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

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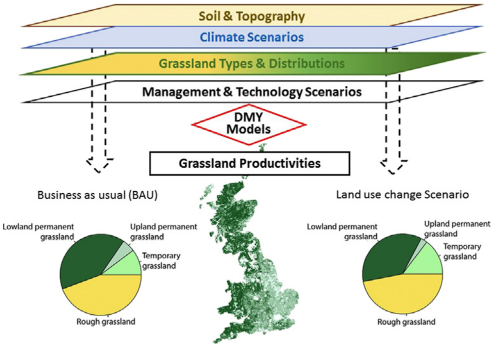
HIGHLIGHTS

- Benchmark yields (9–12.5 t/ha) provide $52 \cdot 10^6$ t from improved grassland.
- Future productivity gains come from technological progress and intensification.
- Closing yield gaps of $20 \cdot 10^6$ t could provide biomass for “E10” biogas mix.
- Lowland intensification can outweigh reversion of upland areas to rough grazing.

GRAPHICAL ABSTRACT



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ABSTRACT

To optimise trade-offs provided by future changes in grassland use intensity, spatially and temporally explicit estimates of respective grassland productivities 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; 1961–1990) 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 benchmark productivities of 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland, respectively, accounted for productivity gains by 2010. By 2050, productivities under medium emission scenario are 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 grassland distributions for Great Britain in 2010 the annual availability of grassland biomass is likely to rise from 64 to 72 million tonnes by 2050. Assuming optimal N application could close existing productivity gaps of ca. 40% a range of management options could deliver additional $21 * 10^6$ tonnes of biomass available for bioenergy. Scenarios of changes in grassland use intensity demonstrated considerable scope for maintaining or further increasing grassland production and sparing some grassland for the provision of environmental ecosystem services.

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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, respectively (Defra, 2016a), which represents a significant land resource used for food. Grasslands also play an important role in supporting biodiversity (Fargione et al., 2009) and in delivering other benefits to society like carbon sequestration, biomass for bioenergy, and recreational opportunities (Hopkins and Wilkins, 2006; O'Mara, 2012; McEniry et al., 2013).

Environmental agencies are increasingly incorporating natural capital and ecosystem services into policy and management of agricultural landscapes (Bryan et al., 2011). With the UK Brexit vote in the 2016 referendum, new options for the future of its farming need to be identified. The debate seeks to balance the arguments for intensifying production with those for incorporating wider sustainability criteria into land use planning (Hill, 2017; Medina and Potter, 2017). For grassland systems, the upland regions of the UK and beyond are particularly vulnerable in this regard (O'Rourke et al., 2016). These areas play a central role in the provision of regulating ecosystem services (Orr et al., 2008); however, the beneficiaries of these services are often far removed in distant urban areas (O'Rourke et al., 2016). Continuously declining N-fertiliser inputs and stocking rates (Defra, 2016b) reflect the traditionally low-input, low-output business model of upland farmers that supports the provision of these societal (Reed et al., 2009) and environmental benefits (Bell et al., 2016) but presents economic challenges for them.

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 optimise 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. Such knowledge allows policy makers to explore options in regions with lower productivity gains of changing grassland management practice that benefit biodiversity and other ecosystem services like carbon sequestration and water quality (Eigenbrod et al., 2011; Phalan et al., 2014; Werling et al., 2014; Reed et al., 2009; Smith, 2014).

The net primary productivity of grasslands can be measured from its annual dry matter production. An earlier presented process-based grass model increased our understanding of past experimental DMYs on 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 production, these estimates need to account for climate change, increased atmospheric carbon dioxide concentration [CO_2] and technological progress, e.g. better genetics and management (Ewert et al., 2005). The impact of past climate change on grassland DMYs is uncertain: While it was found to be rather small (Coleman et al., 1987; Chang et al., 2015) or undetectable (Jenkinson et al., 1994), forecasts are that future climate change is likely to improve productivity and quality of grasslands (Hopkins and Del Prado, 2007; Izaurralde et al., 2011). Earlier scenarios found little change in DMYs for Scotland (Cooper and McGechan, 1996), in spite of increased [CO_2] being likely to stimulate pasture growth (Soussana and Luscher, 2007).

Technological progress in terms of plant breeding and improved agronomy are most likely to continue increasing grassland productivity (Hopkins and Wilkins, 2006). An annual increase of the potential DMY of 0.25 to 0.76% seems possible (e.g. Wilkins and Humphreys, 2003; Harmer et al., 2016). Actual on-farm grassland yield gains varied between countries and grassland types (Smit et al., 2008) and they were low on permanent grassland (0.35% annually) due to less frequent reseeding (Chang et al., 2015). For semi-natural grasslands used for rough-grazing, productivity cannot be improved genetically but influenced by changing growing conditions, e.g. improving the hydrology or adjusting stocking density (Sozanska-Stanton et al., 2016; Worrall and Clay, 2012).

Against this background, 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 identify productivity gaps in reference to current benchmark DMYs, particularly with respect to declining DMYs because of low N application rates; and (iv) to perform spatial analyses of the impacts of conversion between grassland types and to investigate changes in total grassland biomass production in Great Britain under varying land use options in comparison to 'Business as Usual' (BAU). Throughout the paper, BAU refers to the distribution of grassland in 2010, with DMYs adjusted for climate change and technological progress in subsequent decades.

