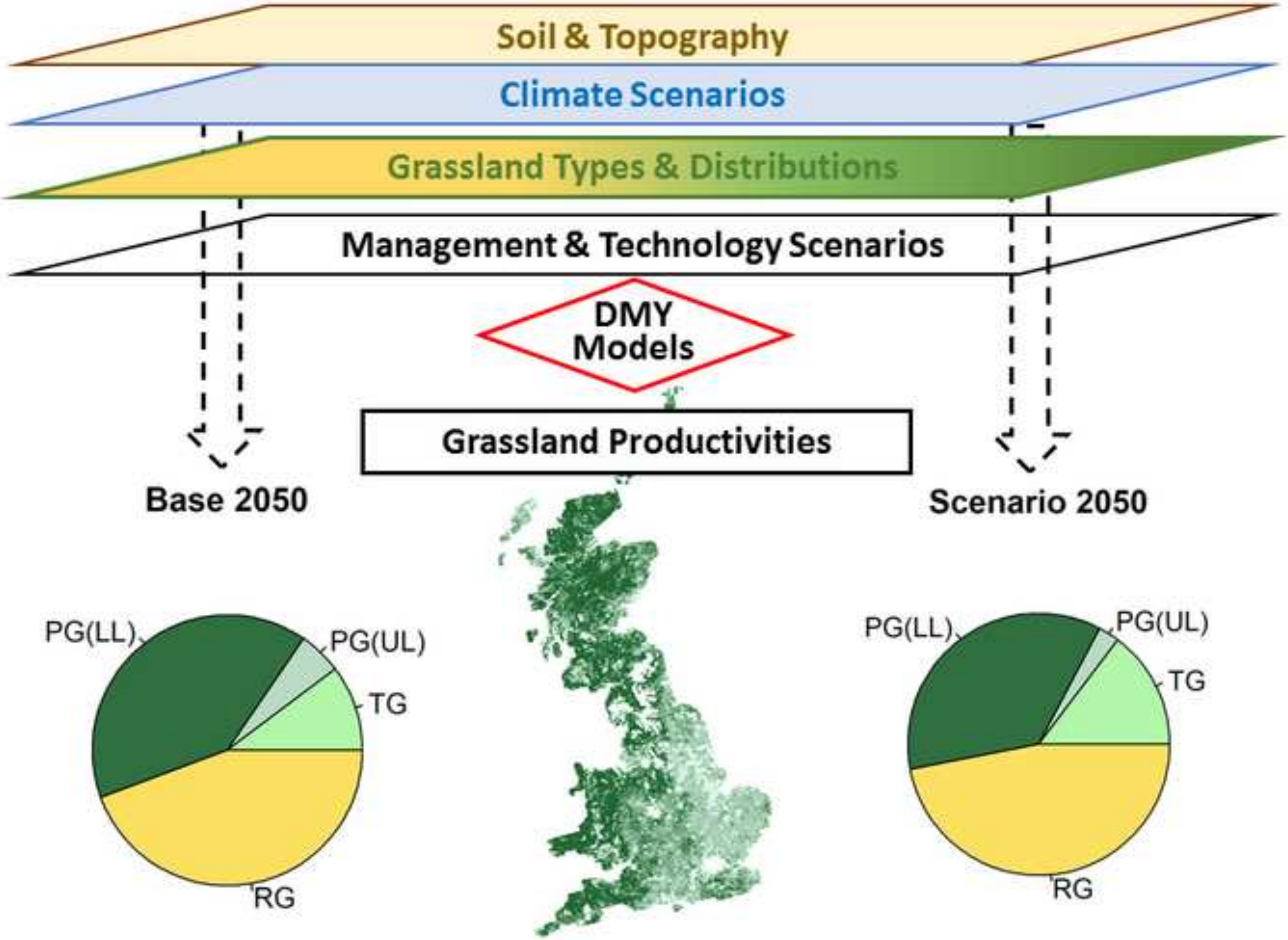
*Graphical Abstract



Qi et al (2017b)-Highlights

Highlights

Benchmark productivity (2010) ranges from 8.7 to 12.5 t/ha on improved grasslands

Future productivity increase comes from technological progress and CO_2 stimulation

Biomass from productivity gaps of 40% can provide other ecosystem services

Increased lowland intensification can outweigh reversion of upland areas to rough grazing

Grassland futures in Great Britain – productivity assessment and scenarios for land use change opportunities

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Paper stats

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Abstract	232
Introduction	881
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Results	1217
Discussion	1848
Conclusions	215
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References	69
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Figures	7
Supplemental Material	6 Tables, 2 Figures

Abstract

To optimise trade-offs provided by future changes in grassland management, spatially and temporally explicit estimates of grassland productivity are required at the systems level. Here, we benchmark the potential national availability of grassland biomass, identify optimal strategies for its management, and investigate the relative importance of intensification over reversion (prioritising productivity versus environmental ecosystem services). Process-conservative meta-models for different grasslands were used to calculate the baseline dry matter yields (DMY) at 1 km^2 resolution for the whole UK. The effects of climate change, rising atmospheric [CO_2] and technological progress on baseline DMYs were used to estimate future grassland productivities (up to 2050) for low and medium CO_2 emission scenarios of UKCP09. UK baseline productivities (1970-1980) of 10.5, 7.9 and 2.6 t/ha were extrapolated to benchmark productivities (2010) of 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland, respectively. By 2050, grassland productivities under medium emission scenario is predicted to increase to 15.5 and 9.8 t/ha on temporary and permanent grassland, respectively, but not on rough grassland. Based on surveyed grasslands areas for Great Britain in 2010 the GIS-modelled distributions of grassland productivity and total availability of biomass were shown at 1 km^2 grid. Assuming that optimal N application could close existing productivity gaps of ca. 40% there are a range of management options available that could deliver additional biomass availability or spare some grasslands for provision of other ecosystem services.

Key words:

Grassland systems, climate change, ecosystem service, land use change, technology progress, yield gap

1 Introduction

Globally, grasslands are the dominant form of agriculture by land area, primarily utilised for the provision of feed for ruminants (Prochnow *et al.*, 2009; Gerssen-Gondelach *et al.*, 2017). In the United Kingdom (UK), grasslands represent over two thirds of agricultural land area, broadly grouped into temporary (1.2 million ha), permanent (6.1 million ha) and rough-grazing (5.0 million ha) types (Defra, 2016a). In 2015, UK grasslands supported 9.9 and 33.3 million heads of cattle and sheep, respectively. This provided 15.2 million tonnes of cow's milk, 0.9 and 0.3 million tonnes of beef and sheep meat for human consumption respectively (Defra, 2016a), representing a significant land resource for food. Grasslands also play an important role in supporting biodiversity (Fargione *et al.*, 2009) and in the delivery of other benefits to society including carbon sequestration, biomass for bioenergy, and recreational opportunities (Hopkins and Wilkins, 2006; O'Mara, 2012, McEniry *et al.*, 2013).

Following the 2016 referendum, in which the UK voted to leave the European Union, options for the future of farming are being explored. At least in part, this debate seeks to balance the views of those favouring intensification of production alongside those who argue for the incorporation of wider sustainability criteria into the land use planning (Hill, 2017). For grassland systems, these competing viewpoints were exemplified in upland regions of the country, which play a central role in the provision of regulating ecosystem services, often for beneficiaries in distant urban areas (O'Rourke *et al.*, 2016). However, farmers in upland regions face substantial challenges to their income associated with a traditional low-input, low-output business model that supports the continued provision of these benefits to society (Reed *et al.*, 2009). The continued decline of N-fertiliser input and stocking rates (Defra, 2016b) are strong indicators for this.

Against this background a key requirement to inform development of farming policy is spatially explicit knowledge of current and future grassland productivity. Benchmarking and understanding the levels of dry matter yield (DMY) and quality are important to optimize productivity for sustainable intensification within grassland systems (O'Donovan *et al.*, 2015). Making use of the productivity gap between or closing the yield gaps within grassland types could increase biomass production for various services and value chains, food, feed or bioenergy (Grau *et al*, 2013; Lusiana *et al*, 2012; Prochnow *et al*., 2009). This would provide opportunities to those areas of the country that might be considered preferential for change, given social, environmental and economic factors. At the same time, such knowledge allows policy makers to explore options for targeting agri-environment schemes to protect biodiversity (Eigenbrod *et al.*, 2011; Phalan *et al.*, 2014; Werling *et al.*, 2014) and important regulating services such as those associated with carbon stocks or water resources (Reed *et al*., 2014; Smith, 2014) in other regions where less significant productivity gains could be achieved with changes in grassland management practice.

The net primary productivity of grasslands can be measured from its annual dry matter production per hectare. An earlier presented process-based grass model increased our understanding of past experimental DMYs of temporary, permanent and rough-grazing grasslands (Qi. *et al.*, 2017). Key biophysical driving variables were up-scaled, building meta models to estimate productivities for each grassland type to assess future productivities. However, these estimates need to account for climate change, increased CO_2 concentration and technological progress, e.g. better genetics and management (Ewert *et al*. 2005). The impact of past climate change on DMYs of grasslands was found to be rather small (Coleman *et al.*, 1987; Chang *et al*., 2015) or undetectable in the long-term Park Grass Experiment (Jenkinson *et al.*, 1994). However, future climate change is likely to improve productivity and quality of grasslands (Hopkins and Del Prado, 2007; Izaurralde *et al.*, 2011), although scenarios a 2 °C temperature increase found little change in DMYs for Scotland (Cooper and McGechan, 1996).

