Combining satellite data and agricultural statistics to map grassland management intensity in Europe

Stephan Estel1,6, Sebastian Mader2, Christian Levers1, Peter H Verburg3,5, Matthias Baumann1 and Tobias Kuemmere1,4

1 Geography Department, Humboldt-University Berlin, Unter den Linden 6, 10099 Berlin, Germany
2 Trier University, Faculty VI, Geography/Earth Sciences, Environmental Remote Sensing and Geoinformatics, 54286 Trier, Germany
3 Department of Earth Sciences, VU University Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, Netherlands
4 Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-University, Unter den Linden 6, 10099 Berlin, Germany
5 Swiss Federal Research Institute WSL, Birmensdorf, Switzerland
6 Author to whom any correspondence should be addressed.

Abstract

The world’s grasslands, both natural and managed, provide food and many non-provisioning ecosystem services. Although most grasslands today are used for livestock grazing or fodder production, little is known about the spatial patterns of grassland management intensity, especially at broad geographic scales. Using the European Union as a case study, we mapped mowing frequency as a key indicator of grassland management intensity. We used MODIS NDVI time series from 2000–2012 to map mowing frequency using a spline-fitting algorithm that detects up to five mowing events within a single growing season. We combined mowing frequency maps with existing maps of livestock distribution and grassland management frequency to identify clusters of similar grassland management intensity across Europe. Our results highlight generally high mowing frequency in areas of high grassland productivity, especially in Ireland, northern and central France, and the Netherlands. Our analyses also show distinct clusters of similar grassland management, representing different grassland-management intensity regimes. High intensity clusters occurred particularly in western and southern Europe, especially in Ireland, in the northern and central parts of France and Spain, and the Netherlands but also in northern and southern Germany and eastern Poland. Low intensity clusters were found mainly in central and eastern Europe and in mountainous regions but also in Extremadura in Spain, Wales and western England (UK). Generally, our analyses emphasize the usefulness of jointly using satellite time series and agricultural statistics to monitor grassland intensity across broad geographic extents. Our maps allow for a new, spatially-detailed view of management intensity in grassland systems and may help to improve regionally targeted land-use and conservation policies.

1. Introduction

Grasslands cover more than 40% of the Earth’s land surface and are widely used for livestock grazing and fodder production, thereby contributing to global food production in major ways (FAO 2006). As the global human population continues to grow and diets become richer in animal-based products, the production of grassland-based livestock products increase as well (Thomas et al 2014, Keyzer et al 2005, Thornton 2010). This in turn puts further pressure on the world’s grasslands and affects their functioning and biodiversity (FAO 2006, Hopkins 2006, Laliberté et al 2010).

Besides food, grasslands provide a range of ecosystem services, many of which are non-provisioning in nature. Grasslands store around 15% of the global organic carbon (Tate and Ross 1997), protect soil fertility, control soil erosion, and influence the hydrological
cycle (Lemaire et al 2005, Sanderson et al 2007, Weigelt et al 2009). In addition, natural grasslands as well as semi-natural grasslands, a result of a long land-use history, are among the species-richest vegetation communities in the world, and therefore have an important conservation value (Dengler et al 2014, Batáry et al 2015, Linnell et al 2015). However, biodiversity and the flows of ecosystem services from grassland systems strongly depend on management intensity (Laliberté et al 2010). Hence, understanding spatial patterns in management intensity in grassland systems is crucial, yet knowledge about this is currently limited, in particular across large spatial extents.

In most grassland systems, management intensity relates to three dimensions: mowing frequency, fertilization, and grazing pressure (Blüthgen et al 2012, Allan et al 2014). Jointly assessing these dimensions is challenging, since they are not independent from each other (Bernhardt-Römermann et al 2011, Herzog et al 2006). For example, fertilizer is often used to foster higher mowing frequency (Bernhardt-Römermann et al 2011), and grazing and mowing are not always mutually exclusive, as nitrogen release from livestock may increase biomass and thus allow for mowing later in the season (Blüthgen et al 2012).

