Annals of Botany **110**: 1263–1270, 2012
doi:10.1093/aob/mcs209, available online at www.aob.oxfordjournals.org

ANNALS OF BOTANY Founded 1887

REVIEW: PART OF A HIGHLIGHT ON BREEDING STRATEGIES FOR FORAGE AND GRASS IMPROVEMENT

The role of grasslands in food security and climate change

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Received: 16 January 2012 Returned for revision: 20 April 2012 Accepted: 21 August 2012 Published electronically: 21 September 2012

• *Background* Grasslands are a major part of the global ecosystem, covering 37 % of the earth's terrestrial area. For a variety of reasons, mostly related to overgrazing and the resulting problems of soil erosion and weed encroachment, many of the world's natural grasslands are in poor condition and showing signs of degradation. This review examines their contribution to global food supply and to combating climate change.
• *Scope* Grasslands make a significant contribution to food security through providing part of the feed requirements of ruminants used for meat and milk production. Globally, this is more important in food energy terms than pig meat and poultry meat. Grasslands are considered to have the potential to play a key role in greenhouse gas mitigation, particularly in terms of global carbon storage and further carbon sequestration. It is estimated that grazing land management and pasture improvement (e.g. through managing grazing intensity, improved productivity, etc) have a global technical mitigation potential of almost 1·5 Gt CO_2 equivalent in 2030, with additional mitigation possible from restoration of degraded lands. Milk and meat production from grassland systems in temperate regions has similar emissions of carbon dioxide per kilogram of product as mixed farming systems in temperate regions, and, if carbon sinks in grasslands are taken into account, grassland-based production systems can be as efficient as high-input systems from a greenhouse gas perspective.
• *Conclusions* Grasslands are important for global food supply, contributing to ruminant milk and meat production. Extra food will need to come from the world's existing agricultural land base (including grasslands) as the total area of agricultural land has remained static since 1991. Ruminants are efficient converters of grass into humanly edible energy and protein and grassland-based food production can produce food with a comparable carbon footprint as mixed systems. Grasslands are a very important store of carbon, and they are continuing to sequester carbon with considerable potential to increase this further. Grassland adaptation to climate change will be variable, with possible increases or decreases in productivity and increases or decreases in soil carbon stores.

Key words: Grasslands, climate change, food security, carbon sequestration.

INTRODUCTION

The FAO reports that permanent meadows and pastures cover 3·4 billion ha or 69 % of the world's agricultural area. The Global Land Cover Characteristics Database (GLCCD) of the US Geological Survey provides a global land area classification by ecosystem type (Table 1) as described by Loveland *et al.* (2000). It divides the earth's terrestrial area into a number of classifications (Table 1). Five of these (Open or Closed Shrublands, Woody and Non-woody Savannas, and Grasslands) are aggregated to form Grasslands which are estimated to cover 50 million square kilometres or 37 % of the earth's terrestrial area (excluding Greenland and Antarctica). Grassland also occupies some of the area classified as Cropland/Natural Vegetation Mosaic. For instance, most of Ireland is in this category. In western Europe, Peeters (2004) reported that grasslands occupy 40 % of the agricultural land area, with the figure being as high as 57, 65 and 72 % in Austria, United Kingdom and Switzerland, respectively. In Ireland, over 90 % of the agricultural area consists of pasture, grass silage or hay, and rough grazing (O'Mara, 2008). This paper reviews current thinking on grasslands in relation to food security and in relation to their associated greenhouse gas footprint, and also assesses both their vulnerability and adaptability to climate change.

THE STATE OF THE WORLD'S GRASSLANDS

Much of the grasslands area outlined above is located in the great natural grasslands of central Asia, sub-Saharan and southern Africa, North and South America and Australia/New Zealand, and most are mainly grazed by ruminants. There are also significant areas of grassland in Europe and North America that often are part of mixed cropland systems. Excellent descriptions of the state of many of the great grasslands of the world by various authors have recently been compiled by FAO (Suttie *et al.*, 2005). These include the grasslands of eastern Africa, South Africa, Patagonia, the South American pampas and campos, central North America, Mongolia, the Tibetan Steppe, the Russian Steppe and Australia.