Nevertheless, the growth of typical pasture crops was stimulated by CO_2 enrichment (Soussana and Luscher, 2007), similar to that observed for cereals (Jaggard *et al.*, 2010). Plant breeding and improved agronomy are likely to continue increasing grassland productivity (Hopkins and Wilkins, 2006). A potential annual increase of DMY in the range of 0.25 to 0.76 percent seems possible (e.g. Wilkins and Humphreys, 2003; Harmer *et al.*, 2016). Annual on-farm grassland yield gains varied between countries and grassland types (Smit *et al.*, 2008), they are low on permanent grassland (0.35% annually) due to less frequent reseeding (Chang *et al*., 2015). Semi-natural grasslands used for rough-grazing, dry matter productivity cannot be genetically improved but productivity can be influenced by changing growing conditions, e.g. influencing the hydrology or adjusting stocking density (Sozanska -Stanton *et al*., 2016; Worrall and Clay, 2012).

The objectives of this study were (i) to estimate DMYs for all grassland types across the UK for current and future climates considering CO_2 enrichment and technological progress. (ii) to assess and map the availability of total dry matter production constrained by grassland areas surveyed in 2010 across Great Britain. (iii) to determine the current benchmark DMYs for each grassland type and identify productivity gaps, particularly with respect to the current decline in below optimal N application rates, and (iv) to perform spatial analyses of the impact of conversion between grassland types and to investigate changes in total grassland biomass production in Great Britain under varying management options.

2 Materials and Methods

2.1 General approach

The meta-models used here were derived from outputs of a process-based model calibrated using a comprehensive set of experimental DMY data measured in the 1970s and 1980s (Qi. *et al.*, 2017). These meta-models accounted for effects of weather, soil available water capacity (SAWC) and N input on DMY. When meta-models were used to calculate DMYs with baseline weather (1961-1990), they were referred to as baseline dry matter yields (BL-DMY). However, since then climate has changed, atmospheric CO_2 concentration increased, and pasture crops with higher growth potential and improved agronomy have been adopted, particularly in temporary and permanent grasslands. The approach of Ewert *et al.* (2005) was followed to calculate the grassland DMYs from 2010s to 2050s, which accounts for the effects of these three yield determining factors: change in climate (CC; f_{CC}), carbon fertilisation effect (CFE; f_{CFE}) due to rising atmospheric [CO_2] and technological progress (TP; f_{TP}).

The DMY in 2010 was calculated using Eqn. 1:

$$Y_{10s}=Y_{base} + Y_{base}*(f_{10s,\,CFE}+f_{10s,\,TP}) \qquad (1)$$

where Y_{10s} is the annual dry matter yield in 2010s, Y_{base} the meta-model calculated baseline dry matter yield (i.e., BL-DMY), $f_{10s,\,CFE}$ is the percentage increase of DMY due to CO_2 fertilisation effect while $f_{10s,\,TP}$ is the percentage of DMY increase due to technological progress from 1980s to 2010s. Instead of projected CC, baseline actual weather data were used.

DMYs in 2020 to 2050 were calculated with Eqn. 2:

$$Y_{t1\ldots4}=Y_{base} + Y_{base}*(f_{t1\ldots4,\,CC} + f_{t1\ldots4,\,CFE} + f_{t1\ldots4,\,TP}) \qquad (2)$$

where $Y_{t1\ldots4}$ is the annual DMY from 2020s to 2050s, $f_{t1\ldots4,\,CC} + f_{t1\ldots4,\,CFE} + f_{t1\ldots4,\,TP}$ represent the percentage of DMY changes due to predicted weather under CC, CFE and TP from 1980s to 2020s, 2030s, 2040s and 2050s, respectively. The percentage of DMY change due to changed climate was calculated as the difference between the weather-governed DMY with the baseline climate and the weather-governed DMY with changed climate divided by the former.

2.1.1 CO_2 fertilisation effect (CFE)

Most experimental evidence indicates that the growth of perennial ryegrass (*Lolium perenne*) was stimulated by CO_2 enrichment and consequently the DMY was increased by an average 0.06%/ppm [CO_2] (range from 0.03 to 0.09%/ppm; **Table S1a**). The percent increase was multiplied with the incremental increase of CO_2 concentration from the baseline (1980s) to the respective later decade.

Atmospheric [CO_2] has increased from 334 ppm in the 1970/80s to the present 400ppm in 2015 at a rate of approximately 2 ppm per year due to anthropogenic forcing (IPCC 2013; Myhre *et al*., 2013). The predicted CO_2 concentrations in the atmosphere from 2020s to 2050s were taken from the projections of the BERN model under low and medium CO_2 emission scenarios (**Table S1b**). The atmospheric [CO_2] of past years were taken from the annual mean records of [CO_2] at Mauna Loa, Hawaii by Earth Systems Research Laboratory (*www.esrl.noaa.gov/gmd/ccgg/trends*). The cumulative fertilisation effects of increased [CO_2] for various decades were calculated and applied accordingly (**Table S2)**.

2.1.2 Contribution of technological progress to grassland productivity

Innovations in technology to improve grassland productivity include breeding varieties with higher potential yield and improved management to better protect and fully reap the genetic potentials. Based on the results of multiple variety trials for perennial ryegrass (Aldrich, 1987; Camlin, 1997; Woodfield, 1999; Easton *et al.*, 2002; Wilkins and Humphreys, 2003; Humphreys, 2005; Smit *et al.*, 2008; Chaves *et al.*, 2009; Lee *et al.*, 2012; Chang *et al.*, 2015; Harmer *et al.*, 2016; McDonagh *et al.*, 2016) the annual mean genetic, potential DMY gain was set to the overall mean of 0.5% (**Table S3a**). This agrees with the average annual on-farm yield increase suggested for temporary grassland (Smit *et al.*, 2008) while for permanent grassland an annual yield gain of 0.35% can be assumed (Smit *et al.*, 2008; Chang *et al*., 2015; **Table S3a**). For rough grazing grassland, which is semi-natural with little agronomic inputs, no technological improvements in dry matter productivity were applied.

For temporary grassland, the DMY was augmented with a technology factor of 0.5% increase per annum above the BL-DMY for both the potential and the on-farm DMY from 1980s to 2050s assuming a full translation of potential DMY increase into on-farm DMY. For permanent grassland, the DMY was augmented with a technology factor of 0.35% increase per annum for the on-farm

DMY from 1980s to 2050s. Thus, the accumulated percentage increases above the BL-DMY were calculated and applied on each of the three types of grassland from 1980s to 2050s (**Table S3b**).

2.1.3 Impact of future weather changes

The meta-models encapsulate the effects of weather variables on DMYs using inputs of changed bioclimatic variables which reflect the weather-governed DMYs for any given future decade. These variable changes fed directly into the meta-models, developed from scenario outputs generated by validated process-based growth model (Qi. *et al.*, 2017), to calculate future grassland productivities. Inputs were soil available water capacity and bioclimatic variables of monthly temperature, precipitation, and global radiation under baseline and future climate change scenarios. The impact of climate change on grassland productivities was the percentage of DMY change which was calculated as the difference between the weather-governed DMY with the baseline climate and the weather-governed DMY with changed climate divided by the former.

2.2 Climate and soil data

The necessary inputs of monthly climatic variables for the baseline (1961-1990) and for decades from 2020s to 2050s were obtained from the most recent UK climate projections (UKCP09, 2009). The monthly maximum and minimum temperature, precipitation and global radiation were initially available at 25km x 25km grid and they were then harmonised into 1 km x 1km grid for the whole UK (Murshed *et al.*, 2012). Relative to the baseline climate (1961-1990), seasonal precipitation and global radiation differed little between the low and medium emission scenario during the 2020s to 2050s across the UK (**Table S4**). The global radiation increased most (1.6 and 3.9%) in spring, less so during summer and autumn. Overall, summer was likely to be drier while winters would be wetter in the future. Under both CO_2 emission scenarios, the UK will be warmer in all seasons. Although absolute temperatures increase most in summer (e.g. 1.2 to 2.2°C until 2050s under medium scenario), the relative increase was greatest in winter and spring (**Table S4**).

These climatic data were used in combination with the spatially distributed soil available water content in the root zone obtained from the European Soil Database at 1 km x 1 km grid, as inputs for the meta-models to calculate the DMYs on temporary, permanent and rough-grazing grassland.

2.3 Nitrogen (N) fertiliser application and DMY response to N inputs

The annual survey of the overall average N applied per hectare to temporary and permanent grassland was conducted by Defra starting from 1960s. The average N applied increased steadily until mid-1990s (Rath and Peel, 2005) but declined from the late 1990s onwards on both, temporary and permanent grassland until 2008 (**Figure S1;** Defra, 2016b) and remained unchanged since. The overall average N use during the recent decade came to 99 and 52 kg/ha on temporary and permanent grassland, respectively.

