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CENTENARY REVIEW

Temperate grassland: key developments in the last century and future perspectives

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SUMMARY

In temperate regions, grassland provides most of the feed requirements for ruminants. Its management has implications for landscape and environmental quality as well as agricultural production. The present paper reviews the key developments in grassland management, production and utilization during the 20th century, focusing primarily on the UK but drawing on research and practice from other areas. Increased production from grassland has arisen from improved understanding of soil and plant nutrition, plant physiology and cultivar improvement, while improved understanding of feed evaluation, ruminant nutrition, grazing management and silage technology have contributed to increased utilization of grassland under grazing and cutting. Permanent and long-term swards occupied most of the total grassland area at both the beginning and end of the century, but inputs of nitrogen resulted in greatly increased herbage production, particularly from the 1960s; this, combined with reseeding and early cutting for silage, led to reduced botanical diversity with ryegrass dominance in lowland areas. Forage legumes were highly regarded at the beginning of the century, then decreased in many areas, but are again recognized as having a key role in low- and medium-input systems. Recognition of the environmental implications of grassland management has increased since the 1980s. This includes the need to reduce nutrient emissions in grassland agriculture, and also the role of grassland in biodiversity protection, carbon sequestration and landscape quality. Research is increasingly focused on addressing these issues and on integrating agricultural management with environmental protection. Improved nutrient management, legume-based systems and agri-environmental schemes, as well as interest in the food quality attributes of particular systems and grassland communities, are important in the medium term. In the longer term the effects of population increase, competition for other land uses and the impacts of climate change could impact on global food supplies and affect future grassland management in the temperate zones.

INTRODUCTION

Grassland is a predominant form of land use in the UK and throughout the world. The present paper focuses on grassland in temperate regions. Throughout this area, grassland feeds provide more than half of the energy and protein consumed by ruminant livestock (Wilkins 2000), with some systems being totally reliant on grassland. Grassland is also a crucial element of the landscape, and grassland and its management have major effects on the quality of soil, water and air. This multi-functional significance of grassland has become of increased significance in the last part of the 20th century (Hervieu 2002; Hopkins & Holz 2005).

The present paper contrasts the characteristics of grassland and grassland management at the beginning and the end of the 20th century, taking the UK as an example. This is followed by discussion of key developments during the century in the advance of grassland knowledge and application. Sections considering grassland production and utilization are followed by consideration of environmental implications. The paper concludes by discussion of some possible future developments in the role of grassland.

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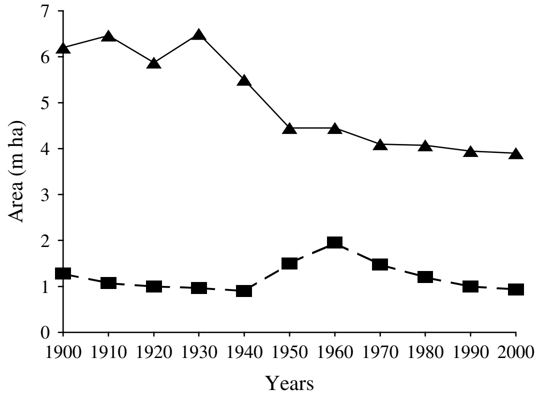

Fig. 1. Changes in the areas of permanent grassland (—▲—) and temporary grassland (–■–) from 1900 to 2000 in England and Wales. From 1975 temporary grassland has been classified as swards 5 years old or under, and permanent grassland as grass over 5 years. An additional area of grassland classified as rough grazing has varied between 1·5 and 2·5 million ha during the century.

GRASSLAND AT THE BEGINNING AND END OF THE 20TH CENTURY

Tremendous changes have occurred in grassland and the way that it is used over the last century. This section highlights contrasts between the beginning and end of that period, focusing mainly on the UK.