Water is a hugely important factor in the use of land. Where water is sufficient, much of the world's natural grasslands have been converted to arable farming, and grazing only remains in these areas on the more marginal lands that are difficult or unfit for cropping. Ramankutty *et al.* (2008) reported that around 20% of the world's native grasslands have been converted to cultivated crops. According to Buringh and Dudal (1987), most of the world's grasslands (five-sixths) are on poor quality land with only one-sixth on land that was classified in the high and medium quality category. Suttie *et al.* (2005) concluded that many of the world's grasslands are in poor condition and showing signs of degradation caused by a variety of reasons, mostly related to overgrazing and the resulting problems of soil erosion and weed encroachment. According to Oldeman (1994), 7·5 % of the world's grasslands have been degraded and the Land Degradation Assessment in Drylands (LADA) concluded that about 16 % of rangelands are currently undergoing degradation (FAO, 2010). Many of the problem arise from the breakdown of traditional tribal authority with centuries-old nomadic and transhumant grazing systems. Population growth, urbanization, collectivization of farms and recent breaking up of collective farms, and land distribution have all contributed to a cessation of these traditional grazing systems in many regions, and their replacement with continuous overgrazing of the better grasslands and their subsequent deterioration. In these conditions, the consequences of drought and soil erosion of grasslands are exacerbated. As discussed below, restoration of degraded lands (including grasslands) represents one of the largest greenhouse gas mitigation potentials in agriculture, but one which faces significant social, political and economic barriers to its achievement.

THE FOOD SECURITY ISSUE

Changes in food demand

The world's population has risen from less than three billion in 1950 to almost seven billion today, and, according to the median variant of the latest United Nations projections (United Nations, 2011), is projected to reach 9·3 billion by 2050 and ten billion by the end of this century. Most of this increase will come from countries in Asia, Latin America and Africa. The populations in the more-developed regions will remain more or less static between now and 2050, and most of the increase will be in the least-developed countries and less-developed regions excluding the least-developed countries (Fig. 1). This will pose significant challenges to the food production system of the world.

As well as population growth, the other driver of increased food demand is growing incomes. Income growth is forecast to be strong in the less- and least-developed countries (OECD/FAO, 2011) at per capita rates of 3·7 % and 4·7 %, respectively. This strong income growth will be reflected in particularly strong food demand as consumers in countries with low but increasing incomes devote a greater share of additional income to diet. Areas where food demand is expected to be particularly strong are eastern Europe, Asia and Latin America, less strong in sub-Saharan Africa, and stagnant in developed countries. In addition, as incomes rise, it is expected that there will be a shift towards more processed and prepared foods with a higher proportion of animal protein. For instance, OECD/FAO (2011) projects an increase in global per capita meat

TABLE 1. *Land classification and area (square kilometres) by ecosystem type*

Classification	km^2	Proportion
Forest/Evergreen/Needleleaf	4 858 707	0·036
Forest/Evergreen/Broadleaf	13 479 749	0·100
Forest/Deciduous/Needleleaf	1 959 892	0·015
Forest/Deciduous/Broadleaf	2 229 308	0·017
Forest/Mixed	9 930 103	0·074
Shrublands/Open	2 636 901	0·020
Shrublands/Closed	20 706 263	0·154
Savannas/Woody	8 405 816	0·062
Savannas/Non-woody	7 607 497	0·056
Grasslands	10 541 721	0·078
Permanent wetlands	984 328	0·007
Croplands	15 206 323	0·113
Urban and built-up	256 332	0·002
Croplands/Natural vegetation mosaic	11 586 898	0·086
Snow or ice	2 621 872	0·019
Barren or sparsely vegetated	18 332 436	0·136
Water bodies	3 494 824	0·026
Total	134 838 970	1·000

Source: http://earthtrends.wri.org/text/forests-grasslands-drylands/for2_2003.pdf (accessed 9 July 2011), based on Loveland *et al.* (2000).