Annual DMYs were measured in N fertiliser response experiments carried out at 21 different sites (Morrison *et al.*, 1980) with N fertiliser used up to 750 kg N/ha; DMY reached their maximum plateau mostly at an N application rate of 600 kg N/ha. The DMYs were normalised using the maximum DMY and expressed as its fraction in percentage (DMY%; see **Figure 1**). The four-parameter rational equation proposed by Morrison *et al*. (1980) was applied to describe the DMY in response to N application (Eq. 3):

$$DMY\% = \frac{a+bN}{1+cN+dN^2} \qquad (3)$$

The estimated coefficients were: a=22.1696, b=0.2373, c=-0.0001944, d=0.000002117 and the variance accounted for (i.e. R^2) was 93.8% (n=126). This equation was used to calculate the yield gap because of reduced N fertiliser usage.

2.4 Total GB grassland yields under contrasting management options

Grassland area was surveyed by Defra in 2010, and is available at a 2km × 2km grid resolution (https://access.edina.ac.uk/agcensus/). For Great Britain (GB), UK without Northern Ireland (NI), grassland covered 9.9896 million ha in total, of which 1.0246, 4.5333 and 4.4317 million ha were temporary, permanent and rough-grazing, respectively. This leaves about 2.5 million hectares of grassland unaccounted for in this scenario analysis, as NI was not included in the Agricultural Census. Analysis explored five land use transition scenarios for GB covering the period 2010 – 2050 (**Table 4**), conducted at a 2km × 2km grid resolution for compatibility with grassland survey data. The focus of the analysis was on changes in management practices, therefore we considered that transitions occur between grassland types without increasing or decreasing overall area of grassland.

The likelihood that farmers will change management practices (i.e. shift from a business model focused on production towards environment-focused management) is determined by complex social and economic drivers arising from past and current experiences that serve to limit farm development pathways (Di Falco *et al.*, 2005; Ingram *et al.*, 2013). To this end our analytic approach does not assume that transitions between grassland management practices will occur in a spatially optimal manner determined by factors such as monetary returns, yields, or carbon stocks. Instead the target area for conversion in hectares (ha) for GB was calculated, and a stochastic algorithm implemented in R (R Core Team, 2017) that randomly assigned conversion of grassland areas for each 2km × 2km grid cell until the target area for conversion was met. For each scenario 1000 permutations were conducted and changes in average yield per 2km × 2km grid cell and for GB total dry biomass production were calculated.

Although the analysis considered conversion of different grassland types, plausible limits to this conversion were identified based on a subset of constraints defined in part by Lovett *et al.* (2009) for energy crops. The constraints are altitude (>=250m to define upland), slope (>=15% representing a technical limit for farm machinery), and distribution of nitrate vulnerable zones (NVZ) across GB (**Table S6**). In determining the location of land use transitions the stochastic algorithm preferentially chose to convert grassland in areas that were consistent with the logic of the scenario based on these constraints. For example, for conversion of rough-grazing to permanent grassland, which implies greater agricultural inputs, initially focused on areas outside NVZ and where the slope was <=15% to allow access for farm machinery. Where the target area for conversion specified within the scenario exceeded area available due to the constraints, the stochastic algorithm initially converted grassland outside the constrained areas before converting grassland within excluded 2km × 2km grid cells.

The first four scenarios explored possible permutations of the transition between differing grassland types that could be achieved through changes in management practice. In the first two instances, a reduction in intensity of management was explored (i.e. Scenario A, Permanent to rough-grazing; Scenario B, Temporary to permanent) and in the second an increase in intensity of production (i.e. Scenario C, Permanent to Temporary; Scenario D Rough-grazing to Permanent). For each scenario, the stochastic algorithm considered transitions of between 0 – 100% of 2010 area in 10% increment intervals. This defines a parameter space over which possible changes to the management regime could occur, allowing examination of the implications for total GB grassland DM production.

The final scenario examined a more complex set of management options informed by recent discussions focused on upland regions. In contrast to the other four scenarios, this fifth scenario (Scenario E) did not explore change in grassland yield associated with changing management practices, rather the aim was to maintain GB grassland DM production. In areas defined as upland (average altitude >=250m) permanent grassland was converted to rough-grazing and the loss of total grassland DM production calculated. Conversion of permanent to temporary grassland in lowland areas was then carried out to compensate for the lost total dry biomass production. As with scenarios A - D, scenario E examined transition of between 0 – 100% of the specific grassland area in 10% increment intervals using the same stochastic approach as the other four scenarios.

3 Results

3.1 Weather-governed, CO_2-and technology-adjusted DMY

The DMY was calculated with the meta-model at 1 km^2 resolution across the UK assuming a single grassland type for all land with SAWC information (i.e. a blanket approach). The UK average blanket DMYs for the baseline and future weather (**Table 1)** indicate little difference between the low and medium emission scenario in the effect of future climate change (weather only) on DMYs within each grassland type. The weather-governed productivity is unlikely to be affected in the future and remained about 10.5 t/ha on temporary grassland. However, productivity of both permanent and rough-grazing, will be reduced by about 0.3 t/ha by climate change in the future. Relatively, the reduction of productivity on rough-grazing grassland could be more than 10% by 2050.

The spatially explicit technology- and [CO_2]- adjusted DMY maps are exemplified in **Figure 2** for the 2010s under the medium emission scenario. The average national blanket DMYs in the UK from 2010s to 2050s show very small differences between the low and medium emission scenarios for each grassland type (**Figure 3**). For rough-grazing grassland the DMYs increase due to rising [CO_2] cannot compensate the negative impact from changed weather variables (i.e. both reduced precipitation and increased temperature in summer) in the future, and the overall productivity of rough-grazing grassland is unlikely to change by 2050. For temporary and permanent grassland, the productivity is predicted to increase steadily at a rate determined by the additive response of technological progress and the increased atmospheric [CO_2] per decade.

3.2 Benchmark DMY constrained by actual grassland areas in GB

Assuming no changes in management regime, the average DMYs based on the actual area of each grassland type can be calculated from 2010s to 2050s (**Table 2**). These average DMYs can be referred to as the benchmark productivities, which were similar for blanket approach and census areas. Taking DMYs in 2010 as representative of current grassland productivities (**Figure 4**), the present benchmark productivity should be 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland in GB, respectively.

After overlaying the NUTS 1 regions over the grassland area and the availability of dry matter production per km^2 grid (**Figure 4**), the total grassland area (**Figure 5a**) and availability of total dry matter production (**Figure 5b**) per region in Great Britain were calculated. Within Great Britain, the total grassland area in 2010 was partitioned 45.7, 13.4 and 40.9% into Scotland, Wales and England, respectively. In terms of grassland type, Scotland contained 41.2, 21.0 and 72.0% while England shared 48.7, 56.6 and 23.0% of temporary, permanent and rough-grazing grassland, respectively. In terms of total DM production, the share was partitioned into 40.3, 45.3 and 14.4% for Scotland, England and Wales, respectively. Within England, the largest grassland area and availability of total DM production were in South West, followed by North West and West Midland.

Defra reported areas of respective grassland types in 2010 for the whole UK (Defra, 2015) and the Agricultural Census in 2010 specified these areas for GB (**Table S5**). The total DM availability on each grassland type can be calculated by multiplying the respective grassland area and its corresponding mean dry matter yield (**Table S5**). The UK national total potential availability of dry biomass can reach 82 million tonnes. Permanent grassland provided the largest proportion of this national total (63%) while temporary and rough-grazing grassland contributed equally to the remaining 37%. Without NI the annual biomass resource shrinks to 64.5 million tonnes.

3.3 Grassland yield gap analysis

The above calculated grassland productivity after considering the effect of climate change, increasing atmospheric [CO_2] and technological progress from 2010s to2050s reflects DMYs measured in the experiments and is the attainable DMY (i.e. water limited potential yield) (van Ittersum *et al.*, 2013). The on-farm, actual DMY is usually smaller than the attainable yield due to other limitations (Lobell *et al.*, 2009; Sadras *et al.*, 2015).

The DM productivity used to model temporary and permanent grassland was measured with annually applied 300 kg N/ha and 150 kg N/ha, respectively (Defra, 2010). The annual N usage on grassland had dropped in recent decade (2006 to 2015) to ca. 99 and 52 kg N/ha on the temporary and permanent grassland, respectively, much below the recommended economic optimum N:150 for permanent and 300 kg N/ha for temporary grassland (Morrison *et al.*, 1980; Hopkins *et al.*, 1990). To estimate the productivity gaps on temporary and permanent grassland, the relative DMYs were calculated using these lower values and estimating the difference from the relative DMYs at the recommended N (Eqn. 3; see **Figure 1)**. The current N shortage resulted in calculated on-farm DMYs about 45 and 39% yield gap (YG) below the attainable DMYs on temporary and permanent grassland, respectively, which correspond to a total actual unused productivity of about 21 million tonnes DM (**Table 3**).