Understanding grassland management intensity is often further hindered by the lack of appropriate data and monitoring systems (Garnett et al 2013, Thornton and Herrero 2010). While satellite remote sensing is the main tool for mapping land use/cover changes (Pettorelli et al 2014, Rindfuss et al 2004), mapping grassland management intensity directly from satellites images remains difficult (Kuemmerle et al 2013, Verburg et al 2011). As a result, only a few studies have mapped grassland management intensity across large areas, all of them only indirectly. For example, the spatial distribution of livestock in Europe was modeled using statistical downscaling of province-level livestock statistics (Neumann et al 2009). Similarly, the fertilizer application was downscaled using nitrogen input statistics at NUTS2 level and livestock distribution (Temme and Verburg 2011). At the global scale, the spatial distribution of livestock was mapped using subnational livestock statistics (Wint and Robinson 2007), which then were used to map livestock production systems (Robinson et al 2014). Global patterns of fertilizer application and manure production were also disaggregated from agricultural statistics (Potter et al 2010). All of these studies were restricted to relatively coarse spatial resolutions, did not consider changes over time, and used partly uncertain statistical data (Verburg et al 2011, Kuemmerle et al 2013, Zaks and Kucharik 2011). A consistent and spatially-detailed assessment of grassland management intensity has not been carried out for any larger region.

Satellite image time series can help to fill this gap. Grassland management often results in only subtle changes in vegetation (e.g. via extensive grazing) or alters the vegetation signal only over short time periods (e.g. via mowing) after which the signal quickly recovers. Dense time series of medium-resolution imagery, such as those from the Moderate Resolution Imaging Spectroradiometer (MODIS), can capture such subtle vegetation and biomass changes, and separate phenological change from management effects (Friedl et al 2010). For example, MODIS Normalized Difference Vegetation Index (NDVI) time series were used to quantify grazing intensity in Inner Mongolia (Kawamura et al 2005). The impact of livestock grazing was monitored using NDVI time series in northern Kenya (Ritchie 2015) and the Gobi desert (Hilker et al 2014). Likewise, the frequency of fallow years on farmland, including pastures, were mapped European wide using a random forest classifier and MODIS NDVI time series (Estel et al 2015). Small scale studies suggest mowing can be captured well with satellite image time series (Asam et al 2015). Moreover, cropping cycles, which are phenologically similar to mowing cycles, have been successfully mapped for Europe (Estel et al 2016), Brazil (Galford et al 2008, Spera et al 2014), India (Biradar and Xiao 2011), the Mekong Delta (Sakamoto et al 2009), China (Le et al 2014), and the mid-western United States (Wordell and Egbert 2008). This suggests that the potential of satellite imagery to derive broad-scale indicators of grassland management intensity has not been fully explored.

Our goal here was to map the spatial patterns of mowing, a key parameter of grassland management intensity. We developed a MODIS-based approach to capture mowing frequency within and across growing seasons across the EU. Our second goals was to combine the resulting mowing maps with existing indicators of livestock distribution and grassland management frequency to map broad grassland management regimes. The EU is an interesting case study in this regard, because it includes 57 million hectare (Mha, in 2007) of permanent grasslands (Huyghe et al 2014), distributed across strong environmental gradients, from the boreal to the Mediterranean zones, and managed at varying intensity, from traditional to agri-business farming. Europe’s long agricultural history has resulted in widespread semi-natural grasslands characterized by high aesthetic value, rich cultural heritage, and high farmland biodiversity (Angelstam et al 2003, Poschlod and Bonn 1998, Stoate et al 2009). These landscapes are threatened by both, intensification (Henle et al 2008, Klein et al 2009), and abandonment (Gellrich et al 2007, Kuemmerle et al 2011). Better knowledge about the spatial patterns of grassland management intensity is therefore important to identify where semi-natural grasslands are at risk (Strijker 2005).

Specifically, we assessed the following research questions:

1. What are the spatial patterns of mowing frequency across the EU’s grasslands, as mapped from MODIS NDVI time series?
2. How do mowing frequency and indicators of livestock distribution on grasslands combine to determine clusters of similar grassland management intensity across Europe?