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. Meta-models belong to the class of empirical models, that once calibrated can be as robust as the process-based models but are much less demanding in terms of input data. DMYs calculated using baseline weather (1961–1990), are referred to as baseline dry matter yields (Y_{base}), calibrated and validated against observations in the 1970s and 1980s. However, since then climate has changed, atmospheric [CO_2] increased, and pasture species with higher growth potential and improved agronomy have been adopted for improved, i.e. 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 dioxide fertilisation effect (CFE; f_{CFE}) due to rising atmospheric [CO_2] and technological progress (TP; f_{TP}).

The DMY in 2010 was calculated using Eq. (1):

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

where Y_{10s} is the annual DMY in 2010s, Y_{base} the meta-model calculated baseline productivity, $f_{10s,\ CFE}$ is the percentage increase of DMY due to CFE using the average [CO_2] of the 2010s, while $f_{10s,\ TP}$ is the percentage of DMY increase due to technological progress from 1980s to 2010s. For Y_{base} and Y_{10s}, the respective means of actual weather variables from 1961 to 1990 and 2001–2010 were used.

Decadal DMYs in 2020 to 2050 ($Y_{t1\ldots4}$) were calculated with Eq. (2):

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

where $Y_{t1\ldots4}$ is the annual DMY from decades of 2020s to 2050s (i.e. decadal intervals), $f_{t1\ldots4,\ CC} + f_{t1\ldots4,\ CFE} + f_{t1\ldots4,\ TP}$ 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 (1961–1990) and the weather-governed DMY with changed climate divided by the former.

2.1.1. Impact of future weather changes

The meta-models encapsulate the effects of weather variables on DMYs using inputs of changed bioclimatic variables that reflect the weather-governed DMYs for any queried future decade. These variable changes fed directly into the meta-models, developed from scenario outputs generated by validated process-based growth models (Qi et al., 2017), to calculate future grassland productivities. Inputs were SAWC and bioclimatic variables of monthly temperature, precipitation, and global radiation under baseline (1961–1990) and future climate change scenarios. The impact of climate change on grassland productivities is expressed as the percentage difference between DMY under the baseline climate (1961–1990) and each climate scenario in decadal steps from 2010 to 2050.

1.1.1 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] from the baseline to the respective later decades.

Atmospheric [CO_2] has increased from 334 ppm in the 1970/80s to the present 400 ppm in 2015 at a rate of approximately 2 ppm per year due to anthropogenic forcing (IPCC, 2013; Myhre et al., 2013). The predicted atmospheric [CO_2] for the 2020s to 2050s were taken from the projections of the BERN model under low and medium CO_2 emission scenarios (Table S1b) in line with earlier studies (Murshed et al., 2012). 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 CFE for the 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 farm scale management to 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% was assumed (Smit et al., 2008; Chang et al., 2015; Table S3a). These TP factors assume an optimum supply of all nutrients and standard cutting/grazing regime of four and two cuts, respectively (see scenarios by Graux et al., 2013). For rough grazing grassland, which is semi-natural with little agronomic inputs, no technological improvements in dry matter productivity were applied. Thus, the accumulated percentage increases above the Y_{base} were calculated and applied on each of the three types of grassland from 1980s to 2050s (Table S3b).

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 25 km × 25 km grid, which were harmonised into 1 km × 1 km 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 × 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 nitrogen (N) applied per hectare to temporary and permanent grassland started in the 1960s. The average N applied increased steadily until the mid-1990s (Rath and Peel, 2005) but declined then from the late 1990s onwards on both, temporary and permanent grassland until 2008 and remained unchanged since (Fig. S1; Defra, 2016b). 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. Annual DMY was aggregated from six cuts in each experiment. The DMYs reached their maximum usually at an N application rate of 600 kg N/ha; incremental DMYs were normalised using the maximum DMY and expressed as their percent fraction (DMY%; see Fig. 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)):

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

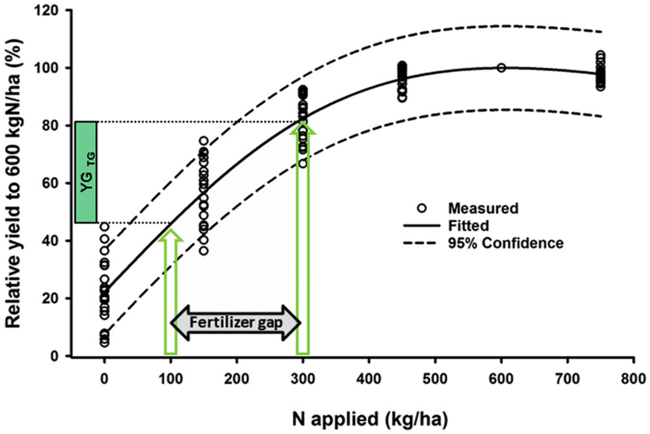

Fig. 1. Yield gap (YG) exemplified for temporary grassland (TG) derived from the response curve of relative dry matter yield (DMY%) to variable N application. The vertical arrows show the reduction of the recommended (300 kg/ha) to the actual N application rate for TG (ca. 100 kg/ha). Response curve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

The estimated coefficients were: a = 22.1696, b = 0.2373, c = −0.0001944, d = 0.000002117 ($R^2 = 0.938$; n = 126). This equation was used to calculate the yield gap caused by reduced N fertiliser usage compared to the respective best practice (economic optima).