In the UK, the areas of permanent grassland and temporary grassland were, respectively, 45 and 40 % higher in 1900 than in 2000. Figure 1, based on agricultural census data for England and Wales only, shows (*a*) the large area of permanent grassland that had developed during the depression years towards the end of the 19th century, (*b*) the large fall that occurred as grassland was ploughed up for increased cereal production during the Second World War and (*c*) the rise and subsequent fall in temporary grass from the middle of the 20th century. Rather similar changes occurred in other European countries (Lee 1988; Park 1988). Changes in the area of permanent grassland were strongly influenced by the price for cereals, with farmers seeking to reduce their costs or diversify their production when cereal prices were low and increasing the grassland area. The situation was rather different in temperate regions that are exporters of livestock products, such as New Zealand and temperate Australia, where increases in the area of grassland occurred in response to increased demand for livestock products and were commonly achieved by increased land clearance (Levy 1937).

Although grassland has been a predominant form of land use throughout this period, the intensity with which the grassland has been used has often been low. Hall (1903) reflected that although the growth of grass plays the major part in the economy of the ordinary farm, grass does not receive the same attention as tillage crops and nothing is done to replenish the soil. Similarly, the grassland improver Morgan-Richardson (1900) said that ‘grass is of all crops the most generally neglected’. Whilst there is still considerable potential to further increase output from grassland, marked increases in productivity have occurred, with Wilkins (1991) estimating an improvement in utilized output per ha of 1·8 % per year from 1950 to 1970 and 1·4 % per year from 1970 to 1985.

Grassland swards in the UK some 100 years ago were botanically very diverse (Faunce-de Laune 1882; Armstrong 1907). This reflected that (a) much of the grassland comprised very old swards, (b) substantial areas of land that had previously been cropped had ‘tumbled down’ to grassland without seeding, (c) where grassland was sown, the seed mixtures used often contained more than 15 species including grasses, legumes and herbs (Elliot 1943) and (d) low inputs of plant nutrients in fertilizers and manures. There was much controversy about the composition of seed mixtures. All advocates in the early 20th century favoured complex mixtures and stressed the importance of legumes such as red and white clover (*Trifolium pratense* and *T. repens*) and herbs such as yarrow (*Achillea millefolium*) and chicory (*Cichorium intybus*). Amongst the grasses, cocksfoot (*Dactylis glomerata*), meadow fescue (*Festuca pratense*) and meadow foxtail (*Alopecuris pratensis*), were generally preferred, whilst the position of ryegrass (*Lolium* spp.) was highly controversial, because of reported poor persistence, low acceptability by stock and low yield (Armstrong 1907). This probably reflected poor quality of seed available at the time and predominance of Italian ryegrass types. In contrast, at the end of the 20th century, seed mixtures in the UK for agricultural use were almost universally based on perennial ryegrass and normally included only one or two other species (Turner 1997). There is now widespread concern by society that so much of the grassland in the UK, and in many other areas of Europe, has relatively few plant species and supports low numbers of invertebrates such as butterflies and bees (Fuller 1987; Frame 2002). Increasing areas of grassland are now being managed under Agri-environmental Schemes in the UK and in other European Union countries, introduced following the EC Regulation 797/85 (EC 1985) which permitted payments to farmers to encourage practices that benefit the environment, and was further widened in scope under the CAP reforms from 2005. Management to increase biodiversity within the framework of agricultural production systems is discussed by Peeters & Janssens (1998) and Isselstein (2005).

Mineral fertilizers became available in the second part of the 19th century, but by 1900 only supplied some 100 000 t of nutrients annually in the UK. Fertilizer use remained low until 1940, but then increased rapidly to reach a peak of 2·5 million tonnes of nutrients by 1987, before falling by some 22% by 2003 (Wilkins 2000; DEFRA 2004). In 1900, nitrogen (N) fertilizer use had been extremely low, though fertilizers supplying phosphorus (P), such as superphosphate and bone meal, were much more widely used. There was, however, much interest in fertilizer use and it was widely appreciated that when P and K were supplied, grassland was extremely responsive to application of N. Many experiments on fertilizers and organic manures were carried out on farms throughout the country, with observations and results reported in the Journal of the Royal Agricultural Society of England and the Journal of the Bath and West Agricultural Society (e.g. Carruthers & Voelcker 1904). The increase in fertilizer use during the second part of the 20th century is well chronicled and discussed further in a later section. The recent fall in use reflects reduced pressure for maximum production per ha, because of reduced stock numbers, as well as more efficient timing and targeting of applications, and increasing areas of grassland being managed for multi-functional purposes.