3.4 Changes in GB total grassland DM production under evolving management scenarios

Out of the four scenarios describing conversion between grassland management options only Scenario A, characterising changes in yield resulting from conversion of permanent grassland to rough-grazing (Abandonment), resulted in a decrease in total DM production in GB by 2050 compared to the baseline 2010 value. Even in this scenario, conversion of up to 20% of total area could be implemented while maintaining a comparable level to total DM production in 2010 (**Figure 6**). Total GB grassland DM production in Scenario B (i.e. temporary to permanent), which represents the other reversion scenario exploring reduced management intensity, showed increases out to 2050 compared to the 2010 baseline value even under the transition representing 100% area conversion.

Scenarios C and D represent lowland and upland intensification of existing grassland management and describe a substantial increase from the 2010 baseline in total GB grassland DM production out to 2050. For example, unconstrained conversion of rough-grazing to permanent grassland (Scenario

D) would increase total GB grassland DM production from 63 million tonnes in 2010 to 107 million in 2050. Taking into account simple constraints (e.g. NVZ, slope) to restrict the area over which increases in management intensity might practically be achieved results in 50% conversion of management intensity for Scenario C and 30% conversion for Scenario D, both yielding an additional 18 million tonnes above the 2010 baseline.

Scenario E explored an alternative future where overall GB DM production was maintained at current levels. In this scenario, there was a reduction in the management in intensity of permanent grassland in upland areas to the west and north of GB, accompanied by conversion of permanent to temporary grassland in lowland regions to maintain total GB grassland yield (**Figure 7**). Given the restriction imposed by the presence of NVZs in England, in our stochastic analyses production of grassland was focused in the north and west of GB representing a shift in management intensity from upland to lowland areas. In terms of land conversion, at the extreme cessation of management of permanent grassland in upland regions would require an increase from 1 million to 1.9 million hectares of temporary grassland to compensate for lost yield. At more realistic conversion levels of 20 – 40 per cent there are options for substantial reductions in management inputs of uplands regions of GB that would require intensification of 200 – 300 thousand hectares of lowland permanent grassland to temporary grassland to make up for lost yield.

4 Discussion

Considering the global importance of grasslands not only as a source of feed and food, but carbon sink, ecological buffer and source or haven of biodiversity, our spatially explicit grassland yield model can provide a valuable evidence-base for policy making. The analysis considered most recent evidence about climatic and physiological control factors and assumed technological developments to be a continuation of past progress, a rather conservative assumption. The most striking features of this analysis are the opportunities that arise from the yield gap and the evaluation of possible futures for changes in grassland management practices across GB.

4.1 Impact of climate change and increased atmospheric [CO_2]

The impact of climate change (reduced seasonal precipitation, increased global radiation and mean temperature) on weather-governed DMYs is very small (**Table 3**) though slightly positive on temporary grasslands (<1%) and marginally negative on rough-grazing grasslands. The largest impact of climate change is likely to be seen on permanent grasslands, with DMY declining by about 2.5 to 5% from 2020s to 2050s. This largely agrees with past findings that the impacts of past climate change on grassland DMYs was found to be small or undetectable (Coleman *et al.*, 1987; Jenkinson *et al.*, 1994). However, Cooper and McGechan (1996) emphasised that site differences in weather patterns will have greater effects on grass conservation and productivity than other predicted effects of climate change.

The effect of rising atmospheric [CO_2] on stimulating growth for C_3-plant species such as perennial ryegrass (http://www.co2science.org/data/plant_growth/dry/l/loliump.php) was assumed to be more conservative than in these larger sets of experiments (0.06% vs 0.11% per ppm [CO_2] increase; **Table S1a**). For temporary and permanent grasslands, the effect of rising [CO_2] are intricately linked to technological progress, and the net effects (**Table 2**) are likely to be smaller than the additive gross effects (**Table S2 and S3b**). Only for rough-grazing grasslands one can see that rising [CO_2] just about compensates the negative effects of weather **(Table 2**). The relative DMY increase is likely to be slightly higher under medium compared to the low emission scenario (+1.6%) due to the difference in atmospheric [CO_2] which is marginally lower than the difference (2.4% between grassland types, **Table S2**) but much smaller than the additive effect of [CO_2] and technology progress. In reality, actual percent DMY increases due to increased [CO_2] depend on other interacting factors such as N fertility in the soil (Daepp *et al.*, 2001), changes in water productivity, evapotranspiration and soil water stress (Deryng *et al.*, 2016).

4.2 How fast is technological progress to improve grassland productivity?

As seen in the results (**Table 2**) the additive increase of grassland DMYs is 24% and 14% between 2010s and 2050s for temporary and permanent grassland, respectively under medium emission scenario, which is somehow smaller that the theoretical progress. This is because of that the percent increase of DMY due to joint CFE and TP effects was 28.0 and 22.0% between 2010s and 2050s for temporary and permanent grassland, respectively under medium emission scenario (**Tables S2 and S3**). Therefore, the efficiency of permanent grassland to exploit the joint CFE and TP effects is lower than under temporary grassland (ca. 63 vs ca. 86 %). This was partly due to the larger negative impact of climate change on grassland productivity on permanent grassland. As permanent grasslands were kept under the same grass species longer (>5 years) than temporary grasslands (<5 years) the introduction of new, more productive cultivars/practices is slower. Compared with the potential yield improving rate in arable crops (Jaggard *et al.*, 2010; Fischer and Edmeades, 2010) the rate of potential yield improvement was slower in pasture grass (Hatfield and Walthall, 2015). Longer breeding cycles (15-20 years), inability to exploit heterosis in commercial pasture crop cultivars and selection in the absence of competing neighbour plants, cause a poor correlation with pasture sward performance.

Agronomists will continue to improve practices that provide overall gains in grassland productivity (Stewart and Hayes, 2011; Barrett *et al.*, 2004). The applications of genomics, marker-assisted selection (MAS) and use of genetically modified grass types are likely to accelerate genetic gains of future grassland productivity. Overall, the UK is well-positioned geographically and the rate of genetic gain achieved was among the top range 4-5% per decade (Wilkins and Humphreys, 2003). These can include higher potential DMY, better quality and more resilience to biotic and abiotic stresses (Williams *et al.*, 2007; Barrett *et al.*, 2015). The current scenarios ignored the exploitation of other high-yielding grassland species, like Italian Ryegrass (*L. multiflorum*), for temporary grassland which will also allow a step change in productivity (Humphrey, 2005).

4.3 Benchmarking grassland productivity and feedstock availability

As in this paper, crop growth models can be used to benchmark on-farm crop production (Lobell *et al.*, 2009; Sadras *et al.*, 2015), quantifying the obtainable yields (i.e. G x E x M yield) for a given variety grown under defined climatic conditions and agronomic management. Thus, benchmark yields are site- and soil type specific, vary from year to year and evolve with time due to difference in weather and technological progress. We calculated the national benchmark DMY in Great Britain by constraining the blanket grassland productivity to the surveyed grassland areas of each grassland type in 2010 (**Table 2**). In addition, the benchmark DMY will increase until 2050 under both, low and medium CO_2 emission scenarios due to rising atmospheric [CO_2] and technological progress.

The UK total potential availability of biomass for the meat and dairy sectors was the sum of the product of respective benchmark DMYs and grassland areas for the main grassland types (Defra, 2015). Based on the consumption of 10 kg DM per day per adult cattle (Allen *et al.*, 2011), the total potential availability of DM could support 4.2 and 14.1 million heads of cattle in 2010 on temporary and permanent grassland, respectively. Based on the consumption of 2.5 kg dry matter per day per sheep (Allen *et al.*, 2011), the total availability of dry biomass could support 16.3 million sheep in 2010 on rough-grazing grassland. If 30% of total DM on the permanent grassland was used by sheep, the potential total herds of sheep and cattle could be 33.2 and 14.1 million, respectively. The statistics in 2010 by Defra reported 10.1 million herds of cattle and calves and 31.1 million herds of sheep and lambs (Defra, 2015). As calves and lambs consume less than adult cattle and sheep, and considering that a significant amount of processed animal compound feed is used in the UK farming systems (Guo *et al.*, 2016), it is apparent that either there was a yield gap between the benchmark and the on-farm actual DMY or the availability of dry biomass was underutilised by the livestock supported by grassland systems.

4.4 Productivity gap on temporary and permanent grassland

The on-farm actual DMY in either of the two improved grassland systems follows the law of minimum with yield-limiting factors being management, biological and abiotic factors. Here we examined the likelihood that productivity gaps are caused by insufficient amounts of N fertiliser applied to temporary and permanent grassland in recent years. The current respective yield gaps of about 45 and 39% estimated, may be overstated, especially for permanent grassland because a substantial proportion of the grassland will be grazed and wastes from the livestock would add between 60 and 80 kg N/ha to the grassland systems depending on whether the grassland is intensively or moderately intensively managed (Defra, 2010). However, these gaps represented average relative yield reduction due to suboptimal applications of N-fertiliser (**Figure 1**). However, the yield gaps could vary across grasslands of different natural productivities (i.e. DMY on fields at 0 N fertiliser, see **Figure 1**) due to difference in N supplied from soil mineralisation).