2.4. Analysis of GB grassland production for different land use transition scenarios

Grassland areas were surveyed by Defra in 2010, and data are available at a 2 km × 2 km 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 ha 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 to 2050 as deviation from BAU (Table 1), conducted at a 2 km × 2 km grid resolution for compatibility with the survey data. The focus of the scenario analysis was on changes in management practices that would result in shifts between different grassland types (e.g. permanent to temporary grassland). Transitions between grassland types did not increase or decrease the overall area of GB grassland.

The likelihood that farmers will change management practices (i.e. shift from BAU production model towards environment focus) is determined by complex social and economic drivers arising from past and current experiences that serve to limit farm development pathways (Di Falco and Perrings, 2005; Ingram et al., 2013). Our analytic approach does not assume optimised transitions between grassland types determined by factors such as monetary returns, yields, or carbon stocks. Instead the target area for conversion in hectares (ha) for GB was calculated by implementing a stochastic algorithm (R Core Team, 2017) that randomly assigned grassland conversion areas for each 2 km × 2 km grid cell until the target area for conversion was met. For each scenario 1000 permutations were conducted and changes in average yield per 2 km × 2 km 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 (≥250 m 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, conversion of rough-grazing to permanent grassland, which implies greater agricultural inputs, initially focused on areas outside NVZ and where slopes were ≤15%. 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 2 km × 2 km grid cells.

Table 1
Scenarios and constraints explored in analyses of the implication of changes in temporary (TG), permanent grassland (PG) and Rough Grazing (RG) use 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 250 m, 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 250 m) with conversion of improved grassland in upland (PG(U)) to semi-natural grassland (RG), and an intensification with conversion of permanent grassland in lowland areas (PG(L)) 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 <15%) and in lowland areas avoidance of areas considered to be in nitrogen vulnerable zones (NVZs). The latter constraint was applied as conversion from PG to TG would entail increased N fertiliser inputs.

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 management intensity was examined (Scenario A, Permanent to Rough-grazing; Scenario B, Temporary to Permanent) and in the second instances an increase in intensity of production (Scenario C, Permanent to Temporary; Scenario D, Rough-grazing to Permanent). For each scenario, the stochastic algorithm considered transitions of between 0 and 100% of 2010 area in 10% increments. This defines a combination of each scenario with 11 transitional steps from 0 to 100% at 10% increments, over which possible changes to the grassland management regime could occur, allowing examination of their 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, Scenario E did not explore change in grassland yield associated with changing management practices, rather the aim was to maintain GB grassland DM production at BAU levels. In areas defined as upland (average altitude ≥ 250 m) 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 and 100% of the specific grassland area in 10% increments using the same stochastic approach.

3. Results

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

'Blanket' DMYs were calculated with the meta-models at 1 km^2 resolution across the UK, assuming a single grassland type for all land with SAWC information. The average blanket DMYs for the baseline (1980s) and future weather (Table 2) indicate little difference between the emission scenarios. Future climatic changes (weather only without CFE) have little effect on average 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. Productivity of permanent grassland and rough-grazing will be slightly reduced (~0.3 t/ha) by future weather, likely due to increased variability of DMYs. By 2050, the productivity on rough-grazing grassland is likely to be reduced by about 10% with an increased coefficient of variation (Table 2).

Maps of the DMY (Fig. 2) show the technology- and [CO_2]-adjusted blanket productivity for all agricultural land in the 2010s applying a [CO_2], equivalent to the medium emission scenario. The national average blanket DMYs in the UK are likely to increase between the 2010s and 2050s for improved grasslands (temporary and permanent) but differences between the DMYs under low and medium emission scenarios are very small (not shown). For rough-grazing grassland the stimulus of rising [CO_2] cannot compensate the negative impacts of future weather (reduced precipitation and increased summer temperatures). The

Table 2
The weather-governed mean national DMYs (t/ha) across the UK as if all available land had been used as a single grassland type (i.e. blanket approach) under baseline (i.e. 1980s), low and medium CO_2 emission scenarios. The figures in bracket are coefficient of variation (%). These DMY levels do not include the CFE and the TP.

CO_2 emission scenario	Grassland	1980s	2020s	2030s	2040s	2050s
Low	Temporary	10.5 (26.4)	10.5 (26.5)	10.6 (26.8)	10.6 (27.0)	10.6 (26.9)
	Permanent	7.8 (26.8)	7.6 (28.2)	7.5 (29.0)	7.4 (29.6)	7.5 (29.2)
	Rough-grazing	2.6 (27.1)	2.5 (28.6)	2.5 (29.2)	2.4 (29.6)	2.4 (30.1)
Medium	Temporary	10.5 (26.4)	10.5 (26.6)	10.6 (26.7)	10.6 (27.0)	10.6 (26.9)
	Permanent	7.8 (26.8)	7.6 (28.3)	7.5 (29.1)	7.4 (29.8)	7.4 (29.6)
	Rough-grazing	2.6 (27.1)	2.5 (28.7)	2.4 (29.4)	2.4 (30.0)	2.3 (30.7)

productivity of rough-grazing grassland is unlikely to change by 2050, while yields on improved grassland types are likely to increase.