The trends for fertilizer use in other western European countries have been broadly similar to those in the UK. All countries had very low rates of application at around 1900, although application rates per ha at the end of the period were higher in Belgium, Denmark and the Netherlands than in the UK, but were lower in Spain, France and Ireland. Holford (1937) noted that fertilizer use in New Zealand increased from 25 000 t in 1900 to 400 000 t in 1925.

The broad pattern of utilization of grassland by grazing and as conserved forage has been maintained throughout this period. A major change was the replacement of hay by silage as the main conserved forage. Silage making was practised on some farms from the late 19th century, but in the 1880s the total quantity of silage made in the UK was estimated as only 25 000 t dry matter (DM) (Brassley 1996). The quantity of silage made was still less than 100 000 t DM by 1947. It did not exceed 1 million t DM until 1965, but then increased rapidly to reach some 11 million t DM by 1985. The production of hay peaked at 9·7 million t DM in 1889, but fell from 8 to 3 million t DM between 1965 and 1985. This change reflected increased mechanization and improvements in the technology of silage making that enabled the rapid and reliable conservation of large quantities of grass with low dependence on the weather. The replacement of hay by silage over this period took place in all other western and northern European countries (Wilkinson & Bolsen 1996). Along with the replacement of hay making by silage making, there was, in the UK, an increase in the proportion of grass used after conservation, rather than by grazing.

The trend has been reversed in the last decade as many farmers have sought to reduce costs through increased reliance on grazing (e.g. Rook & Penning 2000). Grazing systems were generally not well defined or efficient until the second half of the 20th century, when systems of controlled grazing in either rotational or on a continuous basis were developed and adopted. It is notable that though there was voluminous writing and many experiments at the beginning of the 20th century on fertilizer treatments and seeds mixtures, little attention was given to grazing management, although Hall & Russell (1912) made an attempt to analyse reasons for the high performance of sheep grazing some of the renowned pastures on the Romney Marsh.

In the UK, grazing has always been the predominant method of summer feeding, but in some other European countries the tradition has been stall feeding with cattle fed cut fresh grass or hay during the summer. Frisch (1978) noted that in Luxembourg in 1900 only some 0·06 of grassland was grazed and the remainder made into hay, whilst by 1977 the area grazed had increased to 0·60. Trends for the importance of grazing in summer to increase were also noted for Sweden by Osvald (1937) and for Germany by Zimmer (1978). However, with increases in the production of maize silage and increased yields per cow, the prevalence of stall feeding has increased in some countries in the last decade.

GRASSLAND PRODUCTION

Understanding and improving the production potential of grassland has been of primary concern to grassland scientists and practitioners for much of the past century, and there is a huge range – at least 10-fold – in the amount of harvested biomass from grassland swards even within the UK. The effect on grassland production (and on livestock production) of soil, climate, plant species and varieties, nutrient supplies and management has long been recognized, but the relative influences of these controlling factors have become understood progressively and critically only during recent decades.

