ARTICLE IN PRESS

European Journal of Agronomy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

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

Aiming Qi[a], Philip J. Murray[b], Goetz M. Richter[a,*]

[a] Dpt. of Sustainable Agriculture Sciences, Rothamsted Research, Harpenden, AL5 2JQ, UK
[b] Dpt. of Sustainable Agriculture Sciences, Rothamsted Research, North Wyke, Okehampton Devon, EX20 2SB, UK

ARTICLE INFO

*Keywords:*
Improved grassland
Semi-natural
Sink-source interaction model
Up-scaling
Water balance

ABSTRACT

Estimating spatially resolved grassland productivity is essential for benchmarking the total UK productive potential to assess food, feed and fuel trade-offs in the context of whole systems analyses. Our objectives were to adapt and evaluate a well-known process-based model (PBM) and estimate productivity of improved (permanent, temporary) and semi-natural grassland systems using meta-models (MM) trained by extensive PBM scenario simulations. Observed dry matter (DM) yields in multi-site nitrogen (N) response (0, 150 and 300 kg N ha$^{-1}$) experiments were well emulated describing the average productivity of rough grazing, permanent and temporary grassland (3.1, 7.4 and 9.8 t DM ha$^{-1}$, respectively). Cross-validated with independent and long-term data (Park Grass Experiment), the PBM explained more variation when considering all systems combined (81%) than across all improved grasslands (61%) but little for rough grazing (26%). The PBM-trained MMs explained 48, 72 and 70% of the simulated yield variation in the grasslands of increasing management intensity, and 43 and 75% of observed variation in the combined improved and all three grassland systems, respectively. Considering the assessment of ecosystem services, like drainage and water productivity, PBM scenario simulations are essential. Compared to improved grassland rough grazing will result in 40% more groundwater recharge due to its lower simulated water use and water productivity (12 versus 25 and 43 kg ha$^{-1}$ mm$^{-1}$ for permanent and temporary grassland, respectively).

## 1. Introduction

Grasslands constitute a major part of the global ecosystem and contribute significantly to food security (Hopkins and Wilkins, 2006; O'Mara, 2012). In temperate areas of north-western Europe, grasslands can occupy more than 50 percent of the agricultural area (Chang et al., 2015; Peeters, 2004). In the UK, grasslands occupy about two thirds of the agricultural land area (Defra, 2016) and, therefore, are essential for farming systems. Currently, out of 12.4 million hectares (M ha) about 10% were "temporary" grassland (< 5 years old) and of the permanent grassland (> 5 years old) 6.1 M ha are classified as "permanent" pasture and 5.1 M ha as "rough grazing" (Defra, 2016). Especially the latter are very diverse (Allen et al., 2011; Morton et al., 2011), and productivity estimates must be based on management intensity (Hopkins, 2008). In the UK, temporary grassland is highly productive, fertilised and frequently re-sown in rotation with arable crops, permanent grassland is moderately productive and rarely re-sown whilst rough grazing is extensively grazed, low in productivity and never re-sown.

Spatially explicit grassland productivity data are needed to benchmark the UK productive potential and to assess trade-offs between different ecosystem services within a whole systems analysis of bioenergy value chains (Guo et al., 2016; Turley et al., 2010). Grassland productivity is affected by pedo-climatic variables such as soil available water capacity (SAWC), temperature and precipitation (Brereton et al., 1996) and depends on the level of management inputs (Chang et al., 2015). Empirical statistical (and static) weather-yield models have been used to estimate dry matter (DM) yields for arable crops (Chmielewski and Potts, 1995; Lobell et al., 2011) and grassland (Hurtado-Uria et al., 2014; Jenkinson et al., 1994; Trnka et al., 2006). Process-based models (PBMs) simulate dynamics of grass growth and DM yield for different species (Hoglind et al., 2001; Schapendonk et al., 1998) and nitrogen (N) availability (Barrett et al., 2005; Jego et al., 2013). These PBMs were designed for high frequency cutting systems, e.g. silage (Topp and Doyle, 2004) and modified to accommodate low frequency cutting (hay) and grazing systems (Barrett et al., 2005). The adequacy of these PBMs to estimate yield variations across different environments and management systems (e.g. Hurtado-Uria et al., 2013; Persson et al.,