3.2. Benchmark productivity constrained by actual grassland distribution in GB

Assuming no changes in land use intensity, the average DMYs were based on the actual areas of each grassland type and calculated from 2010s to 2050s (Table 3). These benchmark productivities were very similar when calculated for the whole country (blanket approach) and the census areas. The DMYs in 2010 represent the current benchmark productivities of 12.5, 8.7 and 2.8 t/ha on temporary, permanent and rough-grazing grassland in GB, respectively. By the 2050s these are likely to increase by up to 24% and 14% on temporary and permanent grassland, respectively. For all grassland types, the productivity is predicted to be more variable as CV% increases slightly (Table 3).

After overlaying the NUTS 1 (Nomenclature of Territorial Units for Statistics) regions with the grassland areas and the dry matter production per 1 km^2 grid (Fig. 3), the total grassland area (Fig. 4a) and total dry matter production (Fig. 4b) per region in Great Britain were calculated. Within Great Britain, the total grassland area in 2010 was partitioned to 45.7, 13.4 and 40.9% between 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 the South West, followed by the North West and the West Midlands.

Defra reported areas of respective grassland types in 2010 for the whole UK totalling 12.54 million ha (Defra, 2015) and the Agricultural Census in 2010 specified these areas for GB only with 9.99 million ha (details in Table S5). The total DM availability for each grassland type was calculated by multiplying the respective grassland areas and their corresponding mean DMYs (Table S5). The UK total potential availability of grassland biomass can reach 82 million tonnes. With 63% permanent grassland provided the largest proportion of this national total while temporary and rough-grazing grassland contributed equally to the remaining 37%. Without NI the annual biomass resource shrinks to 64.5 million tonnes, of which 40 million tonnes come from permanent grassland.

3.3. Grassland yield gap analysis

The above projected grassland productivities consider all factors from 2010s to 2050s reflecting the attainable DMYs (i.e. water limited potential yield, van Ittersum et al., 2013). The actual on-farm DMYs are usually smaller than the attainable yields due to other limitations (Lobell et al., 2009; Sadras et al., 2015), like fertiliser management.

The modelled DM productivity for permanent and temporary grassland was based on best practice application rates of 150 and 300 kg N/ha, respectively (Defra, 2010). The annual N usage on grassland had dropped to ca. 99 and 52 kg N/ha on the temporary and permanent grassland, respectively, much below these recommended economic optimums of 150 and 300 kg N/ha for permanent and temporary grasslands, respectively (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 (Eq. (3); see Fig. 1). The current N shortage resulted in a yield gap (YG) calculated from on-farm DMYs of about 45 and 39% below the attainable DMYs on temporary and permanent grassland, respectively. This corresponds to a total actual unused production of about

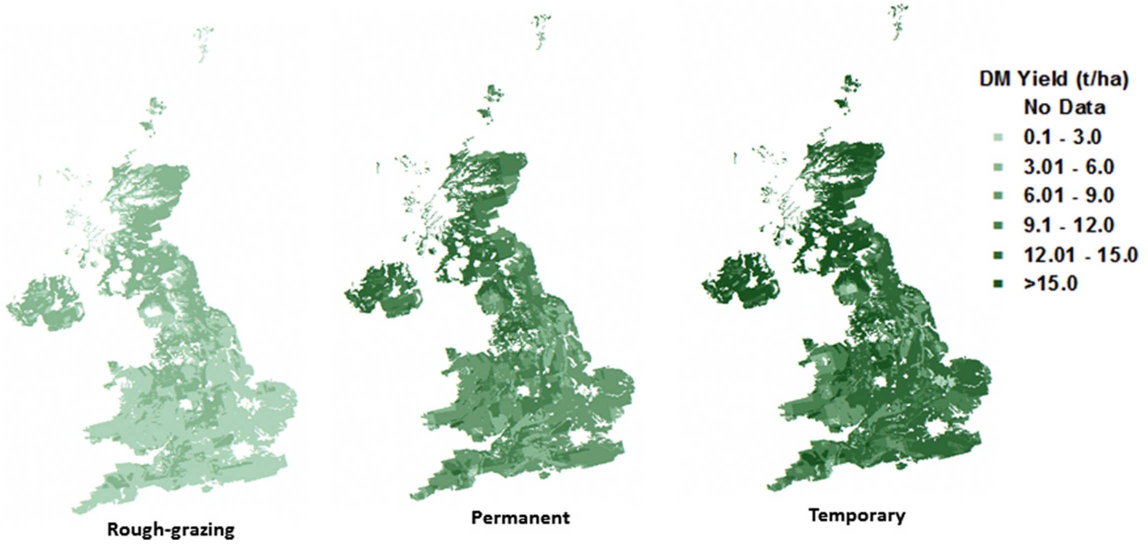

Fig. 2. Spatially explicit technology- and CO_2-adjusted dry matter yields (DMYs) on different single grassland types ("blanket approach") at 1 km^2 grid resolution in 2010 in the UK.