2. Data and methods

Our study region encompassed 27 EU-countries (EU-27) covered by the CORINE 2000 (Coordinated Information on the European Environment, (EEA 2012)) grassland classes ‘Pasture’ and ‘Natural grassland’ at a resolution of 100 × 100 meters (SI, figure S2 available at stacks.iop.org/ERL/13/074020/mmedia). Our approach to capture the grassland management intensity consisted of four steps. First, we derived mowing frequency maps based on the MODIS NDVI time series and a spline analysis (SPLIT). This yielded the number of mowing events from 2001–2012 as well as the average number of mowing events for years where management was detected. Second, we used MODIS NDVI time series to map fallow/active grassland annually and subsequently the grassland management frequency (i.e. the number of years grassland were found to be managed from 2001–2012). Third, to capture grazing intensity and organic fertilizer input to grasslands, we used existing, downscaled livestock distribution data. Finally, we combined all three indicators and mapped spatial clusters of similar grassland management across the EU using self-organizing maps.

2.1. Grassland management frequency

The grassland management frequency is a result of our own previous work (Estel et al 2015), where we had generated annual maps of fallow (neither mown nor intensively grazed) and managed grassland from 2001–2012. The grassland management frequency, which do not separate mowing from other management activities, was derived by counting how many years a grassland pixel was identified as managed. That means we calculated the sum of managed years for each pixel across the entire time series from 2001–2012, (for a more details see the SI or Estel et al (2015)).

2.2. Mowing frequency

Knowledge about how often a grassland is mown within a growing season is important since higher mowing frequency is often reached by fertilizer application with possible negative environmental effects. To calculate mowing frequency, we used a pre-processed MODIS NDVI time series (2000–2012) from both MODIS sensors onboard the satellites Aqua and Terra. The preprocessing was conducted to improve the quality of the NDVI time series and their comparability across Europe, considering the strong climate gradients (for a more detailed description of the pre-processing see supporting information or Estel et al (2015)).

Our approach based on spline analysis (SPLIT) and followed the assumption that mowing represents a disturbance-type event during the phenological course of grassland. Fallow or unmanaged grassland is typically characterized by a smooth, bell-shaped NDVI profile over the growing season (figure 1). In contrast, a mowing event leads to abrupt changes in the grassland profile, which thus differ substantially from unmanaged grasslands (i.e. multiple peaks and troughs between them due to mowing events (Estel et al 2015)). Using these distinct features, we mapped the number of mowing events by counting the number of troughs in the NDVI profile within each year over the full time period (SI, figure S3), assuming that these represent mowing (Asam et al 2015, Schuster et al 2015).

To capture sequences of peaks and troughs within one year, we used the spline analysis of time series (SPLITS) algorithm, which describes time series based on polynomial B-spline models (for detailed information about SPLITS see SI and (Mader 2012). As this algorithm detects all troughs regardless of their size, it is necessary to select relevant troughs which represent mowing (figure 1). We determined the optimal threshold above which a trough was counted as a mowing event by first counting mowing events for a wide range of candidate thresholds along the trough, ranging from 0%–90% (in 10% steps). Second, we selected a random sample of 25 points for each of our six classes (from no mowing to five mowing events) from the threshold-free mowing frequency map (0%). We then cross-checked the resulting 300 points for the years 2009 and 2012 by visual interpretation of the normalized NDVI profile and counted the apparent troughs. Next, we selected the threshold (from 0%–90%) with the highest agreement between mowing events identified visually and by our algorithm and used this threshold for all further analyses (SI, figure S1). Once mowing frequency was mapped for each year, we mapped subsequently, for each pixel the average number of mowing events for all years where management was detected in our previous study (Estel et al 2015).
To test the robustness of our mowing model, respectively the ability of our algorithm to detect troughs, we used another 300 randomly selected points for a visual interpretation of the normalized NDVI time series and calculated standard accuracy metrics for the 10% threshold (Foody 2002, Olofsson et al 2013), including an error matrix, overall accuracy, and class-wise user’s and producer’s accuracies (see SI for details). In addition, we compared our mowing frequency to a large sample of ground observations of mown or unmown grassland, available from the land use/land cover area frame survey (LUCAS) conducted in 2009 (23 countries) and 2012 (27 countries) (for detailed information about LUCAS data see SI or Estel et al 2015).