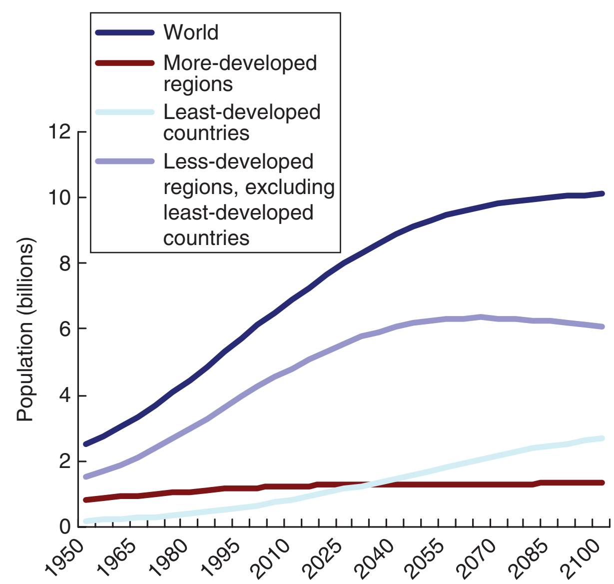

FIG. 1. World population projections (source: United Nations, 2011).

consumption from 32·6 to 35·4 kilogram over this decade. However, it is expected that most of this growth in consumption up to 2020 (due to both increased per capita consumption and increased population) will be in poultry meat (+29 %) and pig meat (+20 %), while beef consumption is projected to increase by only 14 % (Table 2). These differences are related to the projected evolution of the relative prices of different meats. In contrast to slowly growing ruminant meat consumption, demand for milk and dairy products is expected to grow strongly at 22 % over the next 10 years. As these trends are likely to continue past 2020, a large increase in demand for food and food potentially produced on global grasslands can be anticipated. Combining FAO (2006) projections of an

TABLE 2. *Growth in global consumption of major food products to 2020*

	Beef (kt cwe)*	Pig meat (kt cwe)*	Poultry meat (kt cwe)*	Sheep meat (kt cwe)*	Dairy products (kt pw)[†]	Cereals (mt)[‡]
Average 2008–2010	64 620	105 705	95 156	12 766	37 135	1039
2020	73 589	126 679	122 489	15 607	45 373	1204
% change	13·9	19·8	28·7	22·3	22·2	15·9

Source: OECD/FAO (2011).
* Thousand tonnes of carcass weight equivalent.
[†] Thousand tonnes of product weight.
[‡] Million tonnes.

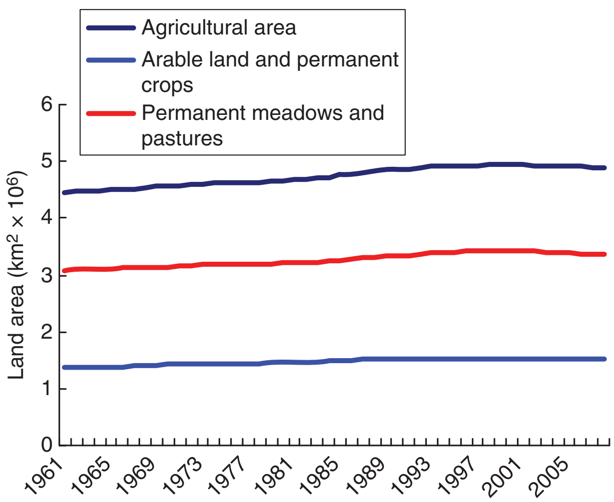

FIG. 2. Global agricultural land area (source: FAOSTAT, 2009 data, http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377; accessed 17 July 2011).

increase in per capita calorie consumption of 12 % in the first half of this century with a projected 52 % increase in population over this period (UN, 2011) gives an increase in calorie consumption of 70 %. In addition, the trends shown in Table 2 of higher growth in consumption of animal products compared with cereals indicates that the growth in consumption of livestock products could be even higher.

The increase in food demand has contributed to land degradation, primarily through overgrazing, as outlined above. This is a complex issue and is related not just to the growing population, but also to political (e.g. land tenure) and social (e.g. urbanization) issues.

Increasing food supply

There has been an expansion of 9·6 % in the world's agricultural land area over the last 50 years (Fig. 2) with increases in both Arable Land and Permanent Crops (9·6 %) and Permanent Meadows and Pastures (8·7 %). However, this increase occurred over the period 1961–1991 and since then, the total area has been static. There is ongoing urbanization of agricultural land, so new land must be brought into production just to maintain the existing area of agricultural land. Increasingly, the land brought into agricultural use is in less-developed areas and in marginal regions with lower fertility and where there is a higher risk of adverse weather events than in more established agricultural production regions. Therefore the extra food required will predominantly have to come from the existing land base. Thus there is a need to improve productivity from the existing land base since the conversion of additional poorer quality land to agricultural uses will otherwise lead to an overall decline in agricultural land productivity.