Table 3
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. The DMY in 2010s was adjusted from 1980s accounting for the CFE and TP during the four decades.

CO_2 emission scenario	Grassland	2010s	2020s	2030s	2040s	2050s
Low	Temporary	12.5 (24.7)	13.1 (24.9)	13.8 (25.2)	14.5 (25.2)	15.3 (25.2)
	Permanent	8.7 (26.1)	8.9 (27.7)	9.3 (28.3)	9.5 (28.7)	9.8 (28.4)
	Rough-grazing	2.8 (26.3)	2.7 (26.6)	2.7 (27.7)	2.7 (28.9)	2.7 (29.1)
Medium	Temporary	12.5 (24.7)	13.2 (24.9)	13.9 (25.1)	14.7 (25.2)	15.5 (25.2)
	Permanent	8.7 (26.1)	8.9 (27.7)	9.3 (28.4)	9.6 (28.9)	9.9 (28.7)
	Rough-grazing	2.8 (26.3)	2.7 (26.6)	2.7 (27.8)	2.7 (29.1)	2.7 (29.3)

21 million tonnes DM (Table 4), which could rise to 30 million tonnes by 2050.

3.4. GB total grassland DM production for land use intensity 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 2010 BAU 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 to the 2010 BAU (Fig. 5). 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 BAU 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 BAU in total GB grassland DM production out to 2050. For example, unconstrained conversion of 100% 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. In both cases constraints maps (e.g. nitrate vulnerable zones; slope) served to restrict the area over which increases in management intensity might practically be achieved to provide a more realistic assessment of increase in total GB grassland DM production. Based on constraints it would be possible to achieve 50% conversion of management intensity for Scenario C and 30% conversion for Scenario D, in both cases yielding an additional 18 million tonnes above the 2010 BAU benchmark, bringing the total production to ca. 90 million tonnes.

Scenario E explored an alternative future where total potential DM production was maintained at calculated DMY in GB during the 2010s to 2050s, assuming optimal N. In this scenario, there was a reduction in the management intensity of permanent grassland in upland areas (PG(U) ≥ RG) to the west and north of GB, accompanied by conversion of permanent to temporary grassland in lowland regions (PG(L) ≥ TG) to maintain total GB grassland yield (Fig. 6). Given the restriction imposed by the presence of NVZs in England, our stochastic algorithm selected for production of grassland that was still focused in the north and west of GB but represented a shift in management intensity from upland to lowland areas. In terms of land conversion, the abandonment of permanent grassland in upland regions would require an increase from up to 1.9 million ha of temporary grassland to compensate for lost yields. At more realistic conversion levels of 20–40%, there are options for substantial reductions in management inputs of uplands regions of GB that would require intensification of only 200 to 300 thousand ha, reseeding and fertilising permanent grassland in the lowlands more frequently to make up for lost yield in upland areas.

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

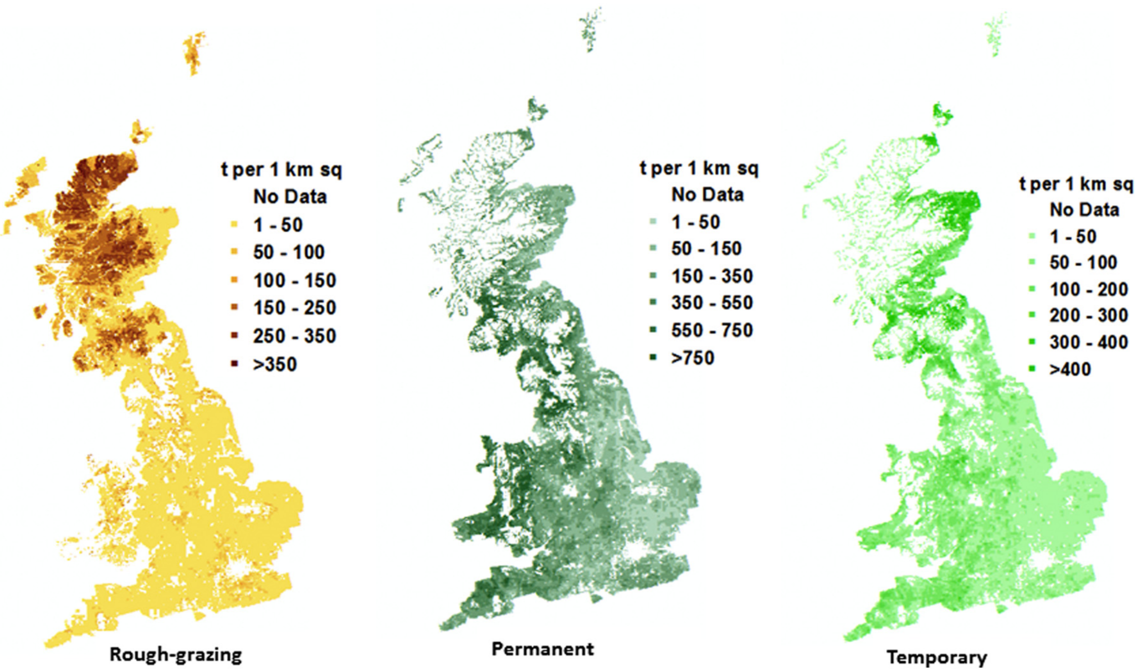

Fig. 3. Spatially explicit availability of dry biomass (t/km^2) for rough-grazing, permanent and temporary grassland based on the respective grassland areas surveyed in 2010 in Great Britain and the technology-and CO_2-adjusted DMYs in 2010s (i.e. from Fig. 2).