2.3. Livestock distribution

We used maps of disaggregated statistics on ruminant livestock (Neumann et al 2009, Temme and Verburg 2011) to capture grazing intensity and organic fertilizer input to grasslands. High livestock density can indicate high grazing intensity on pastures where livestock is free-ranging during the growing season. Conversely, where livestock is principally kept in shelters and feedlots, high livestock density is related to elevated levels of fertilization on grassland, due to the necessary distribution of excrements coming from concentrated livestock rearing. Thus, our livestock distribution maps are first-order proxies of both, grazing pressure and organic fertilizer input, though our indicator does not consider high grazing intensity on pastures where livestock is principally kept in shelters and feedlots. We used livestock statistics of cattle, sheep, and goats available at NUTS-2 level and re-classified them into four livestock unit (LSU) classes: (1) 0–25 LSU km\(^{-2}\), (2) 25–50 LSU km\(^{-2}\), (3) 50–100 LSU km\(^{-2}\), and (4) >100 LSU km\(^{-2}\). These NUTS-level data were then transferred to a 1 km grid using a statistical downscaling approach based on regional regression models (Neumann et al 2009, Temme and Verburg 2011).

2.4. Typical cluster of grassland management intensity

Grassland management systems differ widely across Europe due to various agro-ecological conditions and management practices. To identify and characterize those systems we used Self Organizing Maps (SOMs), a topology-preserving clustering algorithm (Kohonen et al 2001), and the three grassland management indicators mowing frequency, grassland management frequency, and livestock distribution. SOMs are an unsupervised clustering technique that reduces a high-dimensional dataset to a two-dimensional map by grouping observations according to their similarity in feature space (Skupin and Agarwal 2008). To identify the optimal number of clusters, we carried out an optimization routine with SOM clusters varying from 2–25 clusters and selected the optimal SOM dimensionality using the Davies-Bouldin index. This index is a cluster separation measure useful to analyze the intra- and inter-cluster variability of data sets in terms of similarity with lower values indicating more homogeneous clusters that are better separated (Davies and Bouldin 1979, Estel et al 2016, Levers et al 2018). The cluster analysis was carried out using the R packages kohonen (Wahrens and Buydens 2007) and clusterSim (Walesiak and Dudek 2014).

3. Results

Applying the SPLITS algorithm on the normalized MODIS NDVI time series yielded reliable mowing frequency maps. Capturing true mowing events from the MODIS NDVI time series using SPLIT required setting a threshold. We tested a wide range of thresholds and the optimal threshold occurred at a change magnitude of 10% (i.e. smaller change magnitudes were not considered as a mowing event). This resulted in a series of annual maps showing four classes (i.e. none, one, two, and three or more mowing events) for the time period 2001–2012. Due to the very small number of pixels with more than three mowing events, we aggregated those pixels into a single class. Evaluating this final set of annual mowing maps revealed an average overall accuracy of 80%. Producer’s and user’s accuracy of the class ‘no mowing’ were highest, ranging between 70% and 90% with an average of 87%. In general, the mowing classes showed decreasing accuracies with increasing mowing frequency (table 1).

The comparison of our mowing maps and the LUCAS surveys from 2009 and 2012 showed an agreement of approximately 89% (2009) and 93% (2012) between LUCAS points labelled as unmanaged grassland and our unmown class (figure 2). Conversely, for around 85% (2009) and 94% (2012) of the points labelled by the LUCAS observers as managed (not grazing), we found at least one mowing signal. This combines to an overall accuracy of around 87% (2009) and 93% (2012).