The data compiled from the annual statistics indicated that the total grassland area gradually declined for about 15 years from 1984, but remained steady until 2015 (**Figure S2**). The decline in total grassland area between 1996 (12.73 M ha) and 2015 (12.38 M ha) was minimal. However, the herd size declined between 1996 and 2015 by 17.6% (12.0 versus 9.9 M heads) and 20.8% (42.1 versus 33.3 M heads) for cattle (including calves) and total sheep and lambs, respectively. The decline in animal number supported by the same grassland area shows that temporary and permanent grasslands were an under-exploited resource. This indicates that some grasslands that are not used for livestock or do not perform to their full production potential. As underperformance of improved grassland has been attributed to infrequent re-seeding and inadequate soil pH (Hopkins *et al.*, 1994), we believe that grassland management offers considerable opportunities for improvement. Closing the yield gaps between the attainable and the on-farm actual DMY is impeded by little empirical information about on-farm DMYs associated with different grassland groups (Oenema *et al.*, 2014). They reported that the on-farm DMY in intensively managed dairy systems ranged from 50 to 80% of the attainable DMY in Chile and from 60 to 80% in the Netherlands.

4.5 Prospects for future grassland production in GB

The analyses presented in Scenarios A – D (**Figure 6**) demonstrates the influence of changing management patterns on GB grassland DM production and illustrates the breadth of options that are available for the development of land use policy in relation to grassland systems. Scenarios A – D provide understanding of changes in total GB grassland yield as management practices are altered over increasing area. By illustrating where constraints to conversion are likely to become an issue we provide a realistic view of changes that could be realised. For example, as demonstrated in Scenario A, a reduction in the intensity of management of 20% of permanent grasslands would have limited impact on total GB grassland DM production in 2050 compared to the 2010 baseline. This is achieved through the adoption of best practice fertiliser application, and based on technological progress and changes in climate to 2050 that are in line with the modelling assumption used in this study. Alternatively, as demonstrated in Scenarios C and D (**Figure 6**), increasing management intensity of areas of grassland that are likely not constrained by biophysical limits or existing policy drivers could make an additional ca. 18 million tonnes per annum of biomass resource available. This resources could be put to multiple uses depending on national priorities. For example, increasing the national herd to support food independence and increased exports, or alternatively the biomass could be used as a resource for energy production through routes such as anaerobic digestion (Prochnow *et al.*, 2009; McEniry *et al.*, 2013).

Scenario E present a simple scenario of changes in grassland management practice across GB that considers how policy might be designed to reflect differing regional priorities. The scenario of improved grassland reversion in upland regions considers a policy focused on mechanisms to support farmers for the delivery and protection of other ecosystem services within systems that may be particularly challenging from a production perspective. These include protection of water quality and carbon stocks, and in certain regions maintenance of landscape characteristics. In scenario E, grassland production would shift to more intensively managed lowland regions to maintain total GB grassland production.

5 Conclusions

DMYs were calculated using meta-models at 1 km^2 grid resolution for different grassland systems in the UK and then projected to the future (2010s to 2050s) accounting for climate change, rising atmospheric [CO_2] and technological progress under low and medium emission scenarios. National baseline productivities (1970s to 1980s) of 10.5, 7.8 and 2.6 t/ha adjusted to benchmark productivities (2010) of 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland, respectively. Future yield increase will mainly come from technological innovation and rising atmospheric [CO_2] and yield increments are likely to be larger on temporary than on permanent grassland, with little change on rough-grazing. Projected grassland DMY could reach 15.5 and 9.8 t/ha on temporary and permanent grassland by 2050 under medium CO_2 emission scenario, respectively. Maps display the regional concentration of grassland productivity and total biomass availability at 1 km^2 grid for GB based on the 2010 survey. Recent decline of N application to sub-optimal N rates has likely resulted in productivity gaps of ca. 40% on improved grassland. Closing some of these productivity gaps can either lead to additional biomass availability or spare some of these grasslands for other uses. Scenarios show that intensification of lowland grasslands can outweigh the reversion of upland grassland areas to rough grazing or low intensity permanent pastures.

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Supplemental Material

Tables

Table S1a: The range and mean percentage of dry matter yield (DMY) increase due to CO_2 fertilisation effect in selected reports found on perennial ryegrass (*Lolium perenne*).

Table S1b: The measured decadal mean atmospheric [CO_2] (part per million by volume: ppm) and projected atmospheric [CO_2] by the BERN carbon cycle model under low and medium CO_2 emission scenarios ending in decades from 1970s to 2050s.

Table S2: The applied percentage increase (f_{CFE}) above the baseline DMY due to fertilisation effect of increased [CO_2] in the atmosphere on all grasslands in1990s to 2050s in the UK.

Table S3a: Estimated annual percent increases in various reports in potential and the on-farm DMY in grasslands of perennial ryegrass attributed to technological progress.

Table S3b: The applied percentage increase above the baseline DMY due to technological progress on all grasslands from the 1990s to 2050s in the UK, that is, f_{TP} in Equations 1 and 2.

Table S4: Percent change in the future decades under low and medium CO_2 emission scenarios relative to the baseline climate scenario (1961-1990) in seasonal precipitation (P), global radiation (R_g) and mean seasonal air temperatures (T_{air}).

Table S5: Total availability of dry biomass in million tonnes (M t) in the UK based on the areas reported for temporary (TG), permanent (PG) and rough-grazing (RG) grasslands in 2010 (Defra, 2015) and using the benchmark DMY calculated for the 2010s (**Table 2**).

Table S6: Distribution of nitrate vulnerable zones in Great Britain (GB) used in the scenario analysis of grassland intensification in cases of changing PG into TG and RG into PG

Figures

Figure S1: National average annual N applied amount (N kg/ha) on temporary and permanent grassland from 1992 to 2015 in Great Britain (Defra, 2016b).

Figure S2: Annual trends in total grassland area, total number of cattle and calves and of sheep and lamb in the UK (https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom). Data on total number of sheep and lamb were not available before 1996.

Figure captions

Figure 1: Yield gap (YG) exemplified for temporary grassland (TG) derived from the response curve of relative dry matter yield (DMY%) to variable N application. The vertical arrows show the reduction of the recommended (300 kg/ha) to the actual N application rate for TG (*ca.* 100 kg/ha). Response curve was derived from experimental data (Morrison *et al.*, 1980); respective N-fertiliser data were extracted from Fertiliser Manual (Defra 2010) and National Statistics (Defra 2016).

Figure 2: Spatially explicit technology- and CO_2- adjusted dry matter yields (DMYs) on different grasslands at 1 km^2 grid resolution in 2010 in the UK.

Figure 3: The technology-and CO_2-adjusted mean national dry matter (DM) yield for temporary (TG), permanent (PG) and rough-grazing (RG) grassland in the UK on the assumption that all available land had been used as single grassland type (i.e. a “blanket” approach) in 2010-2050s under medium (a) and low (b) emission scenarios.

Figure 4: Spatially explicit availability of dry biomass (t/km^2) for rough-grazing, permanent and temporary grassland based on the respective grassland areas surveyed in 2010 in Great Britain and the technology-and CO_2-adjusted DMYs in 2010s (i.e. from **Figure 2**).

Figure 5: Regional areas (a) and availability of total dry matter (b) at the NUTS (Nomenclature of Territorial Units for Statistics) level 1 based on the digitised areas for temporary (TG), permanent (PG) and rough-grazing (RG) grasslands surveyed in 2010 in Great Britain.

Figure 6 Changes in total dry matter (TDM) production on grassland in Great Britain (tonnes per year) from 2010 to 2050 under a low CO_2 emission scenario. Scenarios explore: (a) conversion of PG to RG (Abandonment); (b) conversion of TG to PG (Reversion); (c) conversion of PG to TG (Lowland Intensification); (d) conversion of RG to PG (Upland Intensification). Benchmark TDM production in Great Britain for the 2010s (●) would change with increasing conversion rates of grassland inside (x) and outside (+) of environmental constraints.

Figure 7: Changes in total areas in GB of temporary (TG), permanent (PG) and rough-grazing (RG) grasslands with increased percentage of conversion of permanent grassland to rough grazing (Abandonment) in upland regions (PG(UL) maintaining total GB grassland dry matter production (*ca*. 71,000,000 tonnes per annum) through intensification of PG to TG in lowland areas (PG(LL)). Productivity in 2050s under low CO_2 emission scenario.

Tables

Table 1: The weather-governed mean national DMY (t/ha) across the UK as if all available land had been used as a single grassland type (i.e. blanket approach) under baseline and future climates.

CO_2 emission scenario	Grassland	Baseline	2020s	2030s	2040s	2050s
Low	Temporary	10.5	10.5	10.6	10.6	10.6
	Permanent	7.8	7.6	7.5	7.4	7.5
	Rough-grazing	2.6	2.5	2.5	2.4	2.4
Medium	Temporary	10.5	10.5	10.6	10.6	10.6
	Permanent	7.8	7.6	7.5	7.4	7.4
	Rough-grazing	2.6	2.5	2.4	2.4	2.3

Table 2: The technology- and CO_2-adjusted national benchmark mean DMY (t/ha) across the UK in accordance with surveyed grassland areas for each grassland type in 2010 overlaid with the meta-model calculated DMY from 2010-2050s.