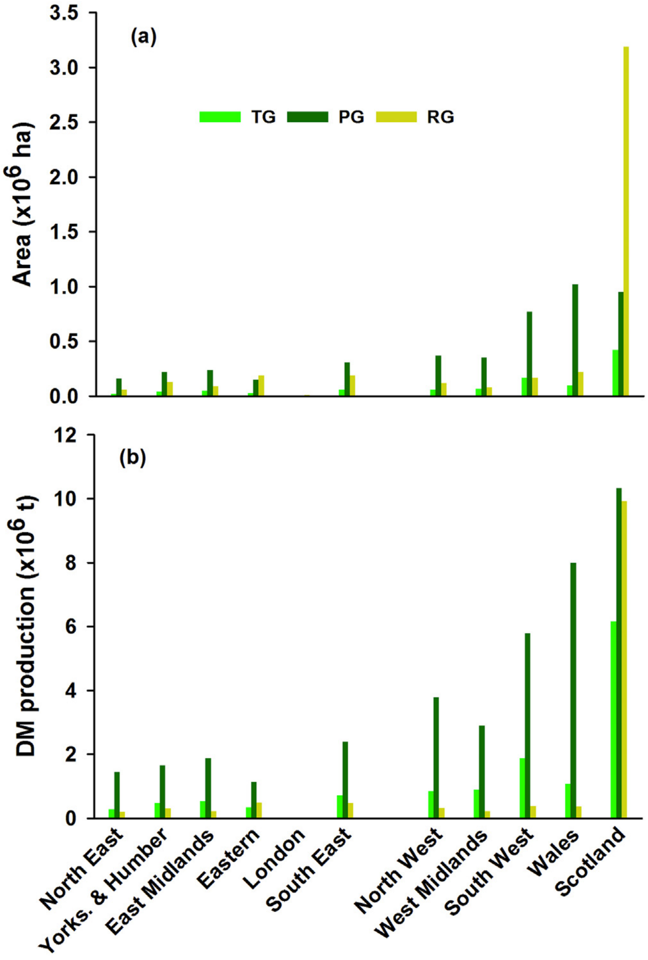

Fig. 4. Regional areas (a) and availability of total dry matter (b) at the NUTS (Nomenclature of Territorial Units for Statistics) level 1 based on the digitised areas for temporary (TG), permanent (PG) and rough-grazing (RG) grasslands surveyed in 2010 in Great Britain.

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. Irrigation is unlikely to be introduced in UK grasslands and ignored in our analysis but could overcome more frequent summer drought in the future, reducing variation of DMYs. The most striking features of this analysis are the opportunities that arise from closing the yield gap and the evaluation of possible futures for changes in intensity of 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 2) 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, which is reflected in increased yield variation (Tables 2 and 3).

The effect of rising atmospheric [CO_2] on stimulating growth for C_3-plant species such as perennial ryegrass 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] is intricately linked to technological progress, and the net effects (Table 3) are likely to be smaller than the additive gross effects (Table S2 and S3b). Only for rough-grazing grasslands can it be seen that rising [CO_2] compensates only marginally for the negative effects of weather (Table 3). The relative DMY increase is likely to be slightly higher under the medium compared to the low emission scenario (+1.6%) due to the difference in atmospheric [CO_2]. These CFE effects are lower than the difference of relative DMY increase between grassland types (~10% by 2050s) and certainly much smaller than the additive effects of [CO_2] (Table S2) and technology progress (Table S3b). Actual DMY increases due to increased [CO_2] depend on other interacting factors such as soil N fertility (Daepp et al., 2001), water productivity 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 3) the actual additive (CFE and TP) increase of DMYs between 2010s and 2050s is up to 24% and 14%, for temporary and permanent grassland, respectively. This is smaller than the applied, potentially possible, joint CFE and TP factors between 2010s and 2050s, which were 28.0 and 22.0% for temporary and permanent grassland, respectively under the medium emission scenario (Tables S2 and S3b). The efficiency to exploit the CFE and TP effects is lower under permanent than temporary grassland (ca. 63 vs 86%). Usually, permanent grasslands in the UK were kept under the same grass species longer (>5 years) than temporary grasslands (<5 years) because the introduction of new, better adapted cultivars and practices is slower. Compared with 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). This is particularly relevant to perennial ryegrass, which was considered in this study. Longer breeding cycles (15–20 years), inability to exploit heterosis in commercial pasture crop cultivars and selection in the absence of competing neighbour plants are reasons for 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 of 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 allow a step change in grassland productivity (Humphreys, 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 attainable yields (i.e. G × E × M yield) for a given variety grown under defined climatic conditions and agronomic management. Thus, benchmark yields vary, are site- and soil type specific and evolve with time due to difference in weather and technological progress. We calculated the national benchmark DMYs in Great Britain by constraining the blanket grassland productivity to the surveyed areas of each grassland type in 2010 (Table 3). These BAU benchmark DMYs will increase until 2050 under both, low and medium CO_2 emission scenarios by about 8 million tonnes due to rising atmospheric [CO_2] and technological progress.