Table 1. Producer’s, user’s, and overall accuracies of mowing frequency classes for the years 2009 and 2012, derived by cross-checking 300 random points against the normalized NDVI profiles and counting the apparent troughs visually.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Producer’s accuracy</th>
<th>User’s accuracy</th>
<th>Overall accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>No mowing</td>
<td>0.92</td>
<td>0.90</td>
<td>0.73</td>
</tr>
<tr>
<td>One mowing event</td>
<td>0.74</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>Two mowing events</td>
<td>0.88</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>Three or more mowing events</td>
<td>0.37</td>
<td>0.27</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Around 64% of the EU’s grassland were mown one or more times per year; around 40% were mowed every year, 20% of all grasslands two times each year, and 4% three times or more. We found a clear divide between western and southern Europe, with high mowing frequency (more than two events per year) especially in Ireland and northern France and medium mowing frequency (more than one mowing events per year). Higher frequency can also be found in some regions in southeastern Europe (e.g. Hungary, Romania, and Bulgaria). Low mowing frequency occurred especially in central and eastern Europe, but also in western and northern UK and in mountain regions (e.g. Alps, Pyrenees, Carpathians, Massif Central, figure 3).

Our grassland management frequency indicator showed that around 74% of Europe’s grasslands were managed in more than six years. The highest grassland management frequencies occurred again in Ireland, the southern UK, France, Spain, and the Netherlands. The lowest management frequencies were located mainly in mountain regions (e.g. Alps, Pyrenees, and Carpathians) and in eastern Europe (figure S4).

Mapping grassland management systems across Europe using SOMs revealed six clusters with distinct combinations of mowing frequency, grassland management frequency, and livestock distribution. To describe these clusters, we provide, for each intensity indicator, averaged z-scores across all grid cells within a clusters. Positive and negative z-scores indicate above or below average values, respectively, whereas values close to zero indicate values close to the overall mean of this indicator for the entire study area (figure 4). When referring to the z-scores of our indicators, we use the categorization high (z-score >1), medium (0.5<z-score<1), low (z-score<0.5). To further ease the interpretation we formed three intensity groups. Based on the z-scores’ positive deviation from zero we grouped clusters into three groups: high (z-score>1), medium (0.5<z-score<1), low (z-score<0.5): high intensity cluster C1 and C2, medium intensity cluster C3 and C4, and low intensity cluster C5 and C6. Note: indicators are not additive. If only one indicator is high the cluster belongs to the high intensity group regardless of the value of the other two indicators.

Clusters 1 and 2 contained at least one indicator with a high positive z-score and can therefore be interpreted as high-intensity clusters. Cluster 1 was characterized by a very high positive z-score for livestock density (+1.68), but medium negative z-scores for grassland management frequency (−0.40) and mowing frequency (−0.81). This cluster was most widespread in northern and southern Germany and the Netherlands, but also in Ireland and in the UK. Cluster 2 had the highest grassland management intensity and was determined by a high positive z-score for livestock density (+1.3) and medium positive z-scores for grassland management frequency (+0.65) and mowing frequency (+0.71). Cluster 2 occurred predominantly in North-West Europe, especially in Ireland, Wales, the Netherlands and northern France.

Clusters 3 and 4 contained at least one indicator with moderately positive z-scores (0.5<z-score<1) and no high positive z-scores. Thus they be referred to as management systems with a medium grassland management intensity. Cluster 3 showed medium positive z-scores for grassland management frequency (+0.78) and mowing frequency (+0.98) and low negative z-scores for livestock density (−0.42) and was located in Ireland, northern and central France, UK, and northern and central Spain and Greece. Cluster 4 had a medium positive mowing frequency (+0.78), medium negative livestock density (−0.92) and a very high negative grassland management frequency. Cluster 4 occurred almost exclusively in the Alps and Pyrenees.

Clusters 5 and 6 had generally low (negative or close to zero) z-scores and are therefore best-described as low-intensity management regimes. Cluster 5 was characterized by low positive grassland management frequency (+0.07), medium negative mowing frequency (−0.53), and medium negative livestock density (−0.58). This cluster occurred mainly in Northern Ireland, the UK, the Netherlands, Germany, and Hungary. Finally, Cluster 6 had the lowest grassland
Figure 3. Spatial distribution of the average mowing frequency (i.e. the average number of mowing events for all years where management was detected).