* Corresponding author.
*E-mail address:* goetz.richter@rothamsted.ac.uk (G.M. Richter).

http://dx.doi.org/10.1016/j.eja.2017.05.002
Received 22 October 2016; Received in revised form 11 May 2017; Accepted 14 May 2017

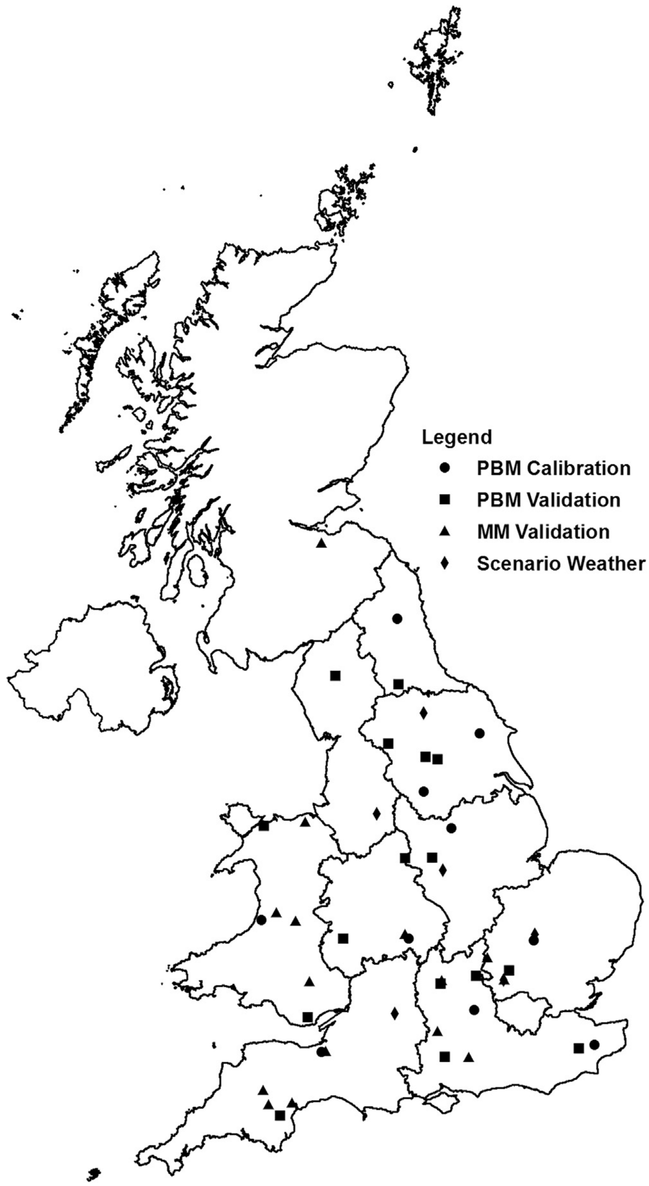


**Fig. 1.** Distribution of sites where multi-year N response experiments were conducted (see **Tables S1** and **S2**). 21 sites by Morrison et al. (1980) plus four sites by Murray (1988), plus PGE (Rothamsted Research, 2006); (●) Set 1: 10 sites to calibrate the process-based model (PBM), Set 2 with 16 sites (■) were used to validate the PBM. Total of 15 sites (▲) were used to validate MMs against independent experimental data (Hopkins et al., 1990; McEwen et al., 1989; and Jones et al., 2006).

2014) encourages scenario simulations over a wide range of pedo-climatic inputs (Smit et al., 2008). Their power lies in the integration of long-term observations at a single site (Jenkinson et al., 1994) and short-term experiments over a wide range of sites (Hoglind et al., 2001).