RUMINANT MILK AND MEAT PRODUCTION

The food products from grassland are milk and meat from ruminant animals. Ruminant animals can be fed on high-grain diets, but usually their diet involves some grazed or conserved grass or other fodder crop. For example, in Ireland, milk production is based predominantly on grazed grass, with some grain feeding and grass conserved as silage as the main winter feed (O'Mara, 2008). In Ireland, beef cattle are fed predominantly on grazed grass with grass silage and some concentrate fed during the winter period, and sometimes high levels of concentrates in the finishing period (O'Mara, 2008). In the United States and Australia, beef cattle are usually reared on pasture and finished on high-grain diets in feedlots. Therefore, while grass is seldom the sole food in ruminant production systems, particularly in developed countries, it usually constitutes a major component of the diet.

Milk and meat from ruminants are significant feedstuffs in the global food supply. Meat from cattle, buffaloes, sheep and goats comprised almost 29 % of global meat supply in 2010 (Table 3), and beef dominates buffalo, sheep and goat meat production. The main regions for ruminant meat production are Asia, Latin and North America, and Europe. Europe is the world region with the greatest bovine milk production (Table 4), but when total milk production is examined, the production of buffalo milk in Asia puts this region ahead of Europe, which is followed by North and Latin America. This milk production, which is mainly from cows, is a more important source of nutrition than ruminant meat. In food energy terms, milk contributes two-thirds as much food energy as total meat production, and twice as much energy as from ruminant meat (O'Mara, 2011), thus underlying the very significant contribution it makes to global food supply. Overall, combining global ruminant meat and milk energy supply, it exceeds total food energy supply from pig meat and poultry meat by 37 % (O'Mara, 2011). Of course, milk and meat production is not solely related to animal numbers: Europe, North America and Australia/New Zealand have 18·7 % of the world's cattle (including 21·2 % of the world's dairy cattle),

TABLE 3. *Global production of meat (000 tonnes) from different species by world region in 2010*

	Cattle	Sheep	Buffalo	Goat	Chicken	Pig	Total ruminant meat	Total meat	Ruminant meat as a % of total meat
Africa	6595	1561	328	1202	4369	1232	9686	15 287	63·4
Northern America	13 319	92	0	0	18 020	12 112	13 412	43 543	30·8
Latin America	15 228	314	0	129	20 205	6514	15 672	42 390	37·0
Asia	13 363	4367	3077	3659	28 658	61 958	24 467	115 082	21·3
Europe	11 034	1167	7	129	13 764	26 968	12 337	53 069	23·2
Oceania	2764	1027	0	27	1048	474	3817	5339	71·5
World	62 304	8529	3412	5145	86 064	109 258	79 390	274 712	28·9

Source: FAOSTAT (2012 data; http://faostat.fao.org/site/339/default.aspx).

TABLE 4. *Global production of whole fresh milk (000 tonnes) from different species by region in 2010*

	Cow milk	Buffalo milk	Sheep milk	Goat milk	Total whole milk
Africa	31 749	2725	3744	2031	40 249
Northern America	95 706	0	0	0	95 706
Latin America	80 519	0	541	41	81 101
Asia	158 168	89 572	9758	4576	262 073
Europe	207 370	218	2603	3378	213 569
Oceania	26 103	0	0	0	26 103
World	599 615	92 515	16 647	10 025	718 802

Source: FAOSTAT (2010 data; http://faostat.fao.org/site/339/default.aspx).

but produce 43 % and 55 % of the world's beef and milk, respectively (FAOSTAT, 2010 data; http://faostat.fao.org/site/339/default.aspx). This is due to the higher animal productivity in these regions.