Figure 4. Cluster of similar grassland management systems, mapped using self-organizing maps, and the positive and negative z-scores (i.e. the amount of standard deviations from the global mean) of each indicator characterizing these cluster.
management intensity, characterized by medium negative livestock density (−0.53), high negative mowing frequency (−1.16) and high negative grassland management frequency (−1.44). This cluster was mainly located in northern and southern Germany, the UK, the Extremadura (Spain), mountainous areas (e.g. Carpathians, central France), eastern Poland, and Latvia.

4. Discussion

4.1. Mapping mowing frequency from satellite images

We carried out the first regional-to-continental scale mapping of mowing frequency based on satellite image time series. Our robustness checks, based on randomly-selected validation points and ground-visited LUCAS points, suggest a reliable separation of mown from unmown grasslands. Our mowing frequency map also corresponded well with maps of grassland productivity in Europe (Smit et al 2008), with more frequent mowing where grassland yields are highest. Assessing the mowing frequency patterns we found, most grassland in Europe were characterized by a relatively low number of mowing events (around 40% of all grasslands were mown once per year). One reason for this may lie in the growing importance of feed crops, which replace forage from grasslands (Huyghe et al 2014).

Consistently high mowing frequency (three or more mowing events per year) occurred mainly in Ireland and southern France, where grasslands are highly productive, and grass-fed livestock is still common (Huyghe et al 2014). Our analyses also showed that the spatial patterns of mowing frequency and grassland management frequency (i.e. 2001–2012) were very similar. This suggests grassland management has been relatively stable over the twelve years we assessed, and that the most intensively managed grasslands occur in a few European regions only (Huyghe et al 2014).

4.2. Combining satellite data and agricultural statistics

Combining our mowing frequency maps with maps of grassland management frequency and livestock distribution highlighted distinct cluster of grassland management frequency across Europe. Three factors appear to explain these patterns and clusters. First, highest grassland intensity occurs in regions with the highest grassland productivity (Huyghe et al 2014, Smit et al 2008), suggesting a concentration on the most suitable sites. We identified two high-intensity clusters (Cluster 1 and 2), corresponded well with areas known for a specialization on intensive livestock or dairy production (Levers et al 2018), especially in the Netherlands, Belgium, northern and southern Germany and Ireland (Robinson et al 2014). Especially, Cluster 2 was clearly related to Europe’s highest dairy cattle densities (Neumann et al 2009) and can thus, despite relatively low mowing and grassland management frequency, be considered highly intensified, a pattern that would have been hard to detect with satellite data alone.

Second, lower grassland management intensity was often found in socio-economically marginal regions facing rural depopulation and abandonment (Cramer et al 2008, Stellmes et al 2013), which receive lower production support for agriculture (LNV 2004), and where marginal agro ecological conditions inhibit grassland intensification (Gellrich and Zimmermann 2007, Griffiths et al 2013, MacDonald et al 2000). Accordingly, we found intermediate grassland management intensity in these areas (Clusters 3 and 4), with lower levels of livestock density but higher mowing frequency, suggesting a concentration on fodder production. Cluster 4 appears to represent the typical grassland management of mountain areas, predominately found in the Alps and Pyrenees, with the fairly low grassland management frequency corresponding to extensive grazing (e.g. transhumance grazing) and low mowing frequency, as documented for wide areas in these mountain ranges (MacDonald et al 2000).