Both, PBMs and statistical models were used to analyse the effect of past weather on observed and attainable yields (Jaggard et al., 2007; Lobell et al., 2011), and the impact of climate change (Lobell and Burke, 2010; Soltani et al., 2016; Wilcox and Makowski, 2014). Trained statistical models ("meta-models") using simulated yields conserve the principal biophysical interactions, capture the difference between systems and avoid the PBMs' requirements for daily weather data (Van Ittersum et al., 2003). Although meta-models (MMs) were not tested against observations of spatially explicit crop productivity at the national or regional scale, they should be reliable proxies for PBMs to estimate spatially explicit crop productivity over large areas (Soltani et al., 2016).

Our objectives are to (1) calibrate and evaluate a PBM for the above mentioned grassland systems in the UK using DM yields measured in experiments performed in the 1970s and 1980s; (2) generate a panel of simulated baseline DM yields for a wide range of soil types in combination with long-term historic weather data across the country; (3) derive MMs for each grassland type incorporating aggregated bioclimatic variables and SAWC; and (4) assess the validity of the MMs in relation to measured DM yields. From the PBM outputs indicators of the water balance and productivity (WP) are derived for each grassland system to discuss opportunities and limitations of the MM approach in terms of the overall objective to assess different ecosystem services (e.g. yield and water use).

## 2. Materials and methods

### 2.1. Experimental systems and data for calibrating and validating the PBM

We considered three systems: temporary grassland, permanent grassland and rough grazing to estimate productivity. Temporary grasslands are the most productive, often consisting of frequently re-sown perennial ryegrasses (*Lolium perenne*) and receive a recommended annual N application rate of *ca.* 300 kg N ha$^{-1}$ (Defra, 2010). Permanent grasslands consist of a mixture of sown and indigenous grasses and legumes; they are of intermediate productivity and receive moderate inputs (annual N applications of *ca.* 150 kg N ha$^{-1}$). However, these recommended N application rates may not be followed on all temporary and permanent grasslands. The extensively used rough grazing are diverse semi-natural grasslands containing various herbaceous species, receive no synthetic N and are areas of low productivity. In the following these systems are termed temporary (300N), permanent (150N) and rough-grazing (0N).

#### 2.1.1. Dry matter yield data

Annual DM yields for calibration and validation were mainly compiled from two N response experiments at multiple sites in England and Wales (Fig. 1; **Table S1**). Data came from re-sown temporary grassland after barley on 21 sites between 1970 and 1973 (Morrison et al., 1980) and from permanent and re-sown grassland on four sites between 1983 and 1986 (Murray, 1988). From both sources DM yield data were selected on 300N, 150N and 0N plots as proxies for temporary, permanent and rough-grazing grassland, respectively. The respective average DM yields were 9.8, 7.4 and 3.1 t ha$^{-1}$ (Table 1), the distribution of the measured DM yields on the 0N plots was slightly skewed due to some exceptionally high yields caused by residual N from the previous arable crop (Fig. S1). For further validation, long-term DM yields were taken from the ongoing Park Grass Experiment (PGE) at Rothamsted Research, using plots with a 0N and 144N treatment from 1960 onward (Fig. S2, plot 3a and 11/1a; pH of 7). These represent respective long-term equilibria for semi-natural and permanent grassland with mixed species and late cutting dates in a wide range of fertiliser and liming treatments (Silvertown et al., 2006). DM yields for further model validation were available for temporary

**Table 1**
Calculated descriptive yield (t ha$^{-1}$) statistics for no fertiliser input (0 kg N ha$^{-1}$, rough-grazing), moderate fertiliser input (150 kg N ha$^{-1}$ or 144 kg N ha$^{-1}$ in case of PGE data, permanent grassland) and high fertiliser input (300 kg N ha$^{-1}$, temporary grassland) pasture grass experiments used for calibrating and validating the process-based model.

| Grassland type | Average | Median | 25th | 75th | SD | Skewness |
|---|---|---|---|---|---|---|
| Rough-grazing | 3.09 | 3.04 | 2.02 | 4.11 | 1.56 | 0.51 |
| Permanent grassland | 7.41 | 7.32 | 5.79 | 9.01 | 2.02 | 0.04 |
| Temporary grassland | 9.76 | 9.61 | 8.34 | 11.14 | 2.03 | 0.01 |