How is biodiversity protection influencing the potential for bioenergy feedstock production on grasslands?

(article starts on next page)

Received: 16 March 2018 | Accepted: 29 August 2018

DOI: 10.1111/gcbb.12568

ORIGINAL RESEARCH

WILEY GLOBAL CHANGE BIOLOGY BIOENERGY

How is biodiversity protection influencing the potential for bioenergy feedstock production on grasslands?

Julia Hansson[1,2] | **Göran Berndes**[3] | **Oskar Englund**[3] | **Flávio L. M. De Freitas**[4] | **Gerd Sparovek**[5]

[1]Climate & Sustainable Cities, Energy, IVL Swedish Environmental Research Institute, Göteborg, Sweden

[2]Department of Mechanics and Maritime Sciences, Maritime Environmental Sciences, Chalmers University of Technology, Göteborg, Sweden

[3]Department of Space, Earth and Environment, Physical Resource Theory, Chalmers University of Technology, Göteborg, Sweden

[4]Division of Sustainability Assessment and Management, KTH Royal Institute of Technology, Stockholm, Sweden

[5]Soil Science Department, University of São Paulo, Piracicaba, SP, Brazil

Correspondence

Julia Hansson, Climate & Sustainable Cities, Energy, IVL Swedish Environmental Research Institute, Göteborg, Sweden.
Email: julia.hansson@ivl.se

Funding information

Svenska Forskningsrådet Formas, Grant/Award Number: Registration number 941-2015-1795; IEA Bioenergy

Abstract

Sustainable feedstock supply is a critical issue for the bioenergy sector. One concern is that feedstock production will impact biodiversity. We analyze how this concern is addressed in assessments of biomass supply potentials and in selected governance systems in the EU and Brazil, including the EU Renewable Energy Directive (RED), the EU Common Agricultural Policy (CAP), and the Brazilian Forest Act. The analysis focuses on grasslands and includes estimates of the amount of grassland area (and corresponding biomass production volume) that would be excluded from cultivation in specific biodiversity protection scenarios. The reviewed assessments used a variety of approaches to identify and exclude biodiverse grasslands as unavailable for bioenergy. Because exclusion was integrated with other nature protection considerations, quantification of excluded grassland areas was often not possible. The RED complements and strengthens the CAP in terms of biodiversity protection. Following the RED, an estimated 39%–48% (about 9–11 Mha) and 15%–54% (about 10–38 Mha) of natural and non-natural grassland, respectively, may be considered highly biodiverse in EU-28. The estimated biomass production potential on these areas corresponds to some 1–3 and 1.5–10 EJ/year for natural and non-natural grassland, respectively (depending on area availability and management intensity). However, the RED lacks clear definitions and guidance, creating uncertainty about its influence on grassland availability for bioenergy feedstock production. For Brazil, an estimated 16%–77% (about 16–76 Mha) and 1%–32% (about 7–24 Mha) of natural and non-natural grassland, respectively, may be considered highly biodiverse. In Brazil, ecological–economic zoning was found potentially important for grassland protection. Further clarification of grassland definitions and delineation in regulations will facilitate a better understanding of the prospects for bioenergy feedstock production on grasslands, and the impacts of bioenergy deployment on biodiversity.

KEYWORDS

biodiversity, biofuel, biomass potential, Brazil, EU, grassland, pasture, protection, sustainability criteria

1 | INTRODUCTION

Bioenergy commonly makes a significant contribution to energy supply in global scenarios aligned with the objective to keep the increase in global average temperature below 2°C (e.g., Chum et al., 2011; IPCC, 2014). Bioenergy feedstocks include residues and waste in the agriculture and forestry sectors, organic post-consumption waste, and biomass from dedicated plantations (here designated "bioenergy plantations"), which are often assessed as the largest, albeit most uncertain, resource (for an overview see, e.g., Berndes, Hoogwijk, & Broek, 2003; Creutzig et al., 2015; Slade, Bauen, & Gross, 2014). Bioenergy feedstock production on grasslands has attracted much interest due to an assessed large potential and because possible greenhouse gas emissions associated with land conversion to bioenergy plantations are lower for grasslands and pastures than for forests (Berndes, Chum, Leal, Sparovek, & Walter, 2016; Chum et al., 2011; Deng, Koper, Haigh, & Dornburg, 2015; Englund, Berndes, Persson, & Sparovek, 2015; Hoogwijk et al., 2003). However, grasslands may support high biological diversity (Fischer, Hizsnyik, Prieler, Shah, & vanVelthuizen, 2009; White, Murray, & Rohweder, 2000).

Biodiversity impacts of land conversion to bioenergy plantations vary depending on the character of the land converted as well as the character of the bioenergy plantations established. Hellmann and Verburg (2010) found relatively small direct effects (but larger indirect effects) on land use and biodiversity in EU-27 of the EU biofuels directive, which required a minimum 5.75% biofuel share in the transport fuel mix in each member state (MS) by 2010 (Directive 2003/30/EC). Frank et al. (2013) estimate that European biofuel expansion in line with the National Renewable Energy Action Plans would cause a 2.2 Mha loss in highly biodiverse areas. Others (Baum, Bolte, & Weih, 2012; Berndes, Börjesson, Ostwald, & Palm, 2008; Dauber, Jones, & Stout, 2010; Firbank, 2008; Holland et al., 2015; Manning, Taylor, & Hanley, 2015; Verdade, Piña, & Rosalino, 2015) found positive biodiversity effects—soil restoration/conservation, reduced water pollution, and enhanced landscape diversity—when bioenergy plantations are integrated into agricultural landscapes. van Meerbeek, Ottoy, Andrés, Muys, and Hermy (2016) proposed that using biomass from protected Natura 2000 areas in the EU as bioenergy feedstock represents an opportunity to reconcile bioenergy and biodiversity protection objectives.

Measures addressing biodiversity concerns can have significant influence on where—and how—lands can be used for bioenergy feedstock production (WBGU, 2009). The literature review performed for the IPCC Special Report on renewable energy sources (Chum et al., 2011) found that assessments of biomass supply potentials commonly consider biodiversity, although the approaches for doing so vary. A recent review of studies focusing on the European bioenergy potential in 2030 specifically considered environmental sustainability criteria and found that all the reviewed studies consider high biodiversity areas but that different definitions and datasets are used to exclude such areas when estimating biomass potentials (Kluts, Wicke, Leemans, & Faaij, 2017).

Examples of global schemes that consider biodiversity include the UN Convention on Biological Diversity (CBD) and the Sustainable Development Goals (UN, 2015). In the EU, the Common Agricultural Policy (CAP) and the Renewable Energy Directive (RED) (European Parliament & Council, 2009a) both include regulations that reflect biodiversity considerations. A recast directive (RED II) recently agreed by the EU institutions maintains the RED criterion that bioenergy feedstock cannot be obtained from land with high biodiversity, such as primary forests or highly biodiverse grasslands (European Commission, 2017).

Restrictions on domestic bioenergy supply in the EU (due to biodiversity considerations or for other reasons) may increase the bioenergy import demand, potentially causing biodiversity impacts outside the EU. Such risks are addressed by requiring that bioenergy used in the EU must comply with the mandatory sustainability criteria in the RED (and RED II) in order to receive public financial support and count toward the overall renewable energy targets, irrespective of geographic origin. Companies can prove compliance through national systems or so-called voluntary schemes recognized by the European Commission.[1]

In this context, Brazil is a potentially large bioenergy exporter to the EU with large grassland areas that potentially could support biofuel production (Berndes et al., 2016; Englund et al., 2015). At the same time, Brazil holds large areas of high value for biodiversity conservation (Kapos et al., 2008). Conversion of forests and other natural vegetation has supported agricultural growth but has also resulted in negative impacts, including loss of biodiversity (Newbold et al., 2015). Impacts of land use and land-use change in Brazil are subject to public debate, as well as substantial scientific activity and legislation/policy development (Sparovek et al., 2016).

This paper investigates how biodiversity protection may influence the potential for bioenergy feedstock production on grasslands. This is done by analyzing how biodiverse grasslands are considered in (a) assessments of biomass supply potentials; and (b) selected governance systems in the EU and Brazil (including the RED, the CAP, the CBD, and the Brazilian Forest Act). The analysis includes estimates of the

[1] https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/voluntary-schemes.

amount of grassland area (and potential biomass production volume) that would be excluded from bioenergy feedstock production in the EU and Brazil in specific biodiversity protection scenarios.

Assessments used different data and methodologies to consider biodiversity, and they rarely provided specific data concerning grasslands, but the review shows that biodiversity considerations can have a significant—and geographically varying—influence on the potential for bioenergy feedstock production. The analyses of governance systems also indicate a significant influence. For EU-28, calculations (based on the RED) show that an estimated 39%–48% and 15%–54% of natural and non-natural grassland, respectively, may be considered highly biodiverse. Similar estimates for Brazil correspond to 16%–77% and 1%–32% of natural and non-natural grassland, respectively. However, the prospects for bioenergy from grasslands on the EU market and the biodiversity impacts of grassland conversion to bioenergy plantations are both uncertain, due to the lack of clear guidance in relation to the RED.

2 | MATERIALS AND METHODS

Highly biodiverse grasslands differ among climatic zones and may include heaths, pastures, meadows, savannas, steppes, scrublands, tundra, and prairies (European Commission, 2014a). The species richness may vary substantially from year to year due to, e.g., management practices.

2.1 | How is biodiversity considered in assessments of biomass supply potentials?

We reviewed the literature to investigate how protection of highly biodiverse areas, in particular, highly biodiverse grasslands, has been considered in assessments of biomass supply potentials. The review included scientific journal articles and reports published in the period 2005–2017 that either specifically model the influence of sustainability constraints on biomass supply potentials, or consider biodiversity protection in quantifications of biomass supply potentials.

Relevant publications were identified based on keyword searches in the Scopus and Web of Science databases (see Supporting Information Table S1 for details on keywords and search strings). Additional publications were identified through the bibliographies in the identified papers. The publications identified as relevant were then reviewed in terms of: (a) aim of the study; (b) geographic coverage and time frame; (c) publication year; (d) approach to considering biodiversity protection for biodiverse grassland, in particular; (e) the possibility of indicating the influence of the biodiversity consideration on the biomass potential; and (f) comparability concerning how giving consideration to highly biodiverse grasslands influences the bioenergy potential. In total, 22 publications that fulfilled the criteria were selected for analysis. Almost all the included studies had a global and/or European scope. One included study focused on Brazil. The results of the review are presented in the Supporting Information Table S2 and summarized in the Section 3.

Global and EU grassland resources were mapped based on published quantifications of global and regional grassland areas. To specifically assess how biodiverse grasslands are protected in a regional context, the following assessment focuses on the EU and Brazil, selected based on their relevance for bioenergy development.

2.2 | How EU policies classify and protect biodiverse grasslands

We reviewed the scientific literature and regulatory documents relevant to the EU to investigate how highly biodiverse grasslands have been considered in the RED, the CAP, and the CBD. The aim was to clarify if different approaches can result in different outcomes concerning biodiversity protection and prospects for bioenergy feedstock production on grasslands in the EU. Three scenarios were developed to enable calculations of how specific approaches to biodiversity protection would exclude grassland areas from cultivation.

Definitions and methods for identifying and delineating biodiverse grasslands were compared to clarify both the range of protective ambition, the degree of redundancy, and/or conflicting definitions, methods, and regulations. We estimated the grassland areas covered by biodiversity considerations based on the RED. For the CAP, grassland areas covered by biodiversity considerations are also reported. These are areas that have been designated environmentally sensitive permanent grassland (ESPG) in MSs, and are mainly based on notifications related to the implementation of the green direct payment scheme (payments to farmers for implementing farming methods that go beyond basic environmental protection) for the year 2015 (European Commission, 2016).

2.2.1 | Method for estimating highly biodiverse grassland areas in the EU

The definitions related to highly biodiverse grasslands in the RED were interpreted and mapped using different geographical information systems (GIS) to present different estimates of grassland areas potentially protected by the RED. The definitions of natural, non-natural, and highly biodiverse grassland for RED purposes are presented in the EU RED section. All GIS operations were done in GRASS GIS using the reference system ETRS89-LAEA Europe (EPSG:3035) with a resolution of 100 m.

Areas referred to as grasslands in the RED were represented by grassland and lands dominated by forbs, mosses, or lichens (European nature information system, EUNIS, classes E) as well as heathland, scrub and tundra (EUNIS classes F) in the Ecosystem types of Europe dataset, which combines CORINE (Coordination of Information on the Environment)-based MAES ecosystem classes with the non-spatial EUNIS habitat classification (EEA, 2017a).