Finally, we found a clear East-West divide in grassland management intensity, likely at least in part a legacy from socialist land management (Lerman and Shagaida 2007, Lerman 2005). Despite substantial intensification during socialism, intensification started later and progressed slower, and many eastern European areas never reached the intensity levels of western Europe (Jepsen et al 2015, Niedertscheider et al 2014, Rozelle and Swinnen 2004). Substantial farmland abandonment occurred in eastern Europe during the 1990s (Alcantara et al 2013, Baumann et al 2011, Kuemmerle et al 2008), and many of these lands remain abandoned (Estel et al 2015). While eastern Europe’s farmers now have access to subsidies under the EU’s common agricultural policy (CAP), the full effect of these, both in terms of production-oriented payments and agro-environment schemes, has yet to unfold (Niedertscheider et al 2014, Sutcliffe et al 2015). Beside the East-West divide we found low intensity cluster (Cluster 6 and Cluster 5) related to widespread long fallow periods or land abandonment. Additionally, Cluster 5 appears to coincide strongly with semi-natural grasslands, which are generally characterized by lower grassland use intensity (Levers et al 2018, Paracchini et al 2008) and high conservation value (Batáry et al 2015).

4.3. Uncertainty

Our validation efforts suggest a robust separation of mown and unmown grasslands and our clusters align plausibly with case study knowledge and known areas of high or low grassland management intensity. Still, a number of sources of uncertainty, and room for improvement, must be noted. First, the accuracy assessment validates the ability of our algorithm to detect
troughs. We are convinced that most of these troughs do in fact represent mowing events, but we cannot make this claim based on the visual inspection of the time series alone, as described in the method section.

Second, we used a conservative grassland mask, which excluded complex mosaic landscapes. Since cropping (e.g. ploughing) results in similar disturbance-type response in NDVI profiles as mowing, and because fields in such mosaic landscapes can be much smaller than a MODIS pixel size (~5.4 ha), reliable mapping of mowing in complex mosaics is challenging and time series of higher resolution data, such as from Landsat or Sentinel satellites, are needed. Mosaic classes are particularly widespread in northwestern France, parts of Belgium and the Netherlands, the Iberian Peninsula, and eastern Europe, where our maps may underestimate the extent and/or intensity of grassland management.

Third, we assume an abrupt change in the NDVI profile of grasslands represents mowing, but we cannot fully rule out that other management practices, such as transhumance and rotational or very intensive grazing, also result in mowing-like signals. Fourth, our method is based on selecting a threshold to define a discrete mowing event. We used one threshold for all of Europe. A more regionalized threshold selection could improve our mapping to account for variations in grassland types and climate regions across Europe, but this would ideally also require more, and geographically distributed, ground truth data on actual mowing events in order to validate regionalized thresholds. We are not aware of any such dataset covering larger areas, such as our study region.

Fifth, while our algorithm reliably separated mown areas from unmanaged ones, there was relatively low user’s and producer’s accuracies for the class that included three or more mowing events per year. One reason for this might be the sudden drop of the NDVI after snow fall, which can lead to a deep trough especially at the end of the growing seasons, which in turn results in erroneous detection of mowing events. This problem occurs especially in regions with a very short growing season such as in Iceland or northern Scandinavia. A more regionalized analysis could improve the detection of mowing events for these areas, but was beyond the scope of this analysis. Finally, the livestock distribution data were not mapped at the pixel-scale, but derived using downscaling procedures. Detailed, gridded observational data are not available at a European wide scale, and these maps are the best data available at present.

5. Conclusion

Grasslands play an important role in global food production, provide important ecosystem services, and support unique biodiversity. Grassland management intensity affects all of these in major ways, yet little is known about spatial patterns in management intensity, especially at broad geographic scales. We developed a MODIS-based mowing frequency indicator and integrated this indicator with downscaled livestock statistics, a proxy for grazing and/or fertilizer intensity, and another MODIS-based grassland management frequency index. Our maps show that spatial patterns of high grassland management intensity generally corresponded well with areas of high grassland productivity, with the highest intensity in Ireland, northern and central France, and the Netherlands, and lowest intensity in Extremadura in Spain, western UK, eastern Europe, and most mountain regions. We identified six clusters with distinct but typical grassland management intensity, reflecting different socio-economic and environmental conditions, and thus likely different environmental impacts of grassland management. This highlights the potential value of our mapping to provide a high-level template for regionalized policies that strive to maintain grasslands, to lessen the environmental impact of grassland intensification, or protect grassland biodiversity (Fischer et al 2012, Lefebvre et al 2012). For example: the EU aims to reduce carbon emissions from agriculture by, among other measures, maintaining permanent grasslands (Gocht et al 2016), and our analyses highlight where such grasslands that indeed receive low management pressure are located. More broadly, our analyses highlight how the combination of satellite image time series and agricultural statistics can help to assess broad-scale grassland management intensity patterns.