ANIMALS AS CONSUMERS OF HUMANLY EDIBLE PROTEIN AND ENERGY

There is concern about the use of grains in animal production that could be used to produce food eaten by humans. However, much of the feed supply for ruminants worldwide comes from forages and low-quality arable crop by-products that are not suitable for use in human nutrition and that are very often grown in areas unsuited to arable agriculture. Oltjen and Beckett (1996) argued that, in considering the efficiency of food production, the quantity of humanly edible energy and protein used in animal feed should be used rather than gross energy efficiency or protein intake/output ratios. They calculated that the humanly edible energy efficiency of two US dairy systems ranged from 57 to 128 % and the humanly edible protein efficiency ranged from 96 to 276 %. The efficiency for beef systems was lower than dairy systems due to high use of grain in feeds: humanly edible energy efficiency of the beef systems examined ranged from 28 to 59 % and humanly edible protein efficiency ranged from 52 to 104 % (all figures based on output divided by intake of humanly edible energy or protein). These US data showing a high efficiency of conversion of humanly edible protein into animal protein (often over 100 %) support a role for ruminant livestock in food production. In addition, animal proteins generally have a greater biological value than vegetable proteins, and thus provide a further gain not measured by gross efficiency calculations. Similar calculations for higher forage systems than used in the USA, as practiced in countries like Ireland and New Zealand, would show higher efficiencies than in the data of Oltjen and Beckett (1996), and would encourage higher utilization of grass and forage in ruminant production in place of grain. An example of this is seen in a study by the Council for Agricultural Science and Technology (CAST) (1999). This study compared energy and protein efficiency of milk and meat production in the USA and South Korea from both a total efficiency and humanly edible efficiency viewpoint. In both countries, the humanly edible efficiency of milk and beef production was higher than on a total efficiency basis. However, while total efficiencies for protein and energy in milk and beef production were higher in the US than in South Korea, the opposite was the case when assessed on a humanly edible basis: the efficiencies were higher in South Korea than the USA. Commenting on this study, Gill *et al.* (2010) attributed this to lower inputs of grains and higher inputs of grass and forage crops in the South Korean systems.

CONTRIBUTION TO CLIMATE CHANGE MITIGATION

Grassland soils are a very significant store of carbon, with global carbon stocks estimated at about 343 Gt C, which is about 50 % more than the amount stored in forests globally (FAO, 2010). In addition to the significant stocks of carbon, grasslands also contribute to climate change mitigation by sequestering additional carbon. Lal (2004) estimated that the soil organic carbon sequestration potential of the world's grasslands is 0·01–0·3 Gt C year^{-1}. European grassland carbon sink activity has been estimated to be between $-0{\cdot}57 \pm 34$ and -104 ± 73 g C m^2 year^{-1} (Soussana *et al.*, 2007; Schulze *et al.*, 2010; negative values indicate carbon sequestration). Values for Irish grasslands are comparable with net sink activity ranging from −52 to −111 g C m^2 year^{-1} (Jones and Donnelly, 2004; Gilmanov *et al.*, 2007; Soussana *et al.*, 2007; Jones *et al.*, 2010). However, there is considerable debate as to whether grassland carbon sequestration is finite with the time period required to reach a new equilibrium dependent on previous land-use and soil clay content. While some estimates of the time-scale for grassland carbon equilibrium range from 30 to 40 years (Falloon and Smith, 2002), other studies have shown that grasslands have a large potential to store additional carbon and may continue to act as a carbon sink for longer periods of time (Poeplau *et al.*, 2011).

The IPCC Fourth Assessment Report (Smith *et al.*, 2007) considered that global agriculture had a large technical mitigation potential of 5·5–6·0 Gt CO_2 equivalent year^{-1}. This is in the context of global emissions from agriculture of 5·1–6·1 Gt CO_2 equivalent in 2005 and projected emissions under a business-as-usual scenario of 8·2 Gt CO_2 equivalent in 2030 (Smith *et al.*, 2007). Most of the technical mitigation potential identified by Smith *et al.* (2007) related to soil carbon sequestration: it was estimated to contribute 89 % of the technical potential. When the cost of mitigation is taken into account, the economic potentials are lower and were estimated at 1·5–1·6, 2·5–2·7 and 4·0–4·3 Gt CO_2 equivalent at carbon prices of 20, 50 and 100 US$ per t CO_2 equivalent.