CO_2 emission scenario	Grassland	2010s	2020s	2030s	2040s	2050s
Low	Temporary	12.5	13.1	13.8	14.5	15.3
	Permanent	8.7	8.9	9.3	9.5	9.8
	Rough-grazing	2.8	2.7	2.7	2.7	2.7
Medium	Temporary	12.5	13.2	13.9	14.7	15.5
	Permanent	8.7	8.9	9.3	9.6	9.9
	Rough-grazing	2.8	2.7	2.7	2.7	2.7

Table 3: The current national on-farm DMY as a proportion of the attainable DMY with recommended economically optimal N application rates (kg N/ha) as calculated by the response curve of relative dry matter yield (DMY%) to N application rate (kg N/ha) **(Figure 1)** and the consequential yield gap on TG and PG in GB (based on total production; **Table S5**).

Grassland	Recommended N rate	Actual N rate	DMY% at recommended N rate	DMY% at actual N rate	Fraction of attainable yield	Yield gap 10^6 t yr^{-1}
Temporary	300	99.1	82.46	45.62	55.3	5.71
Permanent	150	51.6	56.72	34.57	61.0	15.40

Table 4: Scenarios and constraints explored in analyses of the implication of changes in grassland management for total grassland dry matter production in Great Britain.

***Scenario A**: Conversion of PG to RG – this represents reduction of production intensity (Abandonment Scenario). Land use change is not constrained by any factors.
***Scenario B**: Conversion of TG to PG – again this represents a reduction of production intensity (Reversion Scenario). Land use change is not constrained by any factors.
***Scenario C**: Conversion of PG to TG – mainly a Lowland Intensification Scenario. Constraints on conversion are imposed where sufficient land is available to meet conversion targets such that preference is given to areas where the average slope is <15% (limit for machinery) and for areas outside NVZs (given that intensification calls for additional fertiliser input).
***Scenario D**: Conversion of RG to PG – mainly an Upland Intensification Scenario. Constraints on conversion are imposed where sufficient land is available to meet conversion targets such that preference is given to areas with an average height below 250m, where the average slope is <15% (limit for machinery) and for areas outside NVZs (given that intensification calls for additional N fertiliser input).
Scenario E: Abandonment of the uplands – this represent both a reduction of productivity in upland areas (defined as those above 250m) with conversion of improved grassland (PG) to semi-natural grassland (RG), and an intensification of lowland areas with conversion of PG to TG. Here, the scenario was designed to hold grassland production (tonnes per year) stationary through changes in land use. Constraints were altitude, slope (average of less than 15%) and in lowland areas avoidance of areas considered to be in NVZs. The latter constraint was applied as conversion from PG to TG would entail increased N fertiliser inputs.

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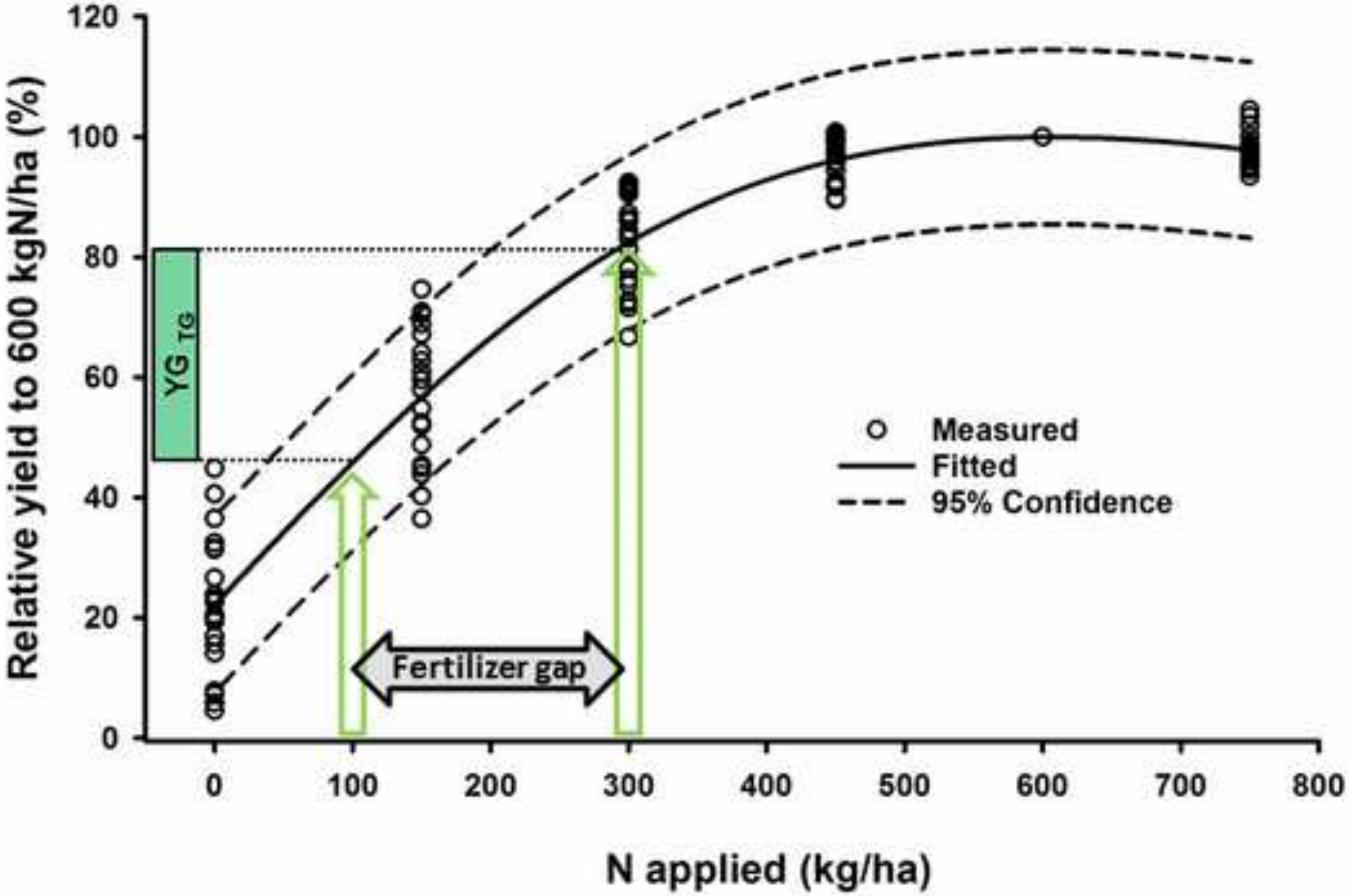
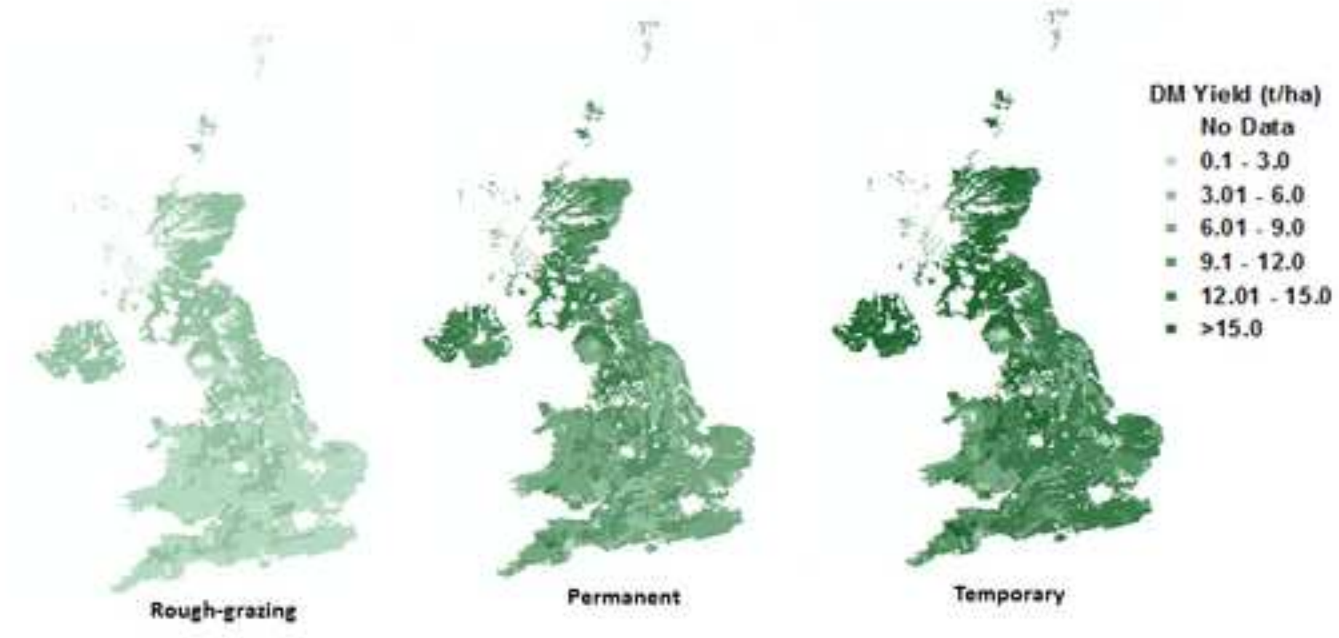