The UK total potential availability of biomass for feed in 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). Theoretically, based on respective consumption rates for cattle and sheep (Allen et al., 2011), the DM under 2010 BAU could support 18.3 million heads of cattle on improved lowland grassland, and 16.3 million sheep from rough-grazing grassland. Allocating 30% of the permanent grassland to sheep, the potential herd sizes of cattle and sheep (14.1 and 33.2 million, respectively) are larger than reported in the 2010 statistics (10.1 and 31.1 million; Defra, 2015). Theoretically, the gap in herd size corresponds to about 17 million tonnes of unused but potentially available feed from grassland. Considering lower consumption rates for calves and lambs and significant amounts of compound feed used (Guo et al., 2016), it is apparent that grassland is an underutilised feedstock for the livestock sector revealing a considerable yield gap between benchmark and actual on-farm DMYs.

4.4. Closing the productivity gap on temporary and permanent grassland?

The actual on-farm DMYs in either of the two improved grassland systems follow Liebig's law of the minimum with yield-limiting 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 estimated yield gaps of 39–45% are much smaller than suggested by Erb et al. (2018) but we agree with their conclusion that "… future research will need to scrutinize the role of land management […] in non-forest ecosystems". Indeed, this study showed that grassland types must be differentiated in terms of productivity and the yield gap may even be overstated, especially for permanent grasslands of which a substantial proportion will be grazed. Wastes from the livestock would return between 60 and 80 kg N/ha to the grassland, depending on its management intensity (Defra, 2010). Furthermore, the average yield gaps due to suboptimal N-fertiliser applications will vary across grasslands of different natural productivities (DMY at zero N, Fig. 1) due to differences in soil N mineralisation. Nevertheless, the return to recommended higher rates of N-fertilisation are likely to increase N_2O emission by 1 to 2 kgN_2O-N (Bell et al., 2016) with a considerable Global Warming potential. However, recognising grassland distribution and spatially explicit management intensity per grassland type would most certainly improve recent estimates of N_2O emission that assumed a blanket management covering all grassland systems (Fitton et al., 2017).

The annual statistics indicated that the total grassland area gradually declined for about 15 years from 1984, but remained steady until 2015 (Fig. S2). The herd size, however, continued to decline from 12.0 to 9.9 M heads for cattle (including calves) and 42.1 to 33.3 M heads for all sheep, respectively. The decline in animal numbers confirms that temporary and permanent grasslands were an under-exploited resource, either not used for livestock or not performing to their full potential. Attributed to infrequent re-seeding, fertiliser application 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 actual on-farm DMYs is impeded by little empirical information about on-farm DMYs of different grassland types (Oenema et al., 2014). They reported that the on-farm DMYs 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 (Fig. 5) demonstrate the potential influence of changing management patterns on GB grassland DM production. Such information can inform development of land use policy. In the scenarios, use of biophysical and policy constraints to conversion provide a realistic view of changes that could be realised given specific policy drivers. For example, reduction in the intensity of management of 20% of permanent grasslands (Scenario A; Fig. 5) would have limited impact on total GB grassland DM production in 2050 compared to 2010 BAU. This is achieved through adoption of best practice fertiliser application and technological progress, coupled with changes in climate. Alternatively, increased intensity of management of grasslands could make an additional ca. 18 million tonnes per annum of biomass resource available (Scenarios C and D; Fig. 5). These additional resources – plus the 20 million tonnes from closing the yield gap – could be put to multiple uses depending on national priorities. For example, increasing the national herd to support food independence and exports, or as a resource for energy production through routes such as anaerobic digestion (Prochnow et al., 2009; McEniry et al., 2013). A gap of $20 * 10^6$ tonnes could provide up to 12.5% of the total gas output or 25% of the gas imports to the UK in 2017 assuming standard conversion rates from grass biomass to biogas.

Outside biophysical and policy constraints, Scenarios A–D assumed management practices may change across all GB. However, future policy will need to be designed to reflect differing regional priorities. This was explored in Scenario E (Fig. 6), which considered reversion of improved grassland in upland regions of GB. Such a focused policy mechanism would support farmers for the delivery and protection of ecosystem services within grassland systems that are challenging from a production perspective. These ecosystem services 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. Overall, the scenario analysis demonstrates that closing the existing gaps of resource use efficiency present large challenges and opportunities for policy-forced changes.