By the 1950s, the basis for designing and conducting grassland field experiments using replicated treatments that could be analysed statistically was well developed (Brown 1954; Grassland Research Institute 1961) and underpinned many of the studies that have elucidated understanding of the factors affecting grassland production. Methodologies had been adapted from those used for arable crops, with grassland agronomists facing the additional complexities of different experimental assessments (e.g. production at successive harvests within a season, rather than the yield at a single end-point) as well as the problems of assessments on swards with grazing animals. From the 1950s onwards, growth analysis techniques were developed to understand the effects of defoliation frequency on herbage growth, and demonstrated the importance of leaf area on regrowths and the contribution of water-soluble carbohydrate reserves (Troughton 1956; Leafe 1974; Hunt 1978). Seasonal variation in production was, and remains, a serious limitation (Laidlaw *et al.* 2006) and is likely to remain so with the uncertainties associated with future climate change. Methods developed to investigate the seasonal productivity of grasses based on serial harvesting and overlapping cuts became widely used from the 1960s. These enabled the plotting of seasonal growth curves showing changes in daily rates of herbage accumulation for species and varieties (Anslow & Green 1966), the method being developed subsequently to remove the effects of growth limitations due to water and nutrient supplies (Corrall & Fenlon 1978). Research on plant physiology from the 1960s led to improved understanding of the reasons for the seasonality of growth, and included studies on single-leaf and canopy photosynthesis (Woledge & Leafe 1976), of the role of tiller and bud dormancy and development (Jewiss 1972) and of changes in canopy development and organic matter accumulation with increasing respiration and senescence (Robson 1973*a*, *b*; Woledge & Parsons 1986). Experimentation on the effects of tiller density and tiller weight on herbage yield were to show that plants with high rates of leaf area expansion had both increased tiller weight and tiller density, with interactions with water supply and nitrogen application (Nelson & Zarrough 1981; Nelson & Sleper 1983), the N supply having an important role in cell production and the physiology of leaf growth (Nelson 1992). These studies provided a scientific explanation for the physiological factors affecting the growth potential of the grass sward through the growing season, including the effect of canopy structure on light penetration, photosynthetic potential of leaves, and the role of tillering in ensuring regrowths after defoliation.

Obtaining improved production, whether from natural pastures or sown swards based on superior germplasm, is dependent on optimizing the conversion of water, carbon dioxide and plant nutrients to utilizable herbage for livestock, essentially through identifying and, where possible, reducing the limiting factors.

Temperature is one of the main environmental determinants of leaf growth and significant incremental increases in grass growth with temperature up to 20 °C have been shown in practice (Colman *et al.* 1974). Research at Hurley in the 1970s furthered understanding of the mechanisms of how temperature affects leaf growth (Peacock 1975). Evidence of field-scale variation with temperature was provided from a 32-site trial in Europe carried out in the 1980s under the auspices of the FAO Sub-network for Lowland Grassland (Corrall 1984; Peeters & Kopec 1996) based on the methodology of Corrall & Fenlon (1978). Temperature (influenced by the altitudinal and latitudinal range) was shown to be an important factor affecting grass growth with up to three-fold differences in herbage production between similarly managed sites, even when the limiting effect of water was removed by irrigation. Although temperature is one factor over which no control is possible in practice, accumulated mean temperature in spring became widely used as a basis for calculating the optimum date for the first application of nitrogen fertilizer (Van Burg *et al.* 1981; Baker 1985).

Water supply, and particularly water stress, has a profound effect on the herbage production potential of sites subject to seasonal water deficit. The introduction in the 1940s of the concepts of potential transpiration and soil moisture deficit and a method to calculate them from meteorological data (Penman 1948, 1963) provided a basis for the design of irrigation experiments, and farm-level application of irrigation, in temperate conditions without the need to measure soil water. In New Zealand in the late 1940s, grassland irrigation using river water and engineered extraction systems was researched and applied on a large scale in the Canterbury Plains region (McPherson 1956). In the UK, research to assess the possibilities of using irrigation to increase grass production during periods of water deficit began in the early 1950s, and progressed to examine factors which influenced water use by the growing sward and management to improve water-use efficiency (Stiles & Williams 1965; Garwood 1974). Irrigation of grass and grass/clover swards was shown to result in considerable benefits in herbage yield, and reduction in the variability of yield both within and between years. The potential for irrigation is greatest in those areas (and years) where demands on water provision tend to be greatest, and when irrigation might be more profitably applied to higher value crops. While at the present there is little interest in its use on grassland, scenarios for changes in UK and European climate in the 21st century, with drier and warmer summers (Hopkins & Del Prado 2006), suggest that there may be considerable potential for the application of this research in the future, providing practitioners can develop suitable water storage and supply systems.