Figure 2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Permanent
Temporary

Figure 3

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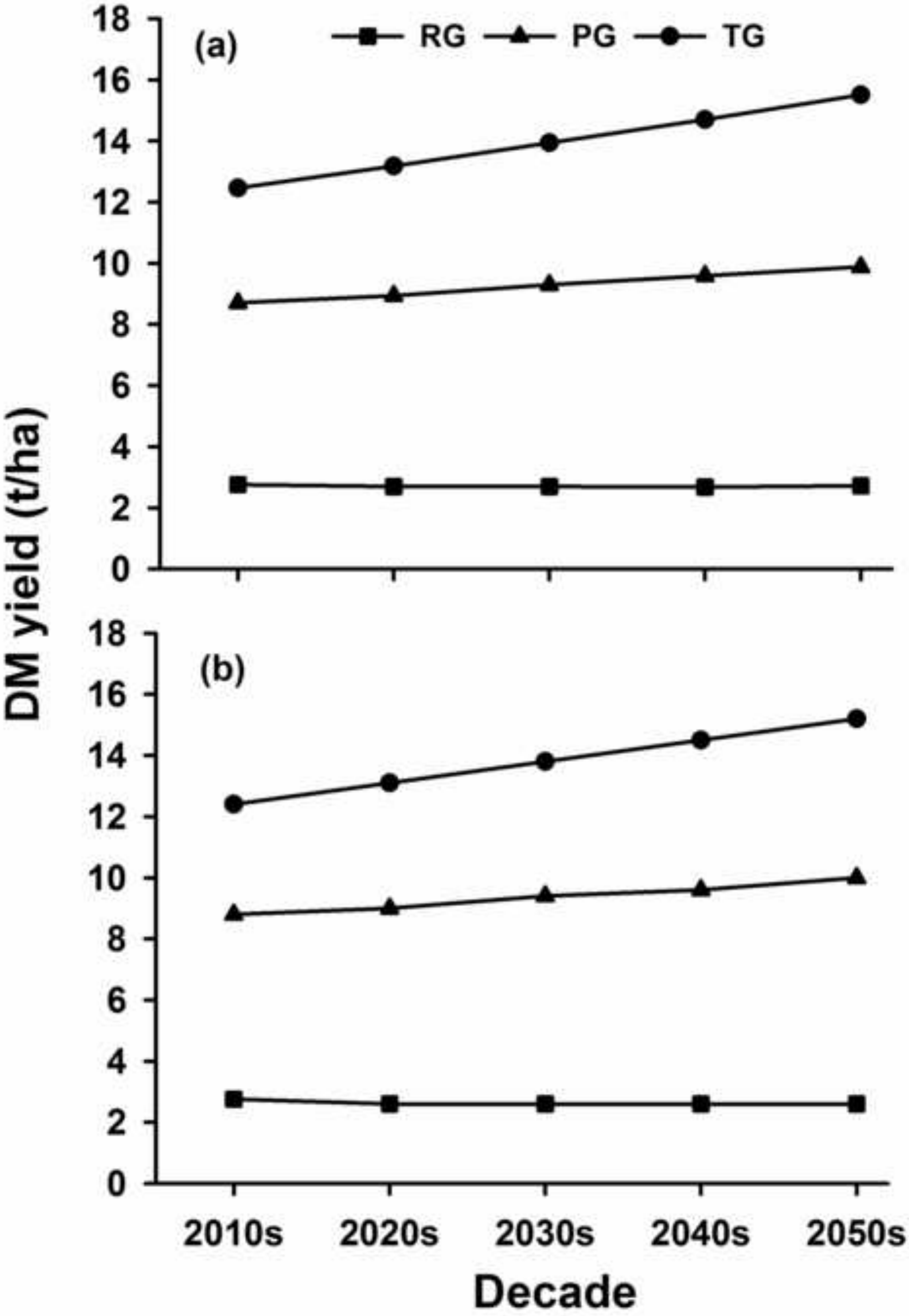

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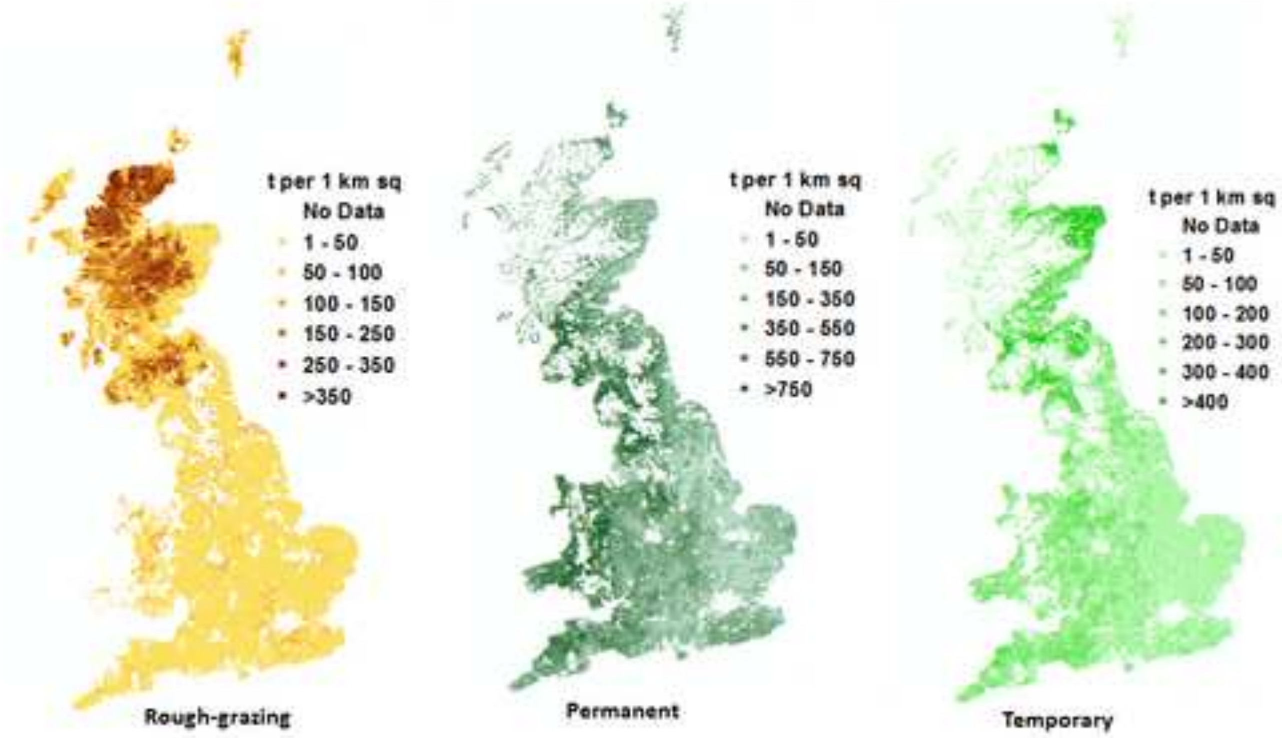

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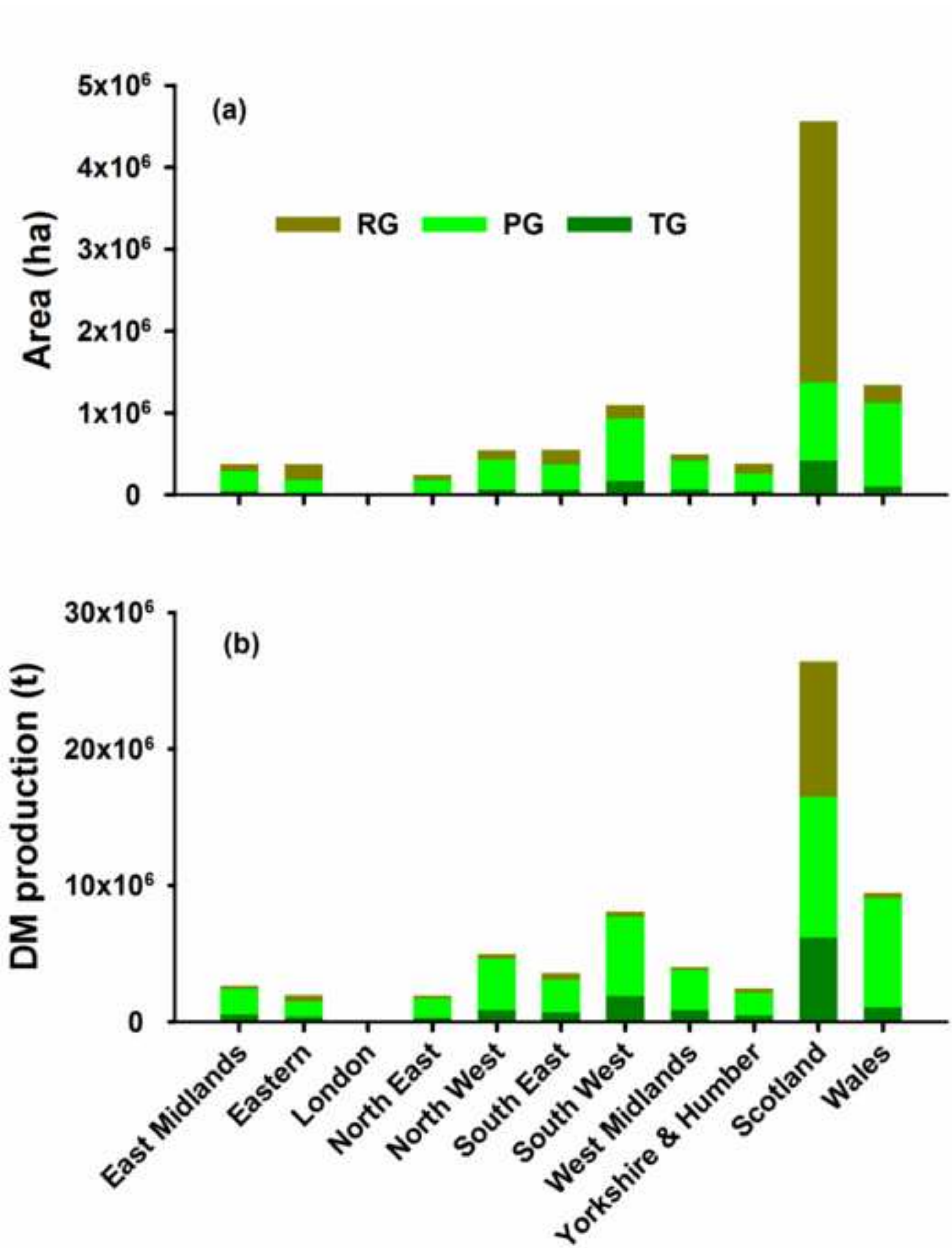