5. Conclusions

The analysis presented here finds substantial increases of future DMYs that can be achieved in UK grasslands, mainly through a combination of technological innovation and improved agronomy. Based on climate projections to 2050, yield increments are likely to be larger on temporary than on permanent grassland, with little change on rough-grazing, where rising atmospheric [CO_2] compensates adverse weather effects. Across a range of scenarios, we demonstrate considerable scope for maintaining or increasing total GB grassland DMY depending on different assumption about the percentage of grassland that would undergo change, management or land use. Such information is critical for policy makers in the UK who are currently engaged in debate around future pathways for farming and the countryside. The scenarios produced

Table 4

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) (Fig. 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

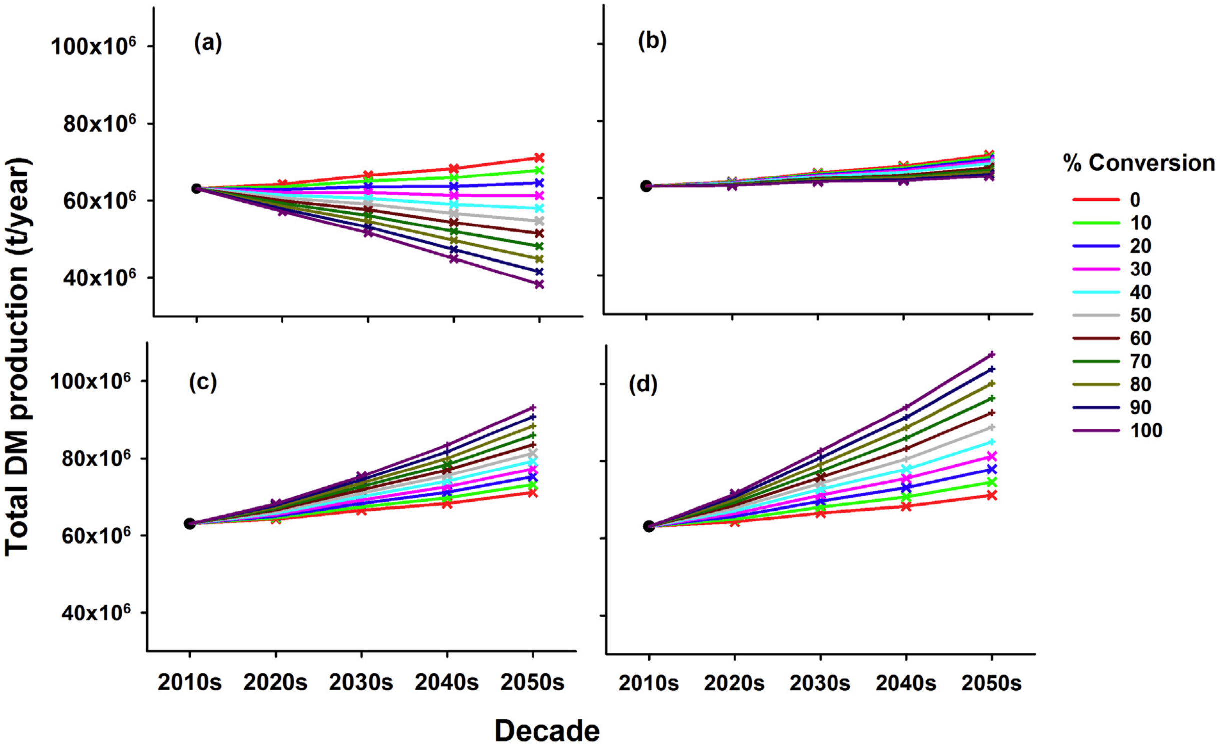

Fig. 5. Changes in total dry matter (TDM) production on grassland in Great Britain (tonnes per year) from 2010 to 2050 under a low CO_2 emission scenario. Scenarios explore: (a) conversion of PG to RG (Abandonment); (b) conversion of TG to PG (Reversion); (c) conversion of PG to TG (Lowland Intensification); (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.

in this study were designed to illustrate the implications of large scale change. To inform policy, the analysis should be further refined to consider local, regional and national priorities for biodiversity and ecosystem services (including production of biomass for energy). Understanding priorities across different scales will allow for a more nuanced consideration of where and how management and land use practices could be altered to deliver benefits to society, and ultimately to consider the best mechanisms to support their delivery.

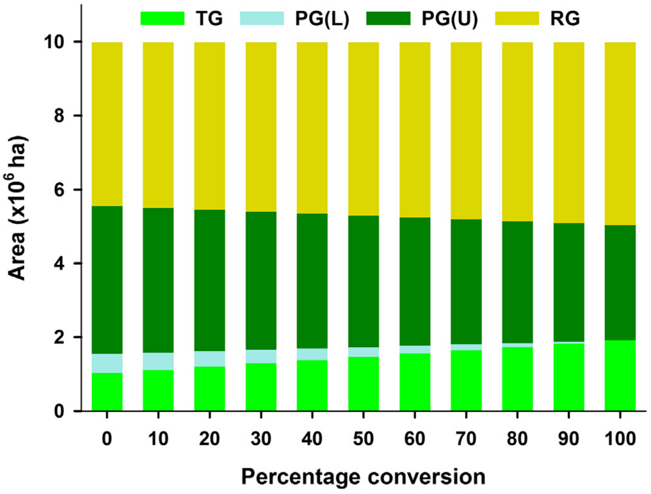

Fig. 6. Changes in total areas in GB of temporary (TG), permanent (PG) and rough-grazing (RG) grasslands with increased percentage of conversion of permanent grassland to rough grazing (Abandonment) in upland regions (PG(U)) maintaining total GB grassland dry matter production (ca. 71,000,000 t per annum) through intensification of PG to TG in lowland areas (PG(L)). Productivity in 2050s under low CO_2 emission scenario.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.03.395.

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