Grazing land management and pasture improvement was one of the options considered by Smith *et al.* (2007), as outlined in Fig. 3. Of the total global mitigation potential of 5·5–6 Gt CO_2 equivalent year^{-1}, almost 1·5 Gt was related to grazing land management and pasture improvement. There are a number of practices that could contribute to reduced greenhouse gas emissions and enhanced sinks in grazing lands.

(1) Grazing intensity. Both under and over grazing can lower carbon sequestration or lead to carbon loss from soils (Rice and Owensby, 2001; Liebig *et al.*, 2005) with the effects inconsistent. The effects of grazing are mediated by changes in the removal, growth, carbon allocation and flora in pastures, and carbon input from ruminant excreta, which affect the amount of carbon in soils.

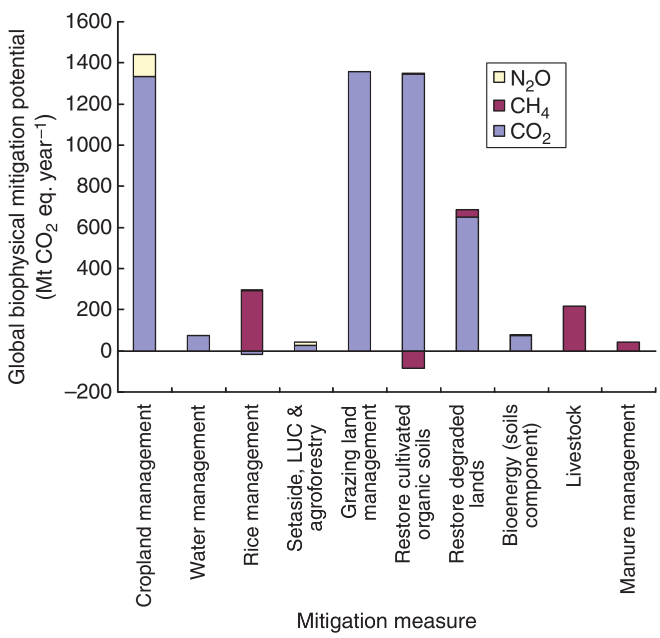

FIG. 3. Global technical mitigation potential (Mt CO_2 equivalent year^{-1}) by 2030 of agricultural management practices (source: Smith *et al.*, 2007).

(2) Increased productivity. Improving the productivity of pastures through practices such as fertilization and irrigation can improve carbon storage in pastures. There can be some offsetting of these gains by nitrous oxide emissions from nitrogenous fertilizers and manures and the energy used in irrigation.

(3) Nutrient management. A positive correlation between C sequestration and N fertilization has been observed in managed grasslands (Jones *et al.*, 2006). Comparisons between management systems have shown that the intensively managed grasslands can sequester over 2 t C ha^{-1} year^{-1} more than extensive systems (Amman *et al.*, 2007). Matching nutrient addition to pasture requirements, thus avoiding excess applications which can result in unnecessarily high nitrous oxide emissions, can lead to a reduction in emissions from grasslands. This is obviously easiest in intensively managed pastures which receive nitrogen fertilizer (or managed application of organic manure) and more difficult in extensively managed pastures where the main nutrient additions are deposition of faeces and urine by grazing animals which are not as easily controlled.

(4) Fire management. Fire can be used to control and improve pastures, but it does cause increased greenhouse gas emissions, directly (release of methane and nitrous oxide) and indirectly (ozone production, smoke aerosols, reduced albedo effect, and reduced tree and shrub cover causing a reduction in carbon stores in soil and biomass). Reducing the frequency and extent of fires, reducing the extent of vegetation present when burning takes place and burning at a time of year when less methane and nitrous oxide are emitted will reduce emissions associated with burning pastures, although it has been reported that the area burned may be ultimately under climatic control (Van Wilgen *et al.*, 2004).

(5) Species introduction. Enhancing species diversity and, in particular, introducing new deep-rooted grasses with higher productivity into the species mix has been shown to increase soil carbon, particularly on low-productivity pastures and savannahs (Tilman *et al.*, 2006).