Acknowledgments

We gratefully acknowledge financial support by the Einstein Foundation Berlin (Germany) and the European Commission (VOLANTE, No. 265104 and HERCULES, No. 603447). We thank P Hostert, T Plieninger, and K-H Erb for fruitful discussions. We are grateful for the thoughtful and constructive comments of two reviewers and an associate editor that improved this manuscript in major ways.

ORCID iDs

Stephan Estel  🏛️ https://orcid.org/0000-0002-7583-9252

References

Alcantara C et al 2013 Mapping the extent of abandoned farmland in central and eastern Europe using MODIS time series satellite data Environ. Res. Lett. 8 35035
Allan E et al 2014 Interannual variation in land-use intensity enhances grassland multidiversity Proc. Natl Acad. Sci. 111 308


Paracchini M L, Petersen J E and Hoogeveen Y 2008 High Nature Value Farmland in Europe. An Estimate of the Distribution Patterns on the Basis of Land Cover and Biodiversity Data (Italy: European Commission, Joint Research Center, Institute for Environment and Sustainability)

Pettorelli N, Laurance W F, de Vries W and Mangerud J 2014 Changes in dispersal processes in the central European landscape since the last ice age: an explanation for the actual decrease of plant species richness in different habitats Acta Botanica Neerlandica 1/49 27–44

Potter P, Ramanukuty N, Bennett E M and Donner S D 2010 Characterizing the spatial patterns of global fertilizer application and manure production Earth Interact 14 1


Poschlod P and Bonn S 1998 Changing dispersal processes in the central European landscape since the last ice age: an explanation for the actual decrease of plant species richness in different habitats Acta Botanica Neerlandica 1/49 27–44

Poschlod P and Bonn S 1998 Changing dispersal processes in the central European landscape since the last ice age: an explanation for the actual decrease of plant species richness in different habitats Acta Botanica Neerlandica 1/49 27–44


Poschlod P and Bonn S 1998 Changing dispersal processes in the central European landscape since the last ice age: an explanation for the actual decrease of plant species richness in different habitats Acta Botanica Neerlandica 1/49 27–44

Potter P, Ramanukuty N, Bennett E M and Donner S D 2010 Characterizing the spatial patterns of global fertilizer application and manure production Earth Interact 14 1


Robinson T P et al. 2014 Mapping the global distribution of livestock PLoS ONE 9 e96084

Rozelle S and Swinnen J F M. 2004 Success and failure of reform. Insights from the transition of agriculture J. Econ. Lit. 42 404–56


Smit H J, Metzger M J and Ewert F 2008 Spatial distribution of grassland productivity and land use in Europe Agric. Syst. 98 208–19

Spera S A, Cohn A S, VanWey L K, Mustard J F, Rudorff B F, Risso J and Adami M 2014 Recent cropping frequency, expansion, and abandonment in Mato Grossso, Brazil had selective land characteristics Environ. Res. Lett. 9 64010

Stellmes M, Röder A, Udelhoven T and Hill J 2013 Mapping syndromes of land change in Spain with remote sensing time series, demographic and climatic data Land Use Policy 30 685–702


Strijker D 2005 Marginal lands in Europe—causes of decline Basic Appl. Ecol. 6 99–106

Sutcliffe I M E et al. 2015 Harnessing the biodiversity value of central and eastern European farmland Divers. Distrib. 21 722–30

Tate K R and Ross D J 1997 Elevated CO2 and moisture effects on soil carbon storage and cycling in temperate grasslands Glob. Change Biol. 3 225–35