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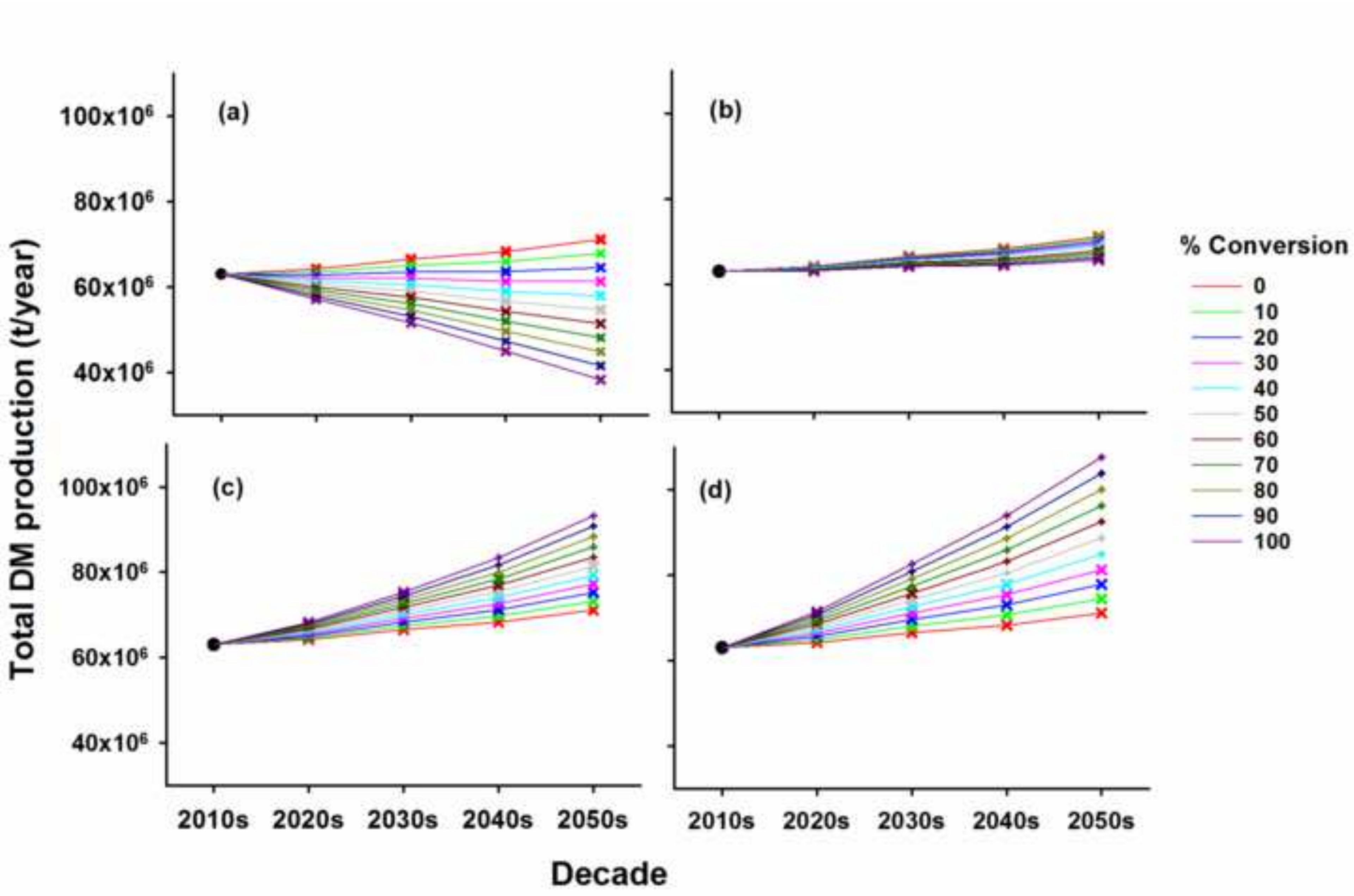
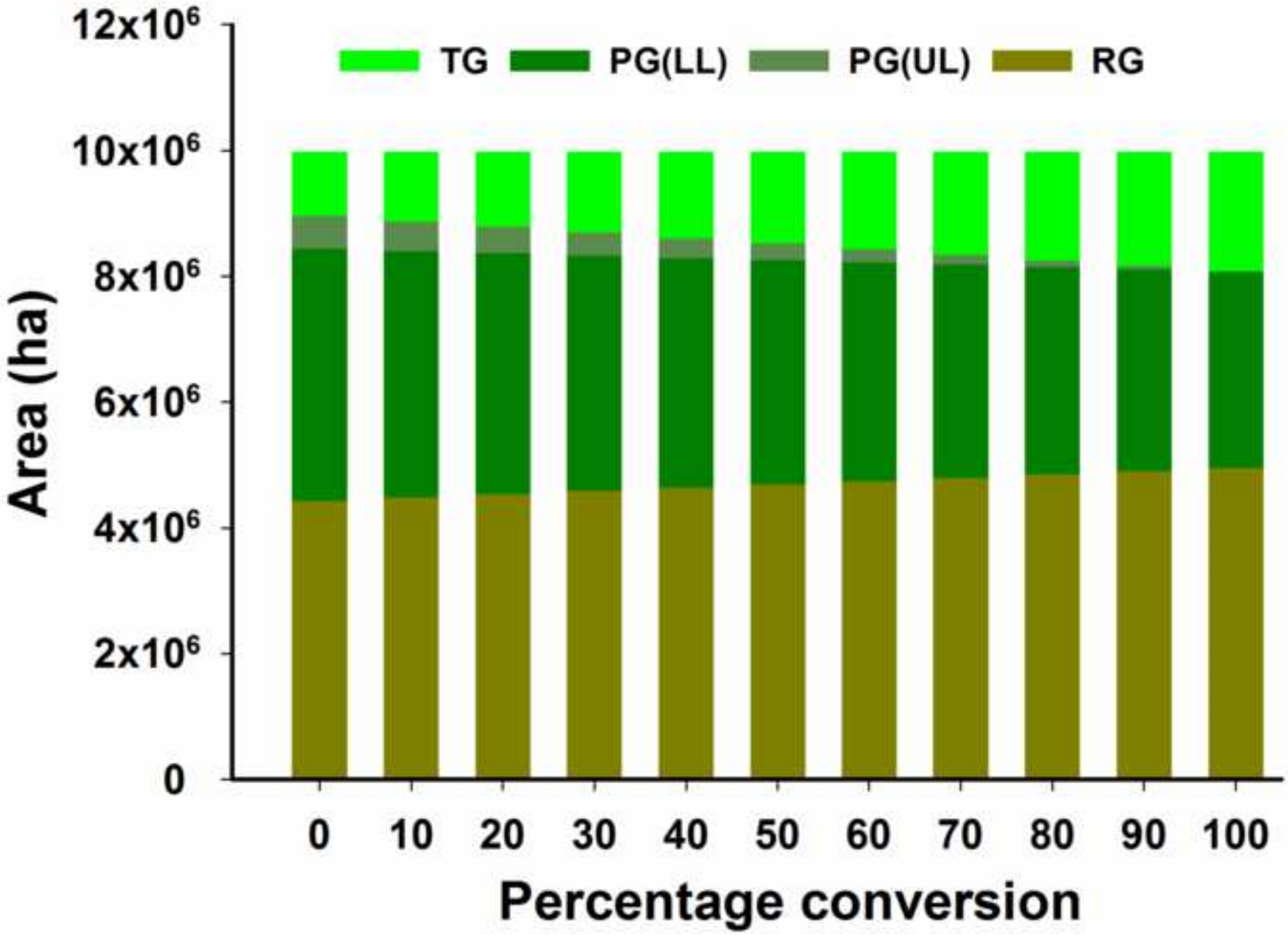


Figure 7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