In the first half of the 20th century, inputs of nutrients to grassland were generally low. This partly reflected the relatively high cost and low availability of artificial fertilizers, as well as a poor appreciation of the role of nutrients in plant growth. Experiments with nutrient additions to grassland date from at least the 1850s on the Rothamsted Park Grass plots (Hall 1903; Richardson 1938) and had shown resultant changes in botanical composition and hay yields. Other trials had been conducted at a county level or by colleges, and experiments in the early 1930s at the newly established ICI Research Station at Jealott's Hill in Berkshire, under the then intensive pasture management system receiving 78 kg N/ha, had demonstrated the benefits of N fertilizers on dry matter yield and crude protein content (Peacock 1978). Yates & Boyd (1965) were to comment later that, even by the 1940s, the UK had no summarized data on fertilizer responses, for grass or other crops. Progressive farmers began to use N fertilizers on sown leys, mainly when strip grazed or mown for silage, from the 1950s, typically at about 50 kg N/ha, though most permanent grassland still received none by the early 1960s (Yates & Boyd 1965). Elsewhere in Europe, notably in Germany and the Netherlands, experiments and farm experience with N fertilizers, particularly from the 1930s, had led to a more rapid adoption of N on grassland than in the UK (de Groot 1966). The first General Meeting of the European Grassland Federation, held in the Netherlands in 1965 (Van Burg & Arnold 1966) took as its theme *Nitrogen and Grassland*. This was to foreshadow one of the most important changes to grassland management to occur in the subsequent decades. Nitrogen use on grassland farms in England and Wales increased by about 7% each year from the late 1960s until the early 1980s (Chalmers *et al*. 1990), by which time fertilizer N had become the most costly single input in the production of high yielding grass (Lazenby 1981). Many field experiments on sward responses to N fertilizers were conducted during this period in the UK and Europe, enabling the plotting of response curves and the effects of site conditions on basal production and yield responses to be derived. Of particular note in the UK were the multi-site ‘Grassland Manuring’ trials of which the ‘GM20’ series was carried out at 21 sites on uniformly managed sown perennial ryegrass harvested at monthly intervals (Morrison *et al*. 1980; Doyle *et al*. 1986). This work demonstrated, for different site conditions, the N rate required for maximum herbage yield; of greater agronomic and economic relevance though was the ability to derive the point at which a given response was reached, such as 10 kg herbage DM/kg fertilizer N. It also provided the basis for improving the efficiency of N use by adjusting N inputs according to summer rainfall and soil water-holding capacity, and the concept of grassland site classes (Baker *et al*. 1991).

In several subsequent trials, the effects of splitting N doses and harvesting at 6-week intervals (‘GM21’) was investigated (Morrison 1980) and in a further development the response of grass swards to fertilizer N was made under both cutting-only and grazing-only managements (‘GM22’). This latter work was to show lower responses to N under grazing, suggesting that the results of fertilizer N experiments obtained under cutting could not be applied uncritically to grazed situations (Jackson & Williams 1979). A number of parallel studies were conducted elsewhere in Europe during the same period, notably in the Netherlands, which were to highlight the sward deterioration effects and subsequent herbage yield loss associated with very high N inputs (above 500 kg N/ha) (Prins 1984).

The use of the other main nutrients that influence grassland production, phosphorus (P), potassium (K) and lime have a longer established role in maintaining grassland production, with soil nutrient testing and information on the effects of sources of nutrients such as basic slag being available since the 19th century (Carruthers & Voelcker 1904). Several long-term experiments were initiated around 1900 at Cockle Park in Northumberland that were to show the importance of basic slag and other P-rich fertilizers in raising the productivity of relatively infertile permanent pasture; benefits being attributed, at least in part, to its effect in promoting the growth of white clover (Elliott & Thomas 1934; Arnold *et al*. 1976). The role of P fertilizers, combined with lime, and also K and N, in improving pasture quality and output, was further amply demonstrated on long-term studies in the Welsh uplands from the 1930s (Milton & Davies 1947; Jones 1967). The inherently low soil P status of soils in New Zealand was addressed through a major drive to improve soil fertility in that country, and Cockayne (1956) records that topdressing with superphosphate was the major factor responsible for increased pasture production and livestock output during the period from around 1920 to the 1950s. Equally important has been the recognition that as N inputs are increased and herbage growth increases so does the potential for removal of other nutrients, particularly K, and which if not replenished in proportion to N can result in reduced response to applied N (Reith *et al*. 1961).