Grassland cells classified in CORINE 2012 (EEA, 2016a) as natural grasslands (land cover classification, CLC: 26), moors and heathland (CLC: 27), or sclerophyllous vegetation (CLC: 28) were considered to represent natural grasslands for these purposes (Figure 1). All grassland cells not classified as natural grassland were identified as non-natural grasslands (Figure 1).

The RED requires that "the natural species composition and ecological characteristics and processes are maintained" for land to qualify as highly biodiverse natural grassland. There is no spatial data readily available to map this. However, the RED specifies certain areas as highly biodiverse natural grassland (European Commission, 2014a). These areas correspond to areas protected under the Natura 2000 network, which is established under the Birds and Habitats directives for the purpose of ensuring the long-term survival of Europe's most valuable and threatened species and habitats.

Three scenarios representing different protection levels for biodiverse grassland areas (base protection, higher protection, and highest protection case) were defined (for a summary see Table 1). As indicated, grasslands protected under Natura 2000 can be expected to fulfill the RED requirement for land to qualify as highly biodiverse. The corresponding natural and non-natural grassland areas are here adopted as a base protection case estimate of the natural and non-natural grassland areas, respectively, in the EU that are not available for producing biomass for conversion to bioenergy products destined for the EU RED market. Two additional estimates of grassland availability are made, based on additional exclusion of grasslands outside Natura 2000 (Table 1). In the higher protection case, natural and non-natural grasslands that are protected by other protection frameworks are also excluded, including, e.g., national parks, wilderness areas, riparian buffers, and other areas or landscape features protected by national legislation in individual MS. In the highest protection case, non-natural grasslands classified as high nature value (HNV) farmland are also excluded. Thus, we assume that grasslands protected by other protection frameworks or classified as HNV farmland have relatively high biodiversity.

For each protection scenario, the land area available for biomass production for bioenergy was estimated by counting how many 100 m cells that exist in each NUTS3 polygon, using the tool "v.rast.stats," and aggregating the results at the country level.

For non-natural grasslands in the RED, biomass production for bioenergy is allowed where evidence is provided that harvesting on a specific grassland area is needed to preserve its grassland status. No attempt was made to identify such grassland areas due to a lack of the information needed for identification (see Section). However, Meerbeek et al. (2016) estimate that the potential biomass supply from conservation

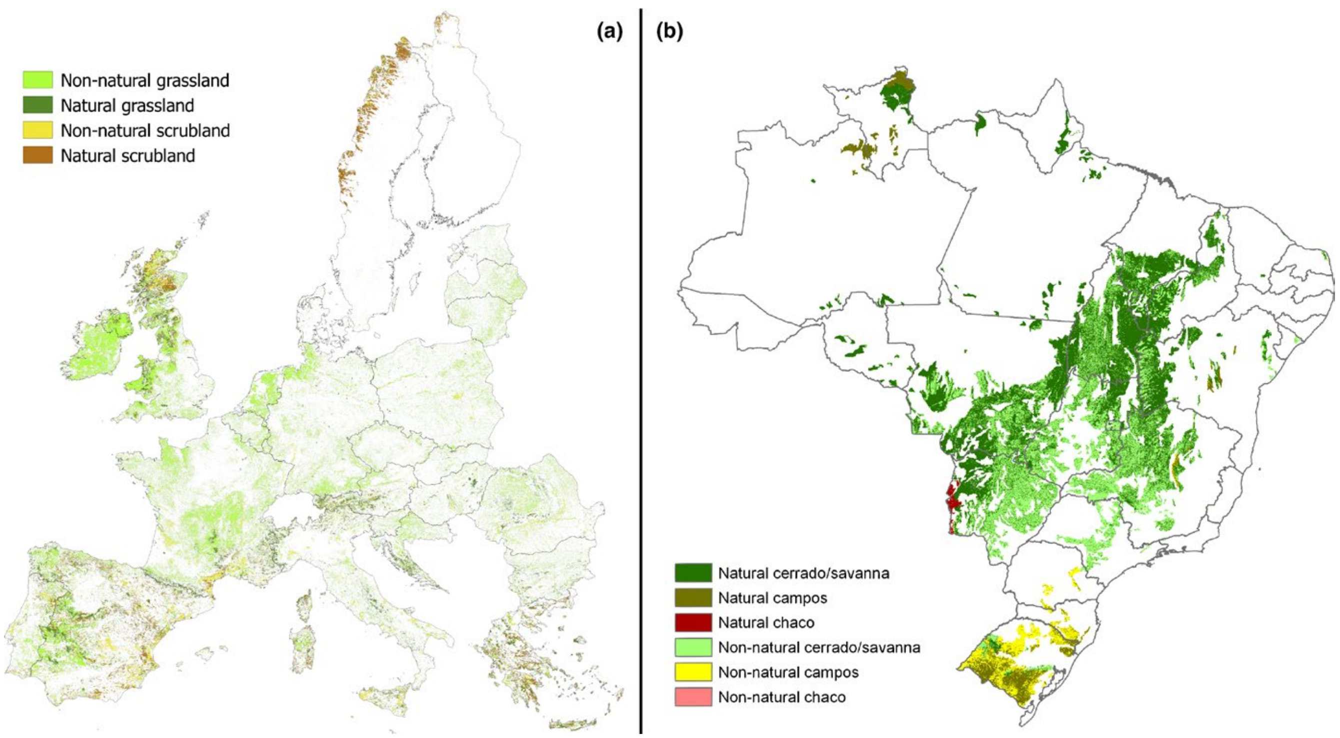

FIGURE 1 Grassland areas and types in (a) the EU based on EEA (2017a) and EEA (2016a), and (b) Brazil based on IBGE (1993)

TABLE 1 Methods for constructing spatial data representing different types of grassland in the EU and Brazil, following definitions related to the Renewable Energy Directive (RED). Natura 2000 is a network of nature protection areas in the EU

Spatial data	Base protection case	Higher protection case	Highest protection case
Grassland	*EU*: Cells of European nature information system (EUNIS) class E and F extracted from existing spatial data (EEA, 2017a) *Brazil*: Polygons from the national vegetation map of Brazil (IBGE, 1993) classifies as Cerrado, Wetlands, Campos, and Chaco vegetation types		
Natural grassland	*EU*: Cells from *Grassland* classified as CORINE Land Cover (CLC) 26 thru 28 in CORINE (Coordination of Information on the Environment) (EEA, 2016a) *Brazil*: Cells from *Grassland* (Brazil) classified as native vegetation in the land cover map in Sparovek et al (2015)		
Non-natural grassland	Cells from *Grassland* not classified as *Natural grassland* extracted based on the approach above		
Highly biodiverse natural grassland	*EU*: *Natural grassland* masked with spatial data of Natura 2000 areas (EEA, 2016b) *Brazil*: *Natural grassland* masked with spatial data of protected public land (Brazil, 2000)	*EU*: *Natural grassland* masked with spatial data of Natura 2000 areas and Nationally designated areas (EEA, 2017b) *Brazil*: *Natural grassland* masked with spatial data of protected public land and private land protected by the Brazilian Forest Act (Brazil, 2000)	*EU*: Not applicable *Brazil*: *Natural grassland* masked with spatial data of protected public land, private land protected by the Brazilian Forest Act, and unprotected land prioritized for biodiversity conservation
Highly biodiverse non-natural grassland	*EU*: *Non-natural grassland* masked with spatial data of Natura 2000 areas (EEA, 2016b) *Brazil*: *Non-natural grassland* masked with spatial data of protected public land (Brazil, 2000)	*EU*: *Non-natural grassland* masked with spatial data of Natura 2000 areas and Nationally designated areas (EEA, 2017b) *Brazil*: *Non-natural grassland* masked with spatial data of protected public land and private land protected by the Brazilian Forest Act (Brazil, 2000)	*EU*: *Non-natural grassland* masked with spatial data of Natura 2000 areas, Nationally designated areas, and high nature value farmland (EEA, 2017c) *Brazil*: *Non-natural grassland* masked with spatial data of protected public land, private land protected by the Brazilian Forest Act, and unprotected land prioritized for biodiversity conservation
Natural grasslands available for conversion into biomass production for bioenergy	All *Natural grassland* not classified as highly biodiverse	All *Natural grassland* not classified as highly biodiverse	Not applicable

(*Continues*)

TABLE 1 (Continued)

Spatial data	Base protection case	Higher protection case	Highest protection case
Non-natural grasslands available for conversion into biomass production for bioenergy	All *Non-natural grassland* not classified as highly biodiverse	All *Non-natural grassland* not classified as highly biodiverse	All *Non-natural grassland* not classified as highly biodiverse

management of open, semi-natural ecosystems inside the Natura 2000 network corresponds to about 225 PJ/year.

Because biomass yields on grassland areas depend on management and local conditions (e.g., vegetation type, soil type, elevation level, slope, and climate), biomass production levels on different grasslands can vary considerably. This study defined three biomass production levels representing different management intensities for grasslands (including varying levels of irrigation). The potential yields were identified for different lignocellulosic short rotation coppice (SRC) crops (willow, poplar, and other SRC) and lignocellulosic grasses (miscanthus, reed canary grass, and switchgrass) for each NUTS 3 region, for three different management levels (low, medium, high, see details below) (Ramirez-Almeyda et al., 2017). The yield data were then combined with the different estimates of grassland area availability to estimate biomass production levels for the different management levels in each NUTS3 polygon (the energy content was assumed to be 18 GJ/Mg dry matter) (McKendry, 2002).

In the low management case, there is no irrigation and the yield level depends on water conditions where the yield level applied is the lower of the yield levels corresponding to (a) 80% of the water-limited potential or (b) 50% of the full theoretical potential. Medium management implies no irrigation except in the establishment phase for some crops, and the yield level applied is the lower of (a) the water-limited potential or (b) 90% of the full potential. In the high management case, irrigation is assumed to be employed wherever needed, supporting a yield level at 90% of the full potential.

2.3 | How Brazilian policies and legislation classify and protect biodiverse grasslands

We reviewed policy and regulatory documents relevant for Brazil to investigate how highly biodiverse grasslands have been considered. Data on Brazilian grassland areas were derived by processing GIS data obtained from the national vegetation map of Brazil (IBGE, 1993), see Figure 1, complemented by a literature review. Brazil hosts a wide range of grassland types broadly grouped into Cerrado, Wetlands, Campos, and Chaco. The Cerrado is the predominant grassland vegetation in Brazil. It is composed of grass vegetation and seasonal tropical forest. Wetlands are mostly covered by seasonally flooded savanna vegetation with small occurrences of forest vegetation. This type of grassland is primarily located in the Pantanal biome and in small patches within the Amazon biome. Most of the Campos vegetation is located in the far south of Brazil and in the state of Roraima (farthest north). Finally, the Chaco vegetation, a kind of steppe savanna, covers a small portion of the state of Mato Grosso do Sul (IBGE, 1993).

The dataset fields "Vegetation type" and "Description" were used to classify map polygons to define grasslands. Polygons with vegetation types Cerrado, Savanna, Chaco "Vegetação Chaquenha", and Campos were treated as grasslands when not described as tree-dense vegetation. Areas classified as boundaries between vegetation types were considered grassland only if all the bordering vegetation types were among the abovementioned categories.

We assessed the legal framework for the protection of biodiverse grassland in Brazil and used the database constructed in Freitas et al. (2017) to (a) estimate the extent of "non-natural grassland" that is defined as the areas, including agriculture land, that are classified as grassland vegetation but are not native grassland and (b) estimate the shares of protected existing natural grassland on public and private lands.

The Brazilian government maps areas of high importance for biodiversity to identify the priority areas for biodiversity conservation, following the CBD. These areas are identified in a participatory process, involving researchers, governmental agencies, and civil society, considering a range of aspects including species richness, occurrence of endemic and threatened species, presence of rare biological phenomena, cost of conservation, importance for biological processes, etc. (Prates, Vasconcelos, & Bayma, 2016). Priority areas constitute an essential tool to guide conservation actions, such as establishment of conservation units (area protection), incentives for restoration of native vegetation on private lands, and creation of public policies to foster sustainable agriculture. The map of priority areas for biodiversity conservation (available since 2004) is updated periodically to incorporate new data and scientific and methodological developments.

Existing databases do not include information about the exact locations of grasslands defined as highly biodiverse.

The biodiverse grassland areas are therefore identified for three scenarios with different levels of protection: base protection, higher protection, and highest protection case (see Table 1). In the base protection scenario, we define highly biodiverse natural and non-natural grasslands as being equal to the areas in the grassland region that are protected as indigenous reserves or conservation units based on Brazil (2000). The higher protection case in addition includes grassland protection on privately owned lands through the Brazilian Forest Act (Brazil, 2000), the central legal framework for the protection of natural vegetation on private rural properties (Freitas et al., 2017; Sparovek, Barretto, Matsumoto, & Berndes, 2015). It requires farmers to preserve the natural vegetation within a minimum buffer zone from watercourses and lakes (riparian zones). Farmers are also obligated to protect the vegetation covering hilltops and steeply sloping areas. Furthermore, a minimum percentage of rural property—35% for properties in the Cerrado biome, 80% in the Amazon, and 20% in other biomes—is required to be set aside as legal reserves for the preservation of natural vegetation (Brazil, 2000).

The highest protection case further includes unprotected lands that are located within priority areas for biodiversity conservation, identified based on the recently released second update of priority areas for biodiversity conservation 2016–2018 (Prates et al., 2016). This version is only complete for the Cerrado, Pantanal, and Caatinga biomes, but these comprise more than 80% of the grassland territory. The remaining 20% found in other biomes (Amazon, Atlantic Forest, and Pampas) is classified as non-priority area, because priority maps are yet not available in these biomes.

To provide indicative estimates of potential biomass feedstock from Brazilian grasslands, we adopt an average yield of 280 GJ/ha/year, which corresponds to the Latin American average value for rain-fed lignocellulosic plants (Berndes et al., 2016). This is a rough estimate that does not reflect the spatial natural yield variability or the yield variation resulting from different management practices.

3 | RESULTS

3.1 | How is biodiversity considered in assessments of biomass supply potentials?

There is no globally established approach to considering biodiversity in assessments of grassland availability for bioenergy feedstock production. As shown in the Supporting Information Table S2, assessments of biomass supply potentials vary in their approaches to considering biodiversity. In some studies (see, e.g., Deng et al., 2015; Smeets & Faaij, 2010), a certain share of the total land area assessed to be available for bioenergy plantations is excluded, but there is no specification of the geographic location of the excluded areas. Most studies, however, exclude specific areas based on information about the location of land deemed to support high biodiversity values, commonly including currently protected areas as well as unprotected areas identified based on various criteria. An exclusion of additional unprotected areas is motivated by the expectation that the total area set aside for nature protection will increase (Cornelissen, Koper, & Deng, 2012; Dornburg et al., 2010; EEA, 2006, 2007 ; Hoogwijk, Faaij, Eickhout, Devries, & Turkenburg, 2005; van Vuuren, Vliet, & Stehfest, 2009) and/or by more explicit considerations. Examples of excluded areas include:

- unprotected areas of high biological diversity and untouched wilderness specified in specific “datasets” including, e.g., Biodiversity Hotspots, Endemic Bird Areas, Key Biodiversity Areas database, and High-Biodiversity Wilderness Areas (Beringer, Lucht, & Schaphoff, 2011; Böttcher, Frank, Havlík, & Elbersen, 2013; Erb, Haberl, & Plutzar, 2012; Frank et al., 2013; Schueler, Weddige, Beringer, Gamba, & Lamers, 2013; WBGU, 2009, details in the Supporting Information Table S2)
- high nature value (HNV) farmland (Böttcher et al., 2013; EEA, 2013; Elbersen et al.., 2013; Frank et al., 2013)
- low-productive (semi)-natural vegetation (Fischer et al., 2009; Smeets, Faaij, Lewandowski, & Turkenburg, 2007)
- a certain share of natural grasslands based on an accessibility factor representing biodiversity concerns (van Vuuren et al., 2009)
- all natural grasslands (de Wit & Faaij, 2010; Fischer, Prieler, Velthuizen, & Berndes, 2010)
- a certain amount of grassland used for livestock grazing (Fischer et al., 2009; Hoogwijk et al., 2005)
- anthropogenic grasslands primarily represented by pasture (Schueler et al., 2013)
- permanent grassland, except for the use of cuttings (EEA, 2006, 2007, 2013 ; Rösch, Aust, & Jörissen, 2013)
- for the EU specifically: Natura 2000 areas and HNV farmland (EEA, 2013; Elbersen et al., 2013) or Natura 2000, other protected areas, and land classified as natural grasslands (de Wit & Faaij, 2010 based on Fischer et al., 2010)

The review showed that biodiversity considerations can influence the estimated global biomass potential considerably, but there was large variation among the studies (ranging from <10% to about 60% reduction at the global level, see Supporting Information Table S2). There was also large variation among regions. For example, Schueler et al. (2013) investigated the share of an estimated total theoretical biomass potential affected by various sustainability considerations in the RED. They found that about 15% of the potential was affected by biodiversity considerations in China and OECD Europe, while 57% and 87%

of the potential was affected in Africa and Latin America, respectively. Specifically for Brazil, Smeets, and Faaij (2010) found that reservation of areas for nature conservation resulted in a 10%–20% reduction in the potential for bioenergy feedstock production.

As biodiversity in most cases is considered for several land types combined, it was not possible to find quantitative information enabling a comparison across the majority of studies that specifically concerned the influence of biodiversity considerations on the potential for bioenergy feedstock production on grasslands. Among the studies that report results specifically for grasslands, Frank et al. (2013) report that about 8% of global grasslands can be considered highly biodiverse (year 2000). Böttcher et al. (2013) classify about 8% (90 Mha) and 5% (120 Mha) of globally managed grasslands and other natural vegetation, respectively, as highly biodiverse (calculated based on area estimates from Böttcher, (2014)). The shares of grasslands that are considered highly biodiverse vary from almost 70% in the EU-27 to 2% in the former Soviet Union, Asia, and Canada (Böttcher et al., 2014).

3.1.1 | Differences in definitions of grassland

In addition to the differences in approaches to considering biodiversity, there are several definitions used to delineate grasslands from other vegetation types (see Hennenberg, Fritsche, & Bleher, 2009 for a comparison of definitions). Thus, a given approach may yield different results depending on which grassland definition is used. As an illustration, Table 2 shows three examples of estimates of global and regional grassland areas based on different assumptions and system boundaries (Dixon et al., 2014; Fischer et al., 2009; White et al., 2000). See Table 2 endnotes and Supporting Information for approaches and detailed grassland definitions.

Among studies that focus on the EU-27, Ketzer, Rösch, and Haase (2017) estimate the permanent grassland area at about 57 Mha (pastures and meadows) and temporary grassland at 10 Mha (2007), and Elbersen et al. (2013) estimate the grassland area at about 65 Mha (2004) and project that it will decrease to about 62 Mha in 2020.

TABLE 2 Estimates of global and regional grassland area (sources: Dixon et al., 2014; Fischer et al., 2009; White et al., 2000). Approaches are briefly described in the table endnotes. Fischer et al. (2009) also include an estimate of the share of grass and woodland available for bioenergy feedstock production. 1 Mha = 0.01 million km^2

Region	Grassland area (Mha) From White et al. (2000)[a]	Grass- and woodland area (Mha) In parenthesis: Potential share available for bioenergy feedstock production. From Fischer et al. (2009)[b], partly as presented in Chum et al. (2011)	Major natural grassland areas, non-natural grasslands excluded (Mha) Based on Dixon et al. (2014)[c]
Europe (including parts of the former Soviet Union)	700	–	–
Europe and Russia	–	900 (13%)	–
Europe and Asia	–	–	1,090
Latin America	590	765 (21%)	560
North America	660	660 (17%)	430
Sub Saharan Africa	1,445	1,070 (26%)	–
North Africa and Middle East	290	110 (1%)	–
Africa	–	–	1,130
Asia (excluding Middle East) and Oceania	1,580	–	–
South and East Asia and Oceania	–	1,070 (10%)	–
Australia and Oceania	–	–	415
Total global grasslands	5,250	4,610 (17%)	3,590

Notes. [a]White et al. (2000)estimate grasslands based on the land cover characterization developed by International Geosphere/Biosphere Program (IGBP) using global satellite data at 1 km resolution including closed and open shrubland, woody savanna, savanna, and non-woody grassland. Natural and pastured grasslands are covered, but some non-natural managed grassland areas are not covered. [b]Based on spatial data for global land cover derived from remote sensing data, Fischer et al. (2009) estimate areas of unprotected grasslands and woodlands potentially available for rain-fed lignocellulosic biofuel feedstock production by excluding unproductive or very low-productive areas as well as forests, grasslands, and pasture currently used to produce food and fodder. [c]Dixon et al. (2014)develop a distribution map of major grassland types and regions representing the International Vegetation Classification (IVC) grassland formations and divisions where grassland occupies, or historically occupied, at least 10% of an ecoregion in the Terrestrial Ecoregions of the World (TEOW) framework. Non-natural grasslands are grasslands primarily planted and maintained for agricultural reasons (pasture, hay, intensive livestock production).

3.2 | How EU policies classify and protect biodiverse grasslands

3.2.1 | EU RED

In the RED, highly biodiverse grassland includes (a) *natural grassland*, i.e., grassland that would remain grassland in the absence of human intervention and which maintains the natural species composition and ecological characteristics and processes; and (b) *non-natural grassland*, i.e., grassland that would cease to be grassland in the absence of human intervention and which is species-rich and not degraded and that had the respective status in or after 2008 (European Parliament & Council, 2009a). The use of raw material from non-natural grasslands is allowed if "evidence is provided that the harvesting of the raw material is necessary to preserve its grassland status" (European Parliament & Council, 2009a).

In 2014, the European Commission (EC) published a definition of the criteria and geographic ranges of highly biodiverse grassland relevant to the RED policy context, see Table 3 (European Commission, 2014a). The highly biodiverse grassland category includes regionally or nationally threatened or unique ecosystems and habitats of significant importance to (a) critically endangered, endangered, or vulnerable species (as classified by the International Union for the Conservation of Nature Red List of Threatened Species or similar nationally approved lists); (b) endemic or restricted-range species; (c) intra-species genetic diversity; and (d) globally significant concentrations of migratory species or congregatory species (European Commission, 2014a).

According to the European Commission (2014a), the following geographic areas of the EU are to be regarded as highly biodiverse grassland: (a) habitats listed in Annex I of the so-called Habitats Directive (European Council, 1992); (b) habitats of significant importance for animal and plant species listed in Annex II and IV of the so-called Habitats Directive (European Council, 1992); and (c) habitats of significant importance for wild bird species listed in Annex I in the so-called Birds Directive (European Parliament & Council, 2009b). These areas are covered by Natura 2000. However, other grasslands might also fulfill the proposed criteria for highly biodiverse grassland. Non-natural grasslands within the listed habitats that require harvesting to preserve the grassland status are a special case for which use of the harvested biomass as biofuel feedstock is allowed. Grassland area in the EU that can be considered highly biodiverse based on the RED is estimated later in this paper.

Due to the lack of clear guidance (prior to the publication of European Commission (2014a)), the majority of voluntary schemes that demonstrate compliance with the sustainability criteria for biofuels and that have been recognized by the European Commission initially applied a simple approach to demonstrating compliance with the criteria for highly biodiverse grassland: no material could be considered compliant with the RED criteria if obtained from grassland areas—irrespective of the biodiversity value (European Commission, 2015). This setup limited the potential use of biomass from all grassland areas and consequently restricted the potential contribution of grassland biomass to the total biomass supply potential.

TABLE 3 Grassland definitions linked to policies relevant for the EU

Policy	Grassland definition
EU Renewable Energy Directive (RED)	As specified in European Commission (2014a): Grassland means terrestrial ecosystems dominated by herbaceous or shrub vegetation for at least 5 years continuously. It includes meadows or pasture that is cropped for hay but excludes land cultivated for other crop production and cropland lying temporarily fallow. It further excludes continuously forested areas as defined in Article 17(4)(b) of Directive 2009/28/EC (European Parliament & Council, 2009a, i.e., RED) unless these are agroforestry systems which include land-use systems where trees are managed together with crops or animal production systems in agricultural settings. The dominance of herbaceous or shrub vegetation means that their combined ground cover is larger than the canopy cover of trees
EU Common Agricultural Policy (CAP)	As specified in European Parliament and Council (2013): the category of permanent grassland and permanent pasture (together, "permanent grassland") refers to land that is used to grow grasses or other herbaceous forage, either naturally (self-seeded) or through cultivation (sown), and that has not been included in the crop rotation for five years or more. The land may be partly covered by other species than grass, such as shrubs and/or trees that can be grazed, provided the grasses and other herbaceous forage remain predominant (European Parliament & Council, 2013) MS can also decide to include land that is managed according to established local practices (which can include grazing) where grasses and other herbaceous forage are traditionally not predominant in grazing areas
UN Convention on Biological Diversity (CBD)	As specified in UNEP/UN (2001): Areas dominated by grasses (members of the family Gramineae excluding bamboos) or grasslike plants with few woody plants. Natural grassland ecosystems are typically characteristic of areas with periodic drought, fire, and grazing by large herbivores. They are often associated with soils of low fertility

TABLE 4 Shares and corresponding grassland areas inside and outside Natura 2000 that are designated as ESPG in the EU MS based on European Commission (2016)

	ESPG area as share of grassland areas inside Natura 2000 (%)	ESPG area in Natura 2000 (ha)	ESPG area outside Natura 2000 (ha)
Austria	9	34,000	–
Belgium	18	14,000	4,100
Bulgaria	100	707,000	–
Cyprus	72	31,300	–
Czech Republic	100	184,400	273,200
Germany	60	695,400	–
Denmark	19	16,800	–
Estonia	2	900	–
Spain	100	4,394,000	–
Finland	100	459,400	–
France	No information	No information	No information
Greece	100	1,189,000	–
Croatia	82	432,500	–
Hungary	94	436,000	–
Ireland	2	3,600	–
Italy	100	1,298,400	–
Lithuania	45	38,600	–
Luxembourg	35	7,400	3,500
Latvia	6	6,800	7,100
Malta	–	–	–
Netherlands	100	127,700	–
Poland	42	404,500	–
Portugal	2	10,100	–
Romania	78	845,700	–
Sweden	100	1,364,000	–
Slovenia	26	32,200	–
Slovakia	96	140,000	–
United Kingdom	60	698,000	22,500
EU−28	75	14,300,000	310,400

3.2.2 | EU Common agricultural policy

The CAP sets the conditions for EU agriculture and needs to be followed by all EU MS. In the CAP, grassland includes permanent grassland and permanent pasture together, referred to as "permanent grassland," but land that is managed according to established local practices (which can include grazing) can also be included (see definition in Table 3).

Under the CAP, the EU MS shall designate so-called environmentally sensitive permanent grasslands (ESPG) in grasslands areas covered by the Habitats Directive (European Council, 1992) or the Birds Directive (European Parliament & Council, 2009b) and in need of strict protection to meet the objectives of those directives. MS may also designate sensitive areas outside the areas covered by the two directives, i.e., outside Natura 2000 areas (European Parliament & Council, 2013). ESPG areas designated by the MS may not be converted or plowed (European Parliament & Council, 2013). ESPG areas can be assumed to represent highly biodiverse grassland areas not possible to use for bioenergy following the CAP.

As part of the CAP, European farmers may also receive payments for maintaining permanent grassland by conserving grassland habitats (European Parliament & Council, 2013). Further, the ratio of permanent grassland to the total agricultural area declared by the farmers in the MS may not decrease by more than 5% compared to a reference ratio for 2015 (European Commission, 2014b; European Parliament & Council, 2013). This illustrates the general ambition to

TABLE 5 Estimated total area of natural and non-natural grassland and of natural and non-natural grassland not available for bioenergy feedstock production in different biodiversity protection scenarios following the RED, and the estimated biomass production potential on the grassland not available for bioenergy feedstock production in the different biodiversity protection scenarios (ranges reflecting low and high management intensities, rounded numbers) is presented

	Estimated grassland area (ha)		Share of natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)		Share of non-natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)		
Member state	Natural	Non-natural	Base protection case	Higher protection case	Base protection case	Higher protection case	Highest protection case
Austria	723,840	1,386,350	26 (19–34)	44 (33–59)	14 (23–41)	25 (40–72)	88 (146–263)
Belgium	12,815	765,610	69 (1–2)	75 (1–2)	10 (9–16)	23 (21–37)	52 (46–83)
Bulgaria	364,630	1,435,870	69 (45–81)	70 (45–82)	32 (82–147)	32 (82–148)	83 (215–387)
Cyprus	149,820	96,720	20 (6–11)	45 (14–25)	13 (3–5)	54 (11–19)	88 (17–31)
Czech Republic	26,320	1,089,130	85 (2.6–4.7)	88 (2.7–4.9)	16 (21–37)	27 (36–64)	80 (105–189)
Germany	155,350	6,343,970	78 (14–26)	86 (16–28)	16 (123–222)	38 (290–523)	57 (433–779)
Denmark	61,680	136,630	66 (4–8)	94 (6–11)	34 (5–9)	57 (8–15)	59 (8–15)
Estonia	28,980	407,530	66 (2–3)	66 (2–3)	6 (2–4)	7 (3–5)	31 (11–20)
Spain	6,206,490	9,478,430	38 (339–861)	39 (349–888)	21 (275–741)	22 (287–771)	71 (925–2,415)
Finland	331,110	172,850	95 (17–31)	95 (17–32)	82 (8–14)	83 (8–14)	92 (9–17)
France	1,889,990	13,829,830	39 (112–225)	60 (173–347)	10 (215–403)	23 (465–862)	42 (860–1,586)
Greece	3,064,140	1,290,590	31 (105–348)	39 (134–439)	18 (28–87)	25 (39–119)	25 (39–119)
Croatia	291,460	1,284,850	58 (32–57)	58 (32–58)	28 (61–110)	29 (63–114)	100 (211–380)
Hungary	217,140	1,135,180	91 (32–58)	92 (33–59)	24 (43–78)	25 (45–82)	67 (122–220)
Ireland	804,860	3,937,540	45 (3–6)	48 (4–7)	4 (14–24)	4 (14–25)	6 (21–38)
Italy	1,944,650	3,870,370	40 (109–233)	43 (118–253)	13 (73–156)	15 (85–180)	51 (292–625)
Lithuania	1,910	1,262,770	64 (<1)	69 (<1)	7 (9–15)	11 (15–26)	32 (41–73)
Luxembourg	0	89,140	–	–	25 (3–5)	41 (4–8)	42 (5–8)
Latvia	5,095	1,321,270	53 (<1)	60 (<1)	8 (10–19)	12 (15–28)	29 (35–63)
Malta	1,590	740	10 (<1)	42 (<1)	4 (<1)	20 (<1)	20 (<1)
Nether Lands	69,020	1,436,310	78 (6–11)	79 (6–11)	4 (7–13)	5 (8–14)	19 (31–56)
Poland	30,330	3,891,650	82 (3–5)	86 (3–5)	24 (108–194)	44 (198–356)	89 (401–723)
Portugal	472,890	1,751,370	40 (28–69)	43 (29–72)	18 (45–120)	20 (49–130)	67 (160–432)
Romania	550,180	4,321,130	53 (42–75)	54 (42–76)	18 (115–206)	19 (122–219)	82 (507–912)

(*Continues*)

TABLE 5 (Continued)

Member state	Estimated grassland area (ha)		Share of natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)		Share of non-natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)		
	Natural	Non-natural	Base protection case	Higher protection case	Base protection case	Higher protection case	Highest protection case
Sweden	2,689,160	627,630	45 (72–129)	48 (77–138)	22 (9–17)	25 (10–19)	67 (32–58)
Slovenia	35,950	379,700	91 (4–8)	97 (5–9)	25 (13–24)	42 (22–40)	91 (48–87)
Slovakia	34,870	476,140	82 (4–6)	84 (4–7)	24 (15–27)	36 (22–40)	75 (46–83)
United Kingdom	2,915,060	8,176,970	23 (64–116)	55 (157–283)	6 (49–88)	27 (229–412)	35 (289–520)
EU−28	22,354,940	70,396,250	39 (1,067–2,410)	48 (1,302–2,898)	15 (1,366–2,821)	24 (2,189–4,341)	54 (5,055–10,183)

protect EU grassland areas in CAP and thereby limit the loss of potentially biodiverse grassland.

About 14 Mha or 75% of permanent grasslands inside Natura 2000 areas is designated as ESPG which can be assumed to represent highly biodiverse grassland area not possible to use for bioenergy following the CAP (European Commission, 2016). See Table 4 for the ESPG shares of the permanent grassland areas inside Natura 2000 by MS, and the corresponding estimated highly biodiverse grassland area. France and Scotland are missing in the reporting, and Malta does not have any permanent grassland (European Commission, 2016). In eight MS all permanent grassland in Natura 2000 areas has been designated as ESPG, and in two additional MS the share is >90% (European Commission, 2016). However, in five countries, <10% of the total permanent grassland in Natura 2000 is ESPG (European Commission, 2016). Five countries have designated some ESPG areas outside Natura 2000, in total about 310,000 ha (Table 4). Thus, the strategies for ESPG designation vary. In total, Spain, Sweden, Italy, and Greece have the largest ESPG areas.

Within the areas designated as ESPG by the MS, the farmers in question declare their grassland on the relevant areas (areas not declared belong to farms that do not benefit from the direct payment scheme or are exempted). About 16% of the total permanent grassland in the EU has been declared ESPG by farmers and is hence protected through this mechanism, in the sense that plowing is prohibited (European Commission, 2016). The level varies considerably among the MS, from almost zero to about 55% (European Commission, 2016). About 40% of the total permanent grassland in Natura 2000 areas in the EU has been declared ESPG and is thus covered by the ban on plowing that restricts the use of this land for bioenergy feedstock production (European Commission, 2016).

3.2.3 | The UN convention on biological diversity

The CBD includes strategies for the conservation and sustainable use of biodiversity. The definition of grassland ecosystems used for CBD purposes (Table 3) does not specifically include non-natural grasslands, but semi-natural grasslands or semi-natural pastures are treated by the CBD.

Biodiverse grasslands are mainly associated with the work program on agricultural biological diversity (CBD, 2000) that aims to promote positive effects and mitigate negative impacts of agricultural systems and practices on biological diversity and to promote the conservation and sustainable use of valuable genetic resources. The CBD as such does not specify a global protection approach specifically for biodiverse grassland, but provides a framework and general principles. For example, a global target to protect at least 10% of each of the world's 14 ecological regions/biomes has been adopted by the

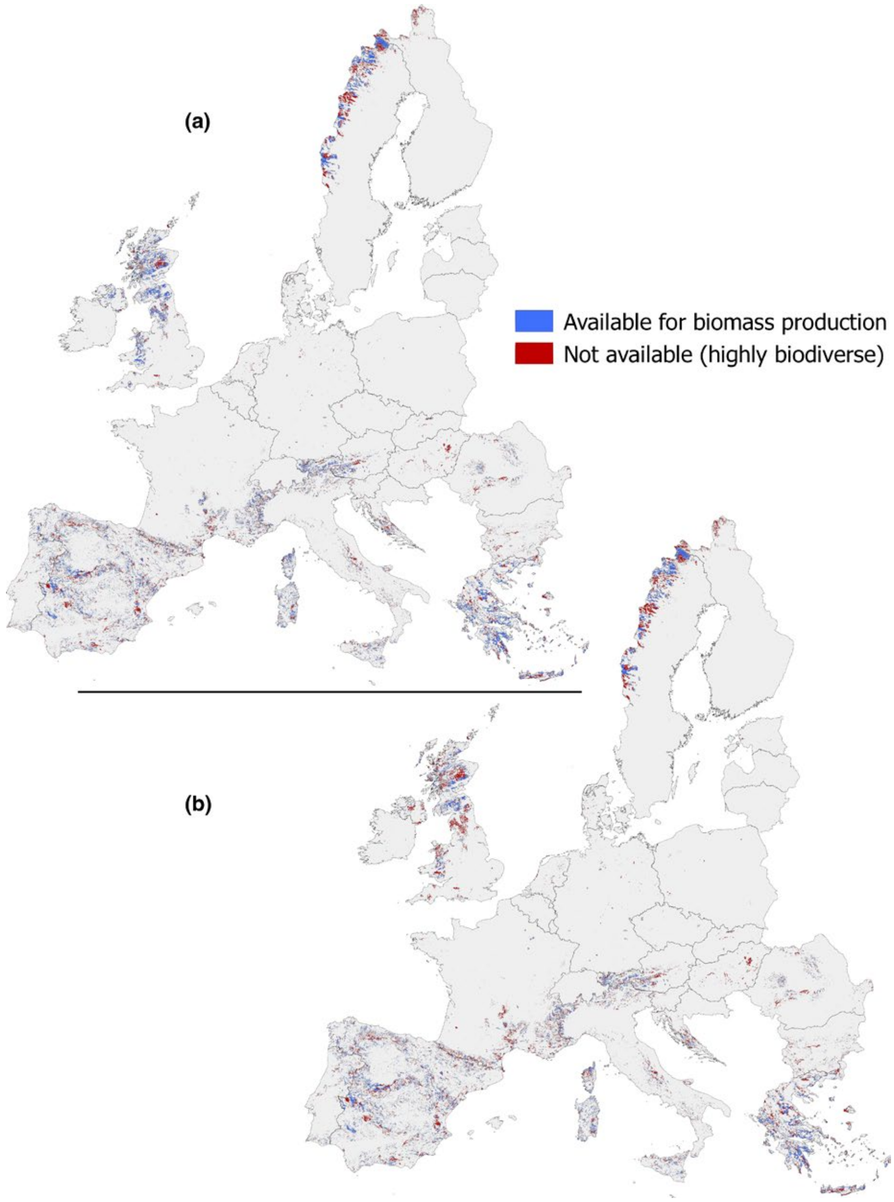

FIGURE 2 Estimated natural grassland areas in the EU-28, following the RED. Blue represents grassland areas available for bioenergy feedstock production and red represents grassland areas assessed to be highly biodiverse in (a) the base protection case and (b) higher protection case. The scenarios are described in Table 1

Conference of the Parties to the CBD (2004). According to the Aichi Biodiversity Target 11, the protected area network should be expanded to at least 17% of the terrestrial area by 2020 and should consider areas of particular importance for biodiversity and ecosystem services (CBD, 2010). The target does not exclude harvesting of protected areas.

The work within the CBD aims to build upon existing agreed international plans of action, programs, and strategies and to support the development of national plans, programs, and strategies concerning agricultural biodiversity (CBD, 2000). In relation to approaches to the sustainable use of biofuels, the CBD refers to other policy documents such as the RED. In this regard, the RED approach for identifying highly biodiverse grassland areas is relevant for illustrating the influence of the CBD on grassland availability for bioenergy feedstock production.

3.2.4 | Estimation of highly biodiverse grassland areas in the EU

Following the definition in the RED, the estimated total grassland area in the EU-28 is approximately 93 Mha, of which about 24% is natural grassland and 76% is non-natural grassland (see Table 5 for national grassland areas).

In the EU, about 39% of natural grassland (8.7 Mha) can be found in Natura 2000 areas and consequently classified as

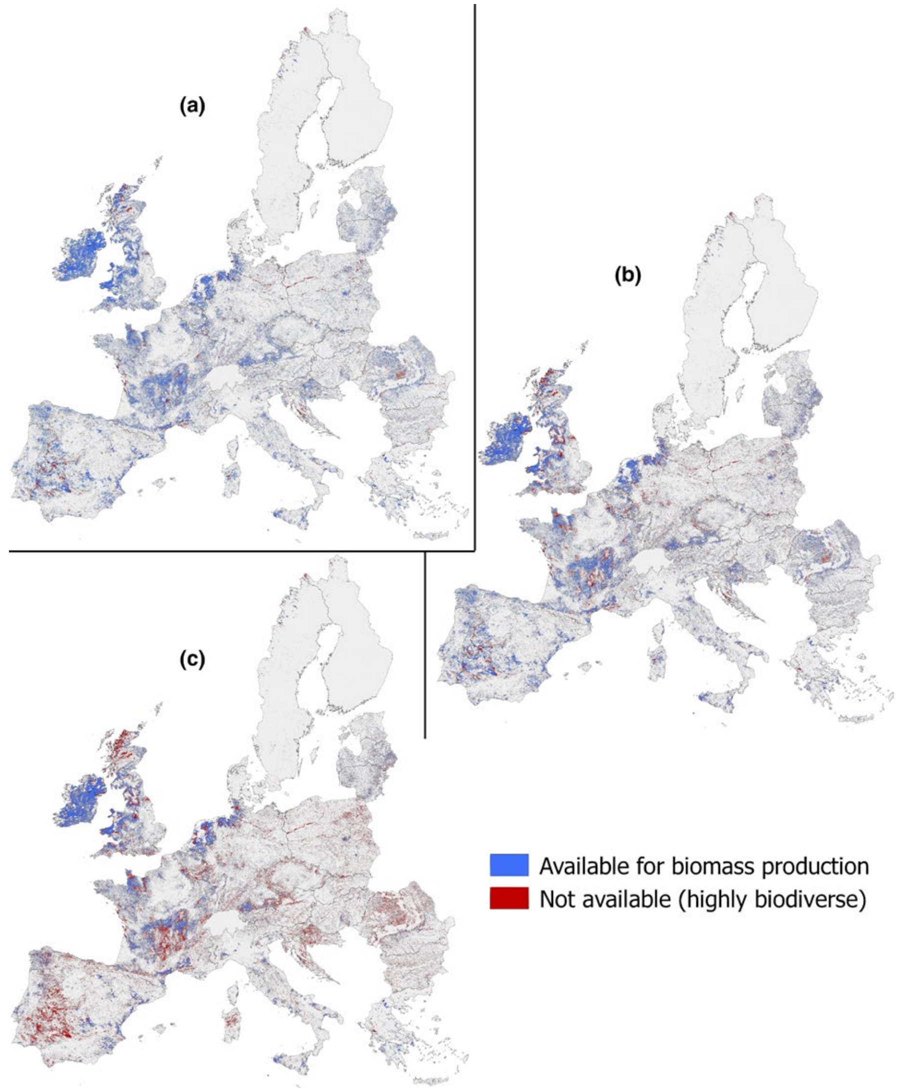

FIGURE 3 Estimated non-natural grassland areas in the EU-28 following the RED. Blue represents grassland areas available for bioenergy feedstock production in (a) the base protection case, (b) higher protection case, and (c) highest protection case. The scenarios are described in Table 1. Red represents grassland areas assumed to be highly biodiverse

highly biodiverse in the base protection case and therefore unavailable for biomass production following the RED (Figure 2). An additional 2.1 Mha are subject to other protection schemes, i.e., about 10.8 Mha (48%) of natural grasslands are categorized as highly biodiverse in the higher protection case (Figure 2). The remaining natural grassland areas are assumed available for bioenergy feedstock production. For shares of natural grassland area not available for bioenergy at the MS level see Table 5.

The total area of non-natural grassland in Natura 2000 (i.e., assumed not available for bioenergy feedstock production in the base protection case) is about 10.3 Mha (Figure 3). About 6.8 Mha is protected by other protection schemes, 21.1 Mha is classified as HNV farmland, and the remaining non-natural grassland is assumed available for bioenergy feedstock production (Figure 3). This implies that 15% of the total non-natural grassland area in the EU-28 is considered highly biodiverse in the base protection case, 24% in the higher protection case, and 54% in the highest protection case. For national shares see Table 5.

For the total EU grassland, the corresponding highly biodiverse shares are 21%, 30%, and 53% (Figure 4).

The potential biomass production on highly biodiverse natural grassland areas i.e., areas assumed not available for bioenergy in EU-28 was estimated at 1.07–2.41 EJ/year and 1.30–2.90 EJ/year for the base protection case and higher protection case, respectively, with ranges reflecting different management intensities. For highly biodiverse non-natural grassland, the potential biomass production was estimated at 1.37–2.82 EJ/year, 2.19–4.34 EJ/year, and 5.06–10.18 EJ/year for the base protection case, higher protection case, and highest protection case, respectively. For corresponding national biomass production levels, see Table 5.

3.3 | How Brazilian policies and legislation classify and protect biodiverse grassland

We estimate that grassland vegetation covers about 173 Mha—20% of the surface of Brazil—mostly located within the Cerrado biome where agricultural expansion over

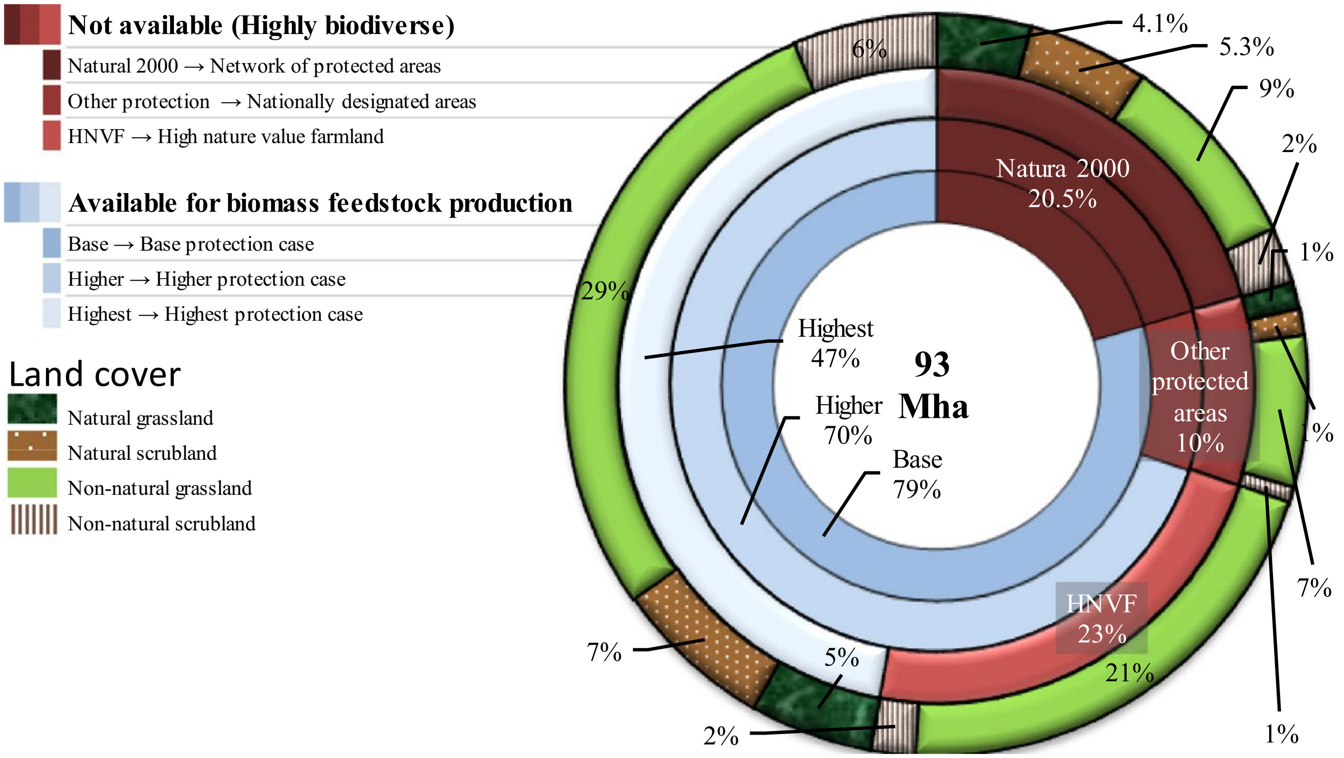

FIGURE 4 Distribution of the total EU grassland area in relation to available and not available land for bioenergy feedstock production in the three assessed protection scenarios representing different legal mechanisms for protecting biodiverse grassland areas

native vegetation has been intensive in recent years. Slightly more than 40% of the pristine natural grassland area has been converted to, e.g., pasture (classified as non-natural grassland), while 60% of the grassland territory remains covered by natural vegetation i.e., natural grassland (see Table 6 for grassland areas on the state level).

In the base protection case, about 16% (16 Mha) and 1% (0.7 Mha) of natural and non-natural grassland, respectively, would be considered highly biodiverse, i.e., protected within the Brazilian network of protected areas (Figures 5 and 6). Most of the unprotected grassland areas are located on privately owned rural property.

In the higher protection case, which also considers the Forest Act, an additional 45 Mha in total is estimated to be excluded from bioenergy feedstock production, with about 56% (56 Mha) and 8% (6 Mha) of the natural and non-natural grassland excluded, respectively (Figures 5 and 6). However, over 40% of the total natural grassland vegetation remains unprotected and legally available for conversion to agricultural land, most of it in regions of high priority for biodiversity conservation.

In the highest protection case, which also considers unprotected lands located within priority areas for biodiversity conservation, an additional 38 Mha of total grassland is excluded from bioenergy feedstock production, with about 77% (76 Mha) and 32% (24 Mha) of the natural and non-natural grassland excluded, respectively (Figures 5 and 6, see Table 6 for highly biodiverse grassland areas on the state level).

The amount of total grassland in Brazil considered highly biodiverse and excluded from bioenergy feedstock production in the base, higher, and highest protection cases is about 9%, 36%, and 58%, respectively (Figure 7).

The potential bioenergy feedstock production on highly biodiverse natural grassland areas in Brazil i.e., areas assumed not available for bioenergy is estimated at 4.4 EJ/year, 15.5 EJ/year, and 21.4 EJ/year for the base, higher, and highest protection case, respectively. For highly biodiverse non-natural grassland, it is estimated at 0.2 EJ/year, 1.6 EJ/year, and 6.6 EJ/year for the base, higher, and highest protection cases, respectively (for state-level results see Table 6).

Legal reserves on private properties represent almost 70% (38 Mha) of the legal protection of natural grassland. The Brazilian legislation recommends that legal reserves be allocated in areas of high importance for biodiversity preservation (Brazil, 2000). Studies are needed at the local level to support the identification of such areas. Decisions regarding the allocation of legal reserves on private properties fall under the state-level branches of the Ministry of Environment. However, in practice, farmers' preferences strongly influence the localization of legal reserves. Farmers usually cultivate the most suitable lands and set aside areas for preservation of native vegetation that are least suitable for agriculture (Freitas et al., 2017). Yet, farmers' preferences concerning land allocation often align with conservation objectives. For instance, setting aside steep terrains contributes to soil

TABLE 6 Estimate of the total natural and non-natural grassland area available (or not) for bioenergy feedstock production in the three biodiversity protection scenarios in Brazil following RED for Brazil. The results are presented at national and state levels

	Estimated grassland area (1,000 ha)		Share of natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)			Share of non-natural grassland area not available for bioenergy (%) The potential biomass production in this area is indicated in parenthesis (PJ/year)		
			Protection case			Protection case		
State	Natural	Non-natural	Base	Higher	Highest	Base	Higher	Highest
Rondônia	514.7	87.6	55 (79)	85 (122)	85 (123)	1 (0)	9 (2)	12 (3)
Amazonas	948.9	1.3	99 (264)	100 (265)	100 (265)	0 (0)	0 (0)	0 (0)
Roraima	3,894	20.7	76 (832)	87 (953)	87 (953)	39 (2)	42 (2)	42 (2)
Pará	1,172.8	102.2	36 (119)	77 (251)	79 (258)	3 (1)	13 (4)	15 (4)
Amapá	1,000.5	17.6	54 (152)	78 (218)	78 (218)	81 (4)	82 (4)	82 (4)
Tocantis	16,105.2	6,247.4	22 (996)	67 (3,032)	86 (3,857)	2 (39)	8 (135)	38 (672)
Maranhão	7,488.9	1,681.2	15 (313)	62 (1,309)	80 (1,683)	1 (7)	8 (39)	30 (141)
Piauí	6,032.8	2,082.5	5 (86)	32 (547)	56 (950)	0 (1)	3 (15)	27 (155)
Ceará	58.1	17.9	0 (0)	31 (5)	43 (7)	0 (0)	2 (0)	26 (1)
Rio Grande do Norte	56.5	44.5	0 (0)	31 (5)	85 (14)	0 (0)	3 (0)	71 (9)
Sergipe	8.4	88.7	0 (0)	72 (2)	72 (2)	0 (0)	5 (1)	5 (1)
Bahia	7,982	3,077.4	6 (127)	33 (730)	76 (1,698)	1 (4)	5 (43)	28 (244)
Minas Gerais	9,634.9	14,603	5 (136)	51 (1,372)	73 (1,980)	1 (54)	7 (302)	38 (1,541)
Espírito Santo	0	0.4	0 (0)	80 (0)	80 (0)	0 (0)	3 (0)	3 (0)
Rio de Janeiro	7.0	6.2	26 (0)	58 (1)	58 (1)	1 (0)	5 (0)	5 (0)
São Paulo	531.0	3,628.3	4 (6)	84 (125)	90 (133)	0 (4)	11 (111)	32 (322)
Paraná	118.1	780.7	15 (5)	77 (25)	78 (26)	2 (5)	17 (38)	28 (62)
Santa Catarina	388.5	978.8	8 (9)	63 (68)	63 (68)	1 (4)	9 (25)	9 (25)
Rio Grande do Sul	6,590.3	7,344	1 (20)	37 (678)	37 (678)	1 (15)	9 (191)	9 (191)
Mato Grosso do Sul	10,149.8	12,912.6	4 (101)	46 (1,297)	79 (2,257)	1 (35)	6 (202)	28 (999)
Mato Grosso	19,563.8	9,697.3	18 (959)	64 (3,527)	85 (4,652)	1 (29)	11 (291)	37 (1,001)
Goiás	6,780.5	10,187.8	8 (156)	51 (966)	81 (1,540)	0 (4)	6 (179)	40 (1,137)
Distrito Federal	113.2	226.9	47 (15)	76 (24)	98 (31)	5 (3)	14 (9)	69 (44)
Brazil	99,140	73,835	16 (4,376)	56 (15,525)	77 (21,393)	1 (211)	8 (1,594)	32 (6,560)

conservation, riparian areas that are preserved contribute to the preservation of freshwater and farmers that leave larger land fragments uncultivated can contribute to improved natural ecosystem connectivity in the landscape.

But there are also reasons to suspect that farmers' preferences do not align with the protection of highly biodiverse natural grasslands. The grassland landscape commonly includes small patches of forest and other non-grassland vegetation types, and farmers may be more likely to set aside these land patches than grassland areas because forest vegetation is commonly believed to have higher conservation value and costs more to convert into agricultural land. More research is needed because there is little empirical evidence supporting this supposition.

The allocation of legal reserves on private rural properties should also consider local ecological–economic zoning (Brazil, 2000), which is a statutory instrument to be elaborated at the state level to guide future public and private land-use interventions (Brazil, 2002). This planning tool aims at balancing socio-economic development and nature preservation, and at identifying areas with high suitability for food and other biomass production as well as areas where conservation should be prioritized (Vasconcelos, Hadad, & Martins Junior, 2014). The ecological–economic zoning may be especially important for grassland conservation, considering that almost half of the existing native grassland in priority areas is unprotected and thus legally available for agriculture (Figure 4). A large part of the grassland area overlaps with the so-called MATOPIBA regions, i.e., the new Brazilian agricultural frontier, where most of the recent conversion of natural vegetation has taken place (Gibbs et al., 2015; Strassburg, Latawiec, & Balmford, 2016).

4 | DISCUSSION

While there was a large variation in approaches among reviewed studies, it appears that biodiversity considerations can have a significant— and geographically varying—influence on the potential for bioenergy feedstock production. Few studies provided information specifically for grasslands, but the information available indicates that this observation also holds for the case of grasslands.

It is difficult to compare and judge whether specific datasets used in studies reflect higher/lower protection ambitions, but Campbell and Doswald, (2009) cautioned that the use of datasets for identifying important non-protected biodiverse areas is insufficient for decision-making related to biofuel production; areas may be excluded where there is low risk that biomass production would impact biodiversity negatively, and, conversely, areas may be designated as available for biomass production where negative biodiversity impacts are likely to occur. As already noted, there is also the concern that indirect effects may reduce the benefits of biodiversity protection.

To effectively address biodiversity concerns, Hennenberg et al. (2009) propose a combination of top-down and bottom-up approaches, including global

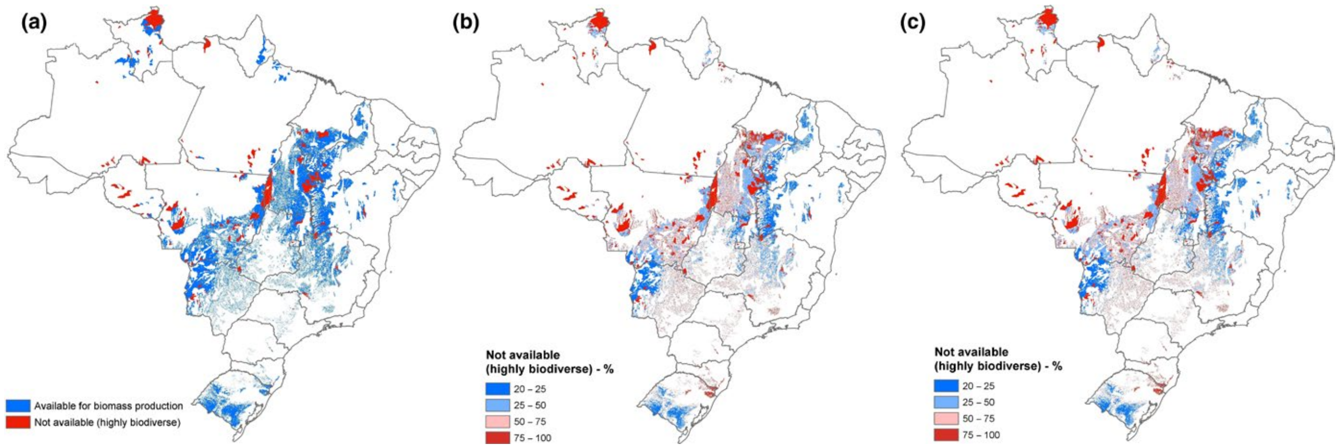

FIGURE 5 Estimated natural grassland areas in Brazil. Blue represents grassland areas available for bioenergy feedstock production and red represents grassland areas assessed to be highly biodiverse in (a) the base protection case, (b) higher protection case, and (c) highest protection case. In (b) and (c), the figures show what percentage of an area is highly biodiverse. The scenarios are described in Table 1

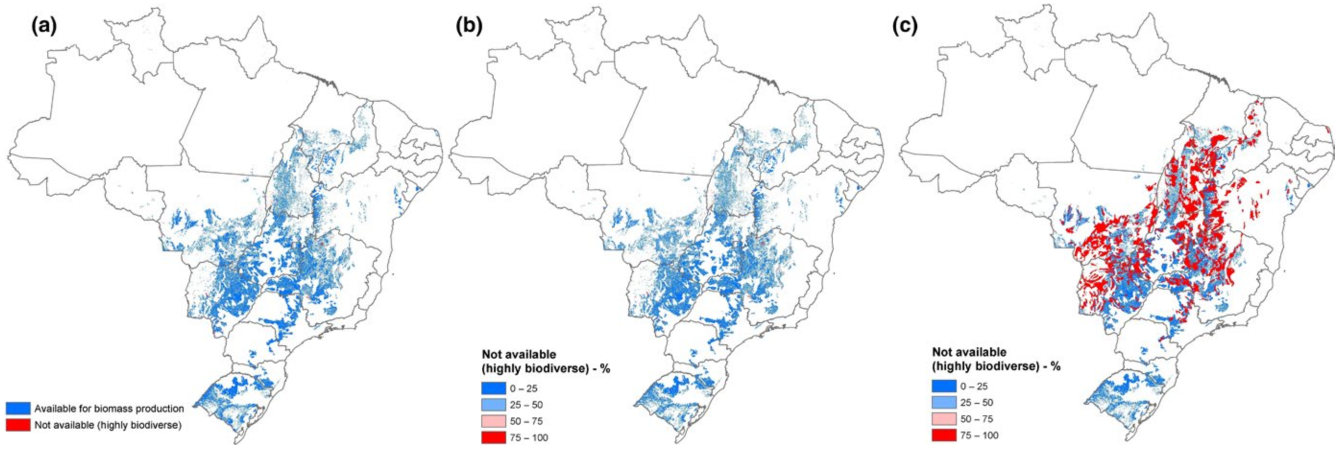

FIGURE 6 Estimated non-natural grassland areas in Brazil. Blue represents grassland areas available for bioenergy feedstock production and red represents grassland areas assumed to be highly biodiverse in (a) the base protection case, (b) higher protection case, and (c) highest protection case. In (b) and (c), the figures show what percentage of an area is highly biodiverse. The scenarios are described in Table 1

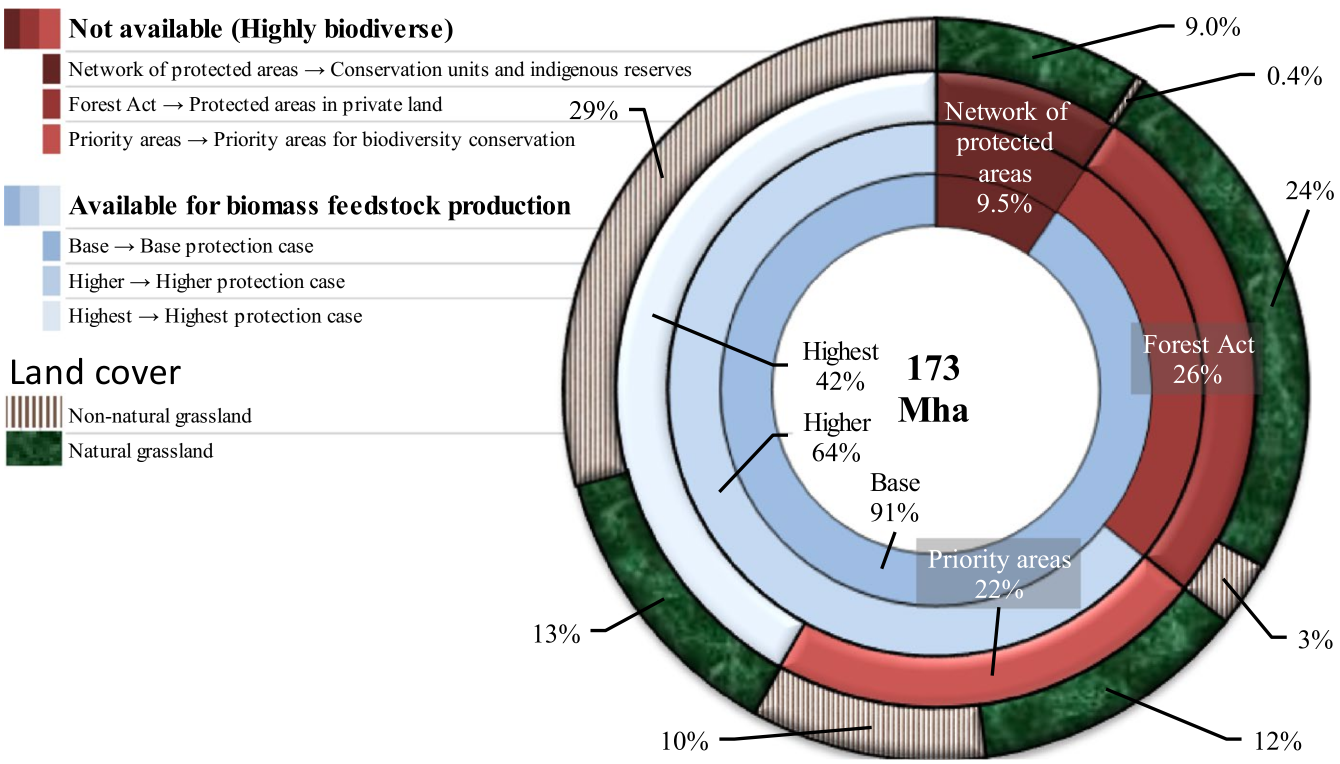

FIGURE 7 Distribution of the total Brazilian grassland area in relation to land available and not available for bioenergy feedstock production in the three assessed protection scenarios representing major legal mechanisms protecting biodiverse grassland, and priority areas for biodiversity conservation

biodiversity programs, national and/or sub-national lists of plant-habitat types for highly biodiverse grassland, and/or lists of characteristic species to determine highly biodiverse grassland. Specifically, Hennenberg et al. (2009) present a national approach, applied to Germany, for identifying highly biodiverse grassland. This approach could potentially be applied to other countries, too. It includes the identification of specific species and assessments by experts and appears likely to accurately identify highly biodiverse grassland areas on a local level. A combination of such national approaches will likely improve the possibility to protect biodiversity and may also provide a better understanding of the influence on prospects for bioenergy feedstock production. A globally coordinated effort to develop databases and standardize methodologies can help avoid inconsistencies among countries.

In the EU policy context, the RED complements and strengthens the ambition to protect biodiverse grasslands in the CAP and the CBD. The RED represents a higher level of ambition regarding the aim to guarantee a certain protection level for highly biodiverse grasslands. It includes the most specific and detailed definition and is more stringent than the CAP, which gives the individual MS more freedom to decide which grassland areas should be protected and consequently not used for biomass plantations. Both the RED and the CAP include natural and non-natural grasslands. A challenge is that the lack of clear definitions and guidance in relation to the RED leads to uncertainty about the prospects for bioenergy from grasslands on the EU market.

Nevertheless, the exclusion of Natura 2000, HNV farmland, and other protected areas, represents a practical approach to considering biodiversity in relation to the RED, even though the approach may include some areas that are protected mainly for other reasons. The approach provides a basis for quantifying grassland availability for biomass production for energy that reflects real-world conditions. The assessment for the EU-28 indicates that some 39%–48% (about 9–11 Mha) and 15%–54% (about 10–38 Mha) of the total natural and non-natural grasslands, respectively, may be considered highly biodiverse. In Brazil, an estimated 16%–77% (about 16–76 Mha) and 1%–32% (about 7–24 Mha) of natural and non-natural grasslands, respectively, may be considered highly biodiverse. Obviously, other restrictions also come into play and the grassland areas where bioenergy feedstock production makes sense will be smaller than what is, in principle, available from a biodiversity protection point of view (e.g., Arodudu, Voinov, & Duren, 2013; Cintas, Berndes, Englund, Cutz, & Johnsson, 2018; van Duren, Voinov, Arodudu, & Firrisa, 2015).

Biodiverse grasslands that need to be managed to maintain grassland status (i.e., non-natural grasslands) represent a specific category that deserves more attention. As noted, the RED and the CAP allow the use of biomass from such grasslands if evidence is provided that harvesting is necessary to preserve its grassland status. Land management for biodiversity preservation will likely be more attractive if the associated biomass harvest generates additional income. Certification systems could consider including this biomass category based on a framework for identifying relevant areas and approving biomass supply associated with appropriate grassland management systems. The RED II includes new text stating that non-natural grasslands be "…identified as being highly biodiverse by the relevant competent authority." It is currently unclear how this will influence how highly biodiverse non-natural grasslands are identified in the EU.

Ecological–economic zoning may be important for protection of highly biodiverse grasslands in Brazil where landowners can potentially produce bioenergy feedstock on grasslands in protected as well as unprotected areas (Berndes et al., 2016; Brazil, 2000). Native vegetation in legal reserves (i.e., protected areas) can be managed for commercial purposes (Brazil, 2000), including biomass production, provided that biodiversity is maintained and native vegetation is not suppressed. However, all management activities require a license, i.e., a management plan for the sustainable use of native vegetation approved by state-level branches of the Ministry of Environment (Brazil, 2000).

Licensed use of legal reserve areas and unprotected native vegetation for biomass production in Brazil might encourage compliance with legislation by making the preservation of native vegetation economically attractive to farmers. Voluntary certification systems combined with market restrictions for uncertified products could be a way to guarantee the preservation of biodiverse grasslands. However, Brazilian grassland areas consist of different vegetation types with varying sensitivity to the harvesting of biomass, and it may be difficult to establish sustainable management plans to avoid biodiversity impacts.

To conclude, the research results reported here provide some new insights into the possible influence of biodiversity considerations on grassland availability for bioenergy feedstock production. But the actual influence will depend on the real-world implementation of the relevant regulations. In this regard, we agree with the recommendation by Slade et al. (2014) on a learning-by-doing approach to identify merits and pitfalls of biomass deployment and improve understanding of the prospects for higher levels of biomass use. Here, one important step is to clarify how definitions and grassland delineation in regulations should be interpreted, because this will have a significant influence on the prospects for bioenergy from grasslands, as well as biodiversity impacts of the bioenergy feedstock production that is allowed under such regulations.

ACKNOWLEDGEMENTS

We are grateful to two anonymous reviewers who provided very valuable comments and helped improve the work considerably. We also thank Paulina Essunger for valuable input. We gratefully acknowledge the economic support received from the Swedish Research Council Formas (for the project "Consideration to highly biodiverse grasslands in sustainability certification and other regulation: implications for bioenergy supply potentials," Registration number 941-2015-1795) and from IEA Bioenergy.

ORCID

Julia Hansson http://orcid.org/0000-0002-8071-2213
Flávio L. M. De Freitas http://orcid.org/0000-0002-8313-5845

REFERENCES

Arodudu, O., Voinov, A., & van Duren, I. (2013). Assessing bioenergy potential in rural areas—A NEG-EROEI approach. *Biomass and Bioenergy*, *58*, 350–364. https://doi.org/10.1016/j.biombioe.2013.07.020

Baum, S., Bolte, A., & Weih, M. (2012). Short Rotation Coppice (SRC) plantations provide additional habitats for vascular plant species in agricultural mosaic landscapes. *BioEnergy Research*, *5*(3), 573–583. https://doi.org/10.1007/s12155-012-9195-1

Beringer, T. I. M., Lucht, W., & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, *3*(4), 299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x

Berndes, G., Börjesson, P., Ostwald, M., & Palm, M. (2008). Multifunctional biomass production systems—An overview with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, *2*(1), 16–25. https://doi.org/10.1002/bbb.52

Berndes, G., Chum, H., Leal, M. R. L. V., Sparovek, G., & Walter, A. (2016). Bioenergy feedstock production on grasslands and pastures: Brazilian experiences and global outlook. IEA Bioenergy Task 43, Report 2016:06.

Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy*, *25*(1), 1–28. https://doi.org/10.1016/S0961-9534(02)00185-X

Böttcher, H. (2014) [Personal communication 2014–11-27 via e-mail regarding more detailed data from Böttcher et al., 2013].

Böttcher, H., Frank, S., Havlík, P., & Elbersen, B. (2013). Future GHG emissions more efficiently controlled by land-use policies than by bioenergy sustainability criteria. *Biofuels, Bioproducts and Biorefining*, *7*(2), 115–125. https://doi.org/10.1002/bbb.1369

Brazil (2002). Ecological-Econimic Zonning Decreto Federal n° 4.297 de 10 de julho de 2002, Numero 4.297. Brazil.

Brazil (2000). *National system of conservation units "Sistema Nacional de Unidades de Conservação da Natureza"*.Law n° 9.985, 2000-07-18, Brasilia, Brazil.

Campbell, A., & Doswald, N. (2009). *The impacts of biofuel production on biodiversity: A review of the current literature*. Cambridge, UK: UNEP-WCMC.

CBD (2000). Decision adopted by the conference of the parties to the convention on biological diversity at its fifth meeting. COP 5

Decision V/5. Agricultural biological diversity: Review of phase I of the programme of work and adoption of a multi-year work programme. Retrieved from https://www.cbd.int/decision/cop/default.shtml?xml:id=7147.

CBD (2004). Decision adopted by the conference of the parties to the convention on biological diversity at its seventh meeting. CoP 7 Decision VII/30: Goal 1, Target 1.1. Retrieved from https://www.cbd.int/doc/decisions/cop-07/cop-07-dec-30-en.pdf.

CBD. (2010). Decision adopted by the conference of the parties to the convention on biological diversity at its tenth meeting, Nagoya, Japan. COP 10 Decision X/2 Strategic goal C, Target 11. Retrieved from https://www.cbd.int/decision/cop/?xml:id=12268.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., … Pingoud, K. (2011) Chapter 2: Bioenergy. In O. Edenhofer, R. Pichs-Madruga, & Y. Sokona et al. (Eds.), *IPCC Special report on renewable energy sources and climate change mitigation* (pp. 209–332). Cambridge, UK and New York, NY: Cambridge University Press.

Cintas, O., Berndes, G., Englund, O., Cutz, L., & Johnsson, F. (2018). Geospatial supply–demand modeling of biomass residues for co-firing in European coal power plants. *GCB Bioenergy*, *2018*, 1–18. in press. doi: 10.1111/gcbb.12532.

Cornelissen, S., Koper, M., & Deng, Y. Y. (2012). The role of bioenergy in a fully sustainable global energy system. *Biomass and Bioenergy*, *41*, 21–33. https://doi.org/10.1016/j.biombioe.2011.12.049.

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., … Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, *7*(5), 916–944. https://doi.org/10.1111/gcbb.12205

Dauber, J., Jones, M. B., & Stout, J. C. (2010). The impact of biomass crop cultivation on temperate biodiversity. *GCB Bioenergy*, *2*(6), 289–309. https://doi.org/10.1111/j.1757-1707.2010.01058.x

de Wit, M., & Faaij, A. (2010). European biomass resource potential and costs. *Biomass and Bioenergy*, *34*(2), 188–202. https://doi.org/10.1016/j.biombioe.2009.07.011

Deng, Y. Y., Koper, M., Haigh, M., & Dornburg, V. (2015). Country-level assessment of long-term global bioenergy potential. *Biomass and Bioenergy*, *74*, 253–267. https://doi.org/10.1016/j.biombioe.2014.12.003

Dixon, A. P., Faber-Langendoen, D., Josse, C., Morrison, J., Loucks, C. J., & Ebach, M. (2014). Distribution mapping of world grassland types. *Journal of Biogeography*, *41*(11), 2003–2019. https://doi.org/10.1111/jbi.12381

Dornburg, V., van Vuuren, D., van de Ven, G., Langeveld, H., Meeusen, M., Banse, M., … Faaij, A. (2010). Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science*, *3*, 258–267. https://doi.org/10.1039/b922422j

EEA (2006). *How much bioenergy can Europe produce without harming the environment?* European Environment Agency EEA Report No 7/2006.

EEA (2007). *Estimating the environmentally compatible bioenergy potential from agriculture*. EEA Technical report No 12/2007.

EEA (2013). *EU bioenergy potential from a resource-efficiency perspective*. European Environment Agency EEA Report No 6/2013.

EEA (2016a). *CORINE Land cover 2012 v. 18. European Environment Agency*. Retrieved from https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012

EEA (2016b). *Natura 2000 End 2016—Spatial lite*. European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/data/natura-8/natura-2000-spatial-data/natura-2000-spatial-lite-1.

EEA (2017a). *Dataset: Ecosystem types of Europe*. European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/data/ecosystem-types-of-europe#tab-related-publications.

EEA. (2017b). *Nationally designated areas (CDDA)*. European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-12.

EEA (2017c). *High nature value (HNV) farmland*. European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/data/high-nature-value-farmland.

Elbersen, B., Petersen, F. U., Lesschen, J. E., Böttcher, J. P., Overmars, H., & Overmars, K. (2013). Assessing the effect of stricter sustainability criteria on EU biomass crop potential. *Biofuels, Bioproducts and Biorefining*, *7*(2), 173–192. https://doi.org/10.1002/bbb.1396

Englund, O., Berndes, G., Persson, M. U., & Sparovek, G. (2015). Oil palm for biodiesel in Brazil—Risks and opportunities. *Environmental Research Letters*, *10*(4), 044002.

Erb, K. H., Haberl, H., & Plutzar, C. (2012). Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, *47*(4), 260–269. https://doi.org/10.1016/j.enpol.2012.04.066

European Commission. (2014a). *Commission regulation (EU) No 1307/2014 of 8 December 2014 on defining the criteria and geographic ranges of highly biodiverse grassland for the purposes of Article 7b(3)(c) of Directive 98/70/EC of the European Parliament and the Council relating to the quality of petrol and diesel fuels and Article 17(3)(c) of Directive 2009/28/EC of the European Parliament and the Council on the promotion of the use of energy from renewable sources*.

European Commission. (2014b). *Commission delegated regulation (EU) no 639/2014 of 11 March 2014 supplementing Regulation (EU) No 1307/2013 of the European Parliament and of the Council establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and amending Annex X to that Regulation*.

European Commission. (2015). *Letter to the voluntary schemes with guidance how to verify protection of highly biodiverse grasslands*. January 29, 2015. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/PAM%20to%20vs%20on%20HBG.pdf.

European Commission. (2016). *Commission staff working document—Review of greening after one year*. PART 3/6, Annex 2. Brussels, 22.6.2016 SWD(2016) 218 final. Retrieved from https://ec.europa.eu/agriculture/sites/agriculture/files/direct-support/pdf/2016-staff-working-document-greening-annex-2_en.pdf.

European Commission. (2017). *Preparation of a new Renewable Energy Directive for the period after 2020*. Retrieved from https://ec.europa.eu/energy/en/consultations/preparation-new-renewable-energy-directive-period-after-2020.

European Council (1992). *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*.

European Parliament and Council (2009a). *Directive 2009/28/EC of the European Parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*.

European Parliament and Council (2009b) *Directive 2009/147/EC of the European Parliament and of the council of 30 November 2009 on the conservation of wild birds*.

European Parliament and Council (2013). *Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17*

December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009.

Firbank, L. (2008). Assessing the ecological impacts of bioenergy projects. *BioEnergy Research*, *1*(1), 12–19. https://doi.org/10.1007/s12155-007-9000-8

Fischer, G., Hizsnyik, E., Prieler, S., Shah, M., & vanVelthuizen, H. (2009). Biofuels and Food Security. OFID (OPEC Fund for International Development) study prepared by IIASA (International Institute for Applied Systems Analysis), Laxenburg, Austria. Retrieved from http://pure.iiasa.ac.at/id/eprint/8969/

Fischer, G., Prieler, S., van Velthuizen, H., Berndes, G., et al. (2010). Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass and Bioenergy*, *34*(2), 173–187. https://doi.org/10.1016/j.biombioe.2009.07.009

Frank, S., Böttcher, H., Havlík, P., Valin, H., Mosnier, A., Obersteiner, M., … Elbersen, B. (2013). How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets? *GCB Bioenergy*, *5*(3), 306–314. https://doi.org/10.1111/j.1757-1707.2012.01188.x

Freitas, F. L. M., Englund, O., Sparovek, G., Berndes, G., Guidotti, V., Pinto, L. F. G., & Mörtberg, U. (2017). Who owns the Brazilian carbon? *Global Change Biology*, *24*(5), 2129–2142. https://doi.org/10.1111/gcb.14011

Gibbs, H. K., Rausch, L., Munger, J., Schelly, I., Morton, D. C., Noojipady, P., … Walker, N. F. (2015). Brazil's Soy Moratorium. *Science*, *347*, 377–378. https://doi.org/10.1126/science.aaa0181

Hellmann, F., & Verburg, P. H. (2010). Impact assessment of the European biofuel directive on land use and biodiversity. *Journal of Environmental Management*, *91*(6), 1389–1396.

Hennenberg, K. J., Fritsche, U. R., & Bleher, D. et al. (2009). *GTZ Project for the Practical Implementation of BioSt-NachV—Subproject Area-related Requirements (Art. 4–7 + 10)—Specifications and recommendations for "grassland" area type (Final draft)*.

Holland, R. A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D., & Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, *46*, 30–40. https://doi.org/10.1016/j.rser.2015.02.003

Hoogwijk, M., Faaij, A., Eickhout, B., Devries, B., & Turkenburg, W. (2005). Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, *29*(4), 225–257. https://doi.org/10.1016/j.biombioe.2005.05.002

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, *25*(2), 119–133. https://doi.org/10.1016/S0961-9534(02)00191-5

IBGE (1993). *Vegetation map*. Rio de Janeiro, Brazil: Ed Brazilian Institute of Geography and Statistics.

IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds Edenhofer O, Pichs-Madruga R, Sokona Y et al]. Cambridge, UK and New York, NY: Cambridge University Press.

Kapos, V., Ravilious, C., Campbell, A., Dickson, B., Gibbs, H., Hansen, M., et al. (2008). *Carbon and biodiversity: A demonstration atlas*. Cambridge: UNEP-WCMC.

Ketzer, D., Rösch, C., & Haase, M. (2017). Assessment of sustainable grassland biomass potentials for energy supply in Northwest Europe. *Biomass and Bioenergy*, *100*, 39–51. https://doi.org/10.1016/j.biombioe.2017.03.009

Kluts, I., Wicke, B., Leemans, R., & Faaij, A. (2017). Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. *Renewable and Sustainable Energy Reviews*, *69*, 719–734. https://doi.org/10.1016/j.rser.2016.11.036

Manning, P., Taylor, G., & Hanley, M. E. (2015). Bioenergy, food production and biodiversity—An unlikely alliance? *GCB Bioenergy*, *7*(4), 570–576. https://doi.org/10.1111/gcbb.12173

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology*, *83*, 37–46. https://doi.org/10.1016/S0960-8524(01)00118-3

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., … Purvis, A. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*, 45–50. https://doi.org/10.1038/nature14324

Prates, A. P., Vasconcelos, J. P. S. D., Bayma, A. P., et al. (2016). 2ª *Atualização das Áreas Prioritárias para Conservação da Biodiversidade 2016/2018*. Brasilia, Brazil:Ed Environment MO.

Ramirez-Almeyda, J., Elbersen, B., Monti, A., Staritsky, I., Panoutsou, C., Alexopoulou, E., … Elbersen, W. (2017). Assessing the potential for non-food crops. In C. Panoutsou (Ed.), *Modelling and optimization of biomass supply chains. Top-down and bottom-up assessment for agricultural, forest and waste feedstock* (pp. 219–252). London, UK: Academic Press, Elsevier Inc.

Rösch, C., Aust, C., & Jörissen, J. (2013). Envisioning the sustainability of the production of short rotation coppice on grassland. *Energy, Sustainability and Society*, *3*(7), 2–17.

Schueler, V., Weddige, U., Beringer, T., Gamba, L., & Lamers, P. (2013). Global biomass potentials under sustainability restrictions defined by the European Renewable Energy Directive 2009/28/EC. *GCB Bioenergy*, *5*(6), 652–663. https://doi.org/10.1111/gcbb.12036

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. *Nature Climate Change*, *4*, 99–105. https://doi.org/10.1038/nclimate2097

Smeets, E. M. W., & Faaij, A. P. C. (2010). The impact of sustainability criteria on the costs and potentials of bioenergy production—Applied for case studies in Brazil and Ukraine. *Biomass and Bioenergy*, *34*(3), 319–333. https://doi.org/10.1016/j.biombioe.2009.11.003

Smeets, E., Faaij, A., Lewandowski, I., & Turkenburg, W. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, *33*(1), 56–106. https://doi.org/10.1016/j.pecs.2006.08.001

Sparovek, G., Antoniazzi, L. B., Barretto, A., Barros, A. C., Benevides, M., Berndes, G., … Precioso, V. (2016). Sustainable bioproducts in Brazil: Disputes and agreements on a common ground agenda for agriculture and nature protection. *Biofuels, Bioproducts and Biorefining*, *10*(3), 204–221. https://doi.org/10.1002/bbb.1636

Sparovek, G., Barretto, A. G. D. O. P., Matsumoto, M., & Berndes, G. (2015). Effects of governance on availability of land for agriculture and conservation in Brazil. *Environmental Science & Technology*, *49*(17), 10285–10293. https://doi.org/10.1021/acs.est.5b01300

Strassburg, B. B. N., Latawiec, A., & Balmford, A. (2016). Brazil: Urgent action on Cerrado extinctions. *Nature*, *540*, 199–199. https://doi.org/10.1038/540199a

UN (2015). *Sustainable development goals*. United Nations. Retrieved fromhttps://www.un.org/sustainabledevelopment/sustainable-development-goals/

UNEP/UN (2001). *Global biodiversity outlook 1*. Secretariat of the Convention on Biological Diversity. Retrieved from https://www.cbd.int/gbo1/default.shtml.

van Duren, I., Voinov, A., Arodudu, O., & Firrisa, M. T. (2015). Where to produce rapeseed biodiesel and why? Mapping European rapeseed energy efficiency. *Renewable Energy*, *74*, 49–59. https://doi.org/10.1016/j.renene.2014.07.016

van Meerbeek, K., Ottoy, S., de Andrés, G. M., Muys, B., & Hermy, M. (2016). The bioenergy potential of Natura 2000—A synergy between climate change mitigation and biodiversity protection. *Frontiers in Ecology and the Environment*, *14*(9), 473–478. https://doi.org/10.1002/fee.1425

van Vuuren, D. P., van Vliet, J., & Stehfest, E. (2009). Future bio-energy potential under various natural constraints. *Energy Policy*, *37*(11), 4220–4230. https://doi.org/10.1016/j.enpol.2009.05.029

Vasconcelos, V. V., Hadad, R. M., & Martins Junior, P. P. (2014). Zoneamento Ecológico-Econômico—Objetivos e Estratégias de Política Ambiental. *Gaia Scientia (UFPB)*, *7*, 119–132.

Verdade, L. M., Piña, C. I., & Rosalino, L. M. (2015). Biofuels and biodiversity: Challenges and opportunities. *Environmental Development*, *15*, 64–78. https://doi.org/10.1016/j.envdev.2015.05.003

WBGU (2009). *Future bioenergy and sustainable land use*. London and Sterling, VA: German Advisory Council on Global Change. Earthscan.

White, R. P., Murray, S., & Rohweder, M. (2000). *Pilot analysis of global ecosystems. Grassland ecosystems*. Washington, DC: World Resources Institute.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Hansson J, Berndes G, Englund O, De Freitas FLM, Sparovek G. How is biodiversity protection influencing the potential for bioenergy feedstock production on grasslands? *GCB Bioenergy*. 2019;11:517–538. https://doi.org/10.1111/gcbb.12568