While Smith *et al.* (2007) estimated that grazing land management and pasture improvement had a technical mitigation potential globally of almost 1·5 Gt CO_2 equivalent in 2030, the economic potential is lower, though still very significant, at 200, 450 and 900 Mt CO_2 equivalent at carbon prices of 20, 50 and 100 US$ per t CO_2 equivalent. In addition, Smith *et al.* (2007) estimated similar economic potentials from the restoration of degraded lands. Practices which contribute to the restoration of degraded grassland such as planting grasses, improved fertility, application of organic manures, reducing tillage and retaining crop residues, and conserving water will increase soil carbon. Much of this degraded land is pastures or former pastures.

GREENHOUSE GAS INTENSITY OF BEEF AND MILK PRODUCTION

A key metric for the efficiency of food production systems in the context of its impact on climate change is the greenhouse gas emissions per unit of food produced. This should account for direct emissions from the system, and emissions embedded in inputs brought into the system or farm. Thus a life cycle assessment (LCA) methodology is appropriate when making such calculations. However, correct analysis of LCA depends on (*a*) use of the appropriate functional unit (e.g. litres milk corrected for protein and fat content as opposed to litres fresh milk) and (*b*) accurate allocation of emissions between different products (e.g. dairy milk and either related dairy products or dairy beef). In a recent study, milk production was compared across a number of types of systems and climatic zones (FAO, 2010). The study was an LCA and included emissions associated with milk production, processing and transportation of milk and milk products. On average, grassland systems had higher emissions than mixed farming systems: 2·72 kilogram compared with 1·78 kilogram CO_2 equivalent per kilogram fat and protein corrected milk (FPCM). The study did not include emissions or sinks related to land use or land use change. It is likely that including a more comprehensive assessment of this (including carbon sequestration under grasslands as discussed above) would have improved the relative position of milk production from grassland systems. Further, when emissions from temperate regions only are compared, the greenhouse gas emissions per kilogram FPCM were remarkably similar between grassland and mixed farming systems (FAO, 2010).

Another major study that was conducted recently compared food production across the 27 member states of the EU (Leip *et al.*, 2010). Again it used an LCA to compare the greenhouse gas intensity of food production inside the farm gate. For milk production, the countries with the lowest emissions per kilogram of milk were Austria and Ireland, the latter having a very high rate of grass utilization in dairy cow diets (O'Mara, 2008). It is interesting that nitrous oxide emissions from grazing animals and mineral fertilizer application were between three and four times higher in the Irish system than the Austrian data, but this was counterbalanced by lower nitrous oxide emissions from manure management and manure application and lower carbon dioxide emissions from electricity use, buildings and machinery. This illustrates that grassland-based milk production can be as efficient as high-input systems from a greenhouse gas perspective. For beef production, it is more difficult to draw conclusions because of the multiplicity of beef production systems in the EU (beef from dairy or beef cows, bull or steer production systems, differing ages at slaughter, etc). Again, Ireland has a very high level of grass utilization in beef production, and the emissions per kilogram of beef produced were amongst the lowest of the 27 EU countries studied by Leip *et al.* (2010).

ADAPTATION OF GRASSLANDS TO CLIMATE CHANGE

Analyses of global circulation model (GCM) simulations have indicated that surface temperatures will increase by, on average, between 0·1 to 0·4 °C decade^{-1} across Europe (Parry, 2000). However, the pattern of change is predicted to vary across a longitudinal and latitudinal gradient, with the highest increases in temperature and decreases in precipitation occurring in Mediteranean Europe, whilst precipitation is forecast to increase in northern Europe (Parry *et al.*, 1999; Parry, 2000). As a result, different responses in terms of grassland management and wider agricultural practices may be required, with increasing intensification focused on northern Europe and a trend towards extensification in southern regions due to resource depletion (Olesen and Bindi, 2002).

Elevated atmospheric CO_2 has been shown to result in increased grass production and enhanced water/nutrient-use efficiency (Körner, 2000). A shift to increased investment in root biomass allied to decreased decomposition rates can also lead to enhanced carbon sequestration under high CO_2 levels (Van Ginkel *et al.*, 1997; Gorissen and Cotrufo, 2000). This reduction in the rate of decomposition may be due to both higher C : N ratios of the plant material and alterations in microbial community structure under elevated CO_2 (van Groenigen *et al.*, 2005). However, an increased C : N ratio of grass that results from exposure to elevated CO_2 can also alter the nutritive value of the sward, with 10–20 % lower foliar N and 20–30% higher sugar/starch levels (Wand *et al.*, 1999; Ehleringer *et al.*, 2002).

Productivity gains resulting from future CO_2 levels may be negated by changing climatic factors, particularly increasing soil moisture deficits. A combination of increasing surface temperature allied to prolonged drought periods can reduce primary productivity impacting on seasonal grass yields (Bloor *et al.*, 2010). Indeed, during the European 2003 and 2006 summer heat waves, carbon sequestration decreased substantially in grasslands in central and southern Europe, primarily due to reductions in photosynthetic uptake resulting from drought stress rather than higher temperatures *per se* (Ciais *et al.*, 2005; Reichstein *et al.*, 2007). In contrast, the Alps and Scandinavia exhibited increased productivity due to higher temperature (Jolly *et al.*, 2005; Vetter *et al.*, 2008). Whilst some projections have indicated a reduction in soil organic carbon stocks in Irish grassland soils in response to predicted increases in temperatures, drier summers and wetter winters (Xu *et al.*, 2011), other modelling studies indicate less impact (Vetter *et al.*, 2008).

CAN GRASSLANDS SIMULTANEOUSLY PRODUCE EXTRA FOOD, COPE WITH CLIMATE CHANGE AND MITIGATE GREENHOUSE GAS EMISSIONS?

There are many factors to consider when answering this question. Certainly, some grasslands can contribute to extra food production by increasing productivity through sowing of improved species and increased fertilization. For example, average stocking rates on livestock farms in Ireland are well below what is achieved on research farms (O'Mara, 2008). Another example is the 40 % increase in milk production in New Zealand achieved between 2000 and 2010 without any change in the combined total of beef and sheep-meat production (FAOSTAT, 2011 data; http://faostat.fao.org/site/377/default.aspx#ancor). While some extra emissions of nitrous oxide can be expected from increased fertilization, generally the emissions per unit product will be reduced following intensification. However, this possible increase in grassland-based food production in some regions has to be balanced against possible reductions from grasslands in other regions that are impacted negatively by climate change. For instance, Thornton *et al.* (2009) reported that increased droughts (both in frequency and duration) would negatively impact on livestock production systems in semi-arid regions.

It is positive that many of the greenhouse-gas mitigation strategies for grasslands which were outlined above will also contribute to improved productivity and to greater resilience of grasslands to events such as drought. Follett *et al.* (2001) reported that soil carbon stocks in grasslands can be rebuilt when management practices that deplete stocks are reversed. Oldeman (1994) reported that improved grazing management could lead to increased pasture production and more efficient use of resources, rehabilitation of degraded grazing lands, and improved profitability. There are many challenges and barriers to achieving uptake of these strategies (FAO, 2010). These can be social (engaging smallholders with uncertain tenure of land to engage in pasture improvement), technical (sequestration rates are low in grasslands and hard to measure) and economic (the cost of reseeding and fertilization). Nevertheless, they give guidance on where effort should be focused in relation to maintaining food production (and associated livelihoods) from grasslands and mitigating and adapting to climate change.

CONCLUSIONS

Grasslands are important for global food supply, with ruminants (which derive at least some of their nutrition from grasslands) producing 37 % more food energy as milk and meat than total food energy supply from pig meat and poultry meat.

Due to the rising population of the world, extra food will need to come from the world's existing agricultural land base (including grasslands) as the total area of agricultural land has remained static since 1991. Ruminants are efficient converters of forages and poor-quality feeds into humanly edible energy and protein, and grassland-based food production can produce food with a comparable carbon footprint as mixed systems. Grasslands are a very important store of carbon, with more carbon stored in global grasslands than in global forests, and they are continuing to sequester carbon. There is considerable potential to increase this further through grazing land management (e.g. through managing grazing intensity, improved productivity, etc) and restoration of degraded grasslands. Grassland adaptation to climate change will be variable, with possible increases or decreases in productivity and increases or decreases in soil carbon stores.

ACKNOWLEDGEMENTS

Thanks to Gary Lanigan, Kevin Hanrahan and Trevor Donnellan for their critical reading, comments and contributions to the manuscript.

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