The use of liming materials to improve soil fertility in the UK probably has a longer history than other forms of fertility amelioration, but in the early decades of the 20th century there was increasing evidence of declining soil pH (Gardner & Garner 1953). The introduction of the lime subsidy in 1937 (which continued for 35 years) encouraged its use on grassland. Studies by Milton & Davies (1947) and Cromack *et al*. (1970) were noteworthy in showing the effects of lime on pasture production, with the first of these reporting that lime had a greater effect than superphosphate. As in all these studies, the role of grazing management and the interaction of grazing intensity and frequency with factors affecting soil fertility have been stressed repeatedly. Particularly noteworthy in this context were the experiments of Martin Jones at Jealott’s Hill in showing the importance of a break in grazing to allow recovery for productive grazing the following season (Jones 1933*a*, *b*).

The studies referred to above greatly influenced advisory and development work to raise the productivity of grassland, in the UK and elsewhere, during most of the past century. However, much grassland continued to be managed extensively and received low fertilizer inputs. From the mid-1980s, concerns about ensuing environmental problems associated with the increased production from grassland agriculture, combined with over-production in some commodities, led to a reappraisal and a need to refine and optimize nutrient inputs. This has included the use of nutrient-budgeting approaches (Weissbach & Ernst 1994; Kayser & Isselstein 2005).

LEYS AND SOWN GRASSLAND

Observations that the presence of significant proportions of perennial ryegrass and white clover in the most productive ('first-grade') permanent pastures (e.g. Armstrong 1907) contributed to these being later selected as the main species for forage improvement. There was advocacy of these as preferred species in much earlier records (Fussell 1964). Robert Elliot's pioneering work on ley farming at Clifton Park in Roxburghshire was first published in 1898, and his apparent success of a system of a 4-year sown ley, with the emphasis on sown grass as a crop, following 4 years with roots and corn crops (Elliot 1943) appears to have had a considerable influence on Stapledon in the period following the establishment of the Welsh Plant Breeding Station in 1919. Elliot's seed mixtures had been botanically very complex, perhaps more appropriate for the particular conditions and impoverished soils of his locality rather than for universal application. A feature of grass breeding from the 1920s onwards was the development of leafy and persistent strains intended to raise sward production and nutritional value while contributing to residual fertility that would contribute to the nutrition of crops sown after the ley had outlived its most useful period. Ryegrasses and clovers, as well as cocksfoot and timothy for more specific purposes, formed the basis of the more simple seed mixtures that Stapledon envisaged as the basis for applying the ley farming system to every ploughable field on every farm (Stapledon & Davies 1948). This approach was advocated because of the perceived higher rate of production from sown swards than permanent swards and also because of the possibilities presented for high yields of cereal crops resulting from the release of nutrients after ploughing. The reality, at least in the UK, was to prove somewhat different as farms became more specialized towards either continuous cereal growing or to livestock farming based on permanent (or infrequently cultivated) grassland. The ley farming concept, however, did much to focus attention on treating the grass sward as a crop whose production depended on attention to detail. It is also a system that is widely practised on organic farms.

From the 1940s, there was a considerable expansion in the use of seeds of cultivated varieties and varietal improvement. Progress in forage breeding since the 1930s was reviewed by Camlin (1997) for grasses and by Rhodes & Ortega (1997) for legumes, highlighting the significant advances to provide increased herbage dry matter yield (over 20% during a 50-year period for perennial ryegrass) and traits for improved herbage quality affecting intake, utilization and persistence, and the establishment of the UK National List trialling system from 1973. Other advances have included the development of tetraploid ryegrass varieties and hybrid Italian × perennial ryegrasses, and the testing of varieties under grazing. Although there has been a progressive dominance of ryegrasses for sown swards in most temperate areas of Europe and elsewhere, in situations where ryegrasses are limited by winter survival (e.g. Nordic countries) there is a continuing role for timothy and meadow fescue. Similarly, the need for drought tolerance in the drier temperate areas ensures a continuing agronomic role for cocksfoot and tall fescue. The attributes of these and other grasses, and their prospects for future use, have been reviewed in some detail by Peeters (2004).

Questions remain on the effect of species and varietal differences on animal output but recent developments have included investigations of the effects of variety on intake (Orr *et al.* 2005; Smit *et al.* 2005) and of traits such as high water-soluble carbohydrate on milk yield (Moorby *et al.* 2006). The application of new technological approaches provides new opportunities to improve varieties for a range of nutritional purposes (Pollock *et al.* 2005).

PERMANENT AND SEMI-NATURAL GRASSLAND

Despite the grassland plough-up campaign of the 1940s and the subsequent advances in forage plant breeding and agronomic advice to farmers, a national survey of grassland in England in 1959 found that that over 0·4 of the permanent grassland surveyed in 1939 had escaped cultivation throughout the wartime period and post-war years (Baker 1960). As subsequent surveys (Forbes *et al.* 1980; Green 1982; Hopkins *et al.* 1988) were to reveal, much of this permanent grassland was to become agriculturally improved through management inputs rather than through reseeding, and many reseeded swards were to remain for a considerably longer period than their original intended duration. A key development of grassland utilization in the later decades of the 20th century was to be an improved understanding of the productivity of permanent grassland.

In 1944, on-farm trials were set up with the support of the Royal Agricultural Society of England to record animal production from sown leys and adjacent areas of old pasture. Liveweight gain was found to be higher from the sown leys than from most permanent swards, the exception being those sites that contained a high ryegrass and clover content, considered to be amongst the best of Midlands fattening pastures.

Permanent swards were shown to gradually improve in response to management (Davies & Williams 1948; Williams & Davies 1954). Mudd & Meadowcroft (1964), having reviewed the literature and concluded that the case for superior productivity from leys remained unproved, initiated further experiments at Great House Experimental Husbandry Farm in the Pennines. These used dairy cows and compared sward types under carefully controlled conditions that ensured consistency in management inputs. Improved production from the ley again occurred in the year after sowing, but by the third and fourth years production from leys and permanent swards was similar and reseeding costs further reduced the economic advantages of the reseeded swards (Mudd & Meadowcroft 1964; Bastiman & Mudd 1971). Similar findings of declining production after reseeding were reported from researchers in the Netherlands, where grassland management has traditionally been more intensive (Hoogerkamp 1979) and by the French agriculturalist Voisin, who argued that the farmer's management was the driving influence of quality and production (Voisin 1960).

In recognition of the importance of permanent grassland in the UK, a detailed and comprehensive study involving 28 000 hectares and some 500 predominantly permanent grass farms in England and Wales was conducted in 1974–77 (Forbes *et al.* 1980). Referred to as the National Farm Study, it collected survey data on sward age and botanical composition, soil, environment, fertilizer inputs, etc. These were analysed together with detailed farm management and livestock records and, for each farm, values for metabolizable energy (ME) requirements and utilized ME outputs were calculated. The study highlighted huge differences between farms in terms of ME output, even among farms using similar levels of fertilizer N, and found that sward age and botanical composition were only weakly correlated with utilized ME output. Measures of actual herbage production were not made on these farms but, in a subsequent development, the productivity and N-response of over-20-year-old permanent grassland swards were compared with identically managed newly reseeded swards at 16 sites (Hopkins *et al.* 1990). This was to show that the botanical composition of permanent swards changed rapidly in response to fertilizer additions, resulting in an increase in the proportion of perennial ryegrass when present; and that while reseeded perennial ryegrass swards outyielded permanent grass in their first harvest year, usually with herbage of higher digestibility, any production advantage in later years was generally apparent only under very high fertilizer N inputs (i.e. above 300 kg N/ha). The age and botanical composition of swards were not the main determinants of herbage production, but the growing conditions of the site and the soil nutrient status and other nutrient additions, factors which in turn affect botanical composition. Of these, it was the realization that nitrogen fertilizer could substantially increase grass production on all or most swards, and the adoption of this by many farmers was to be one of the key developments affecting grassland production by the 1980s.

Parallel with developments involving N fertilizers on grass swards was the alternative approach of using sown swards containing legumes. Pastures containing white clover have long been seen as a driver of low-cost production systems, particularly in New Zealand (Lancashire 1990) and a feature of low input systems in the UK and elsewhere. Concerns over the energy consumption associated with fertilizer N, and recognition of the N-fixation potential and high feed value of legume forage, raised the profile of legumes in the 1980s (Thomson 1984). It is widely held that grass-legume swards are typically capable of similar levels of production as grass swards receiving around 200 kg/ha of fertilizer N. Since the 1980s, international collaboration between researchers has been considerable, with improvements in both varietal attributes and agronomic understanding of legume utilization under a range of conditions. Their potential for high production and profitability in silage systems is considerable, with red clover in particular outperforming all other silage systems based on N-fertilized grass (Topp & Doyle 2004). Under grazing, there are a range of legumes, in addition to white clover, whose potential has been poorly exploited in practice, that can provide acceptably high levels of production under low-input systems (Rochon *et al.* 2004).

Since the 1960s, progress in agricultural machinery and herbicide technology have encouraged the development of renovation methods for improving the forage yield and herbage quality of permanent and ageing sown grassland, without the need for full conventional reseeding. Research has shown the potential for introducing clovers and grass varieties of high yield potential by surface seeding or sod seeding into existing swards, usually with specialist seed drills, and often in combination with short-term chemical suppression of the existing vegetation (Allen 1980; Williams & Hayes 1990). Success with these methods has been variable. The approach has been adopted on extensively managed grasslands in some UK uplands, and especially on larger land holdings in central and eastern Europe where either economic or soil and site conditions would be inappropriate for conventional reseeding. A symposium of the European Grassland Federation (BAL 1991) reviewed this subject.

GRASS QUALITY AND UTILIZATION

Quality

Concepts of the quality of grass around 1900 were not well developed. In the UK, the major accent was on the content of crude protein in grass, although in some studies analyses of minerals and proximate components according to the Weende method were also made. It was realized that there was much variation in the digestibility of grassland feeds and papers describe determinations of digestibility *in vivo*. The Weende system, developed in Germany (Henneberg & Stohmann 1860), was widely used in most European countries and formed the basis for calculation of starch equivalent (Kellner 1926) from the contents of ether extract, crude fibre, nitrogen-free extract and crude protein, together with estimates of digestibility of these fractions and their energetic value. In an early issue of the *Journal of Agricultural Science, Cambridge*, Crowther & Ruston (1912) reported the effects of time of cutting on yield and composition of hay and highlighted the need in management for compromise between the high yields obtained with late cutting and the high digestibility obtained with early cutting, an issue that is still of crucial importance for successful grassland systems. They concluded that the best results were obtained from cutting in early July, a cutting date that would now seem rather late.

Great progress was made in the second half of the 20th century in increasing the understanding of the nutritive value of grassland feeds and the development of techniques for assessing components of nutritive value appropriate for research and for practical feed evaluation.

Attention in the early 1900s centred largely on crude protein, crude fibre and digestibility. In a classic series of experiments, Woodman developed further the work on grass maturity started by Crowther & Ruston (1912). He studied the effects of growth stage, cutting interval and seasonality on chemical composition of grass and on *in vivo* digestibility (Woodman *et al.* 1926, 1927) and provided convincing evidence on the very high quality of grass when cut at weekly intervals.

Although there was a general negative relationship between crude fibre content and DM digestibility, this was not applicable across a wide range of situations. The first breakthrough in improving the prediction of *in vivo* digestibility came from the development at Hurley of the *in vitro* digestibility technique (Tilley & Terry 1963). This simulated the key processes in the animal, with the incubation of dried ground samples of herbage with rumen liquor and a mineral buffer being followed by enzymic digestion with acid pepsin. The quantity of DM that disappeared was numerically close to values for *in vivo* digestibility and correlations between *in vitro* and *in vivo* digestibility were close and robust across a wide range of grassland feeds. There was rapid and widespread adoption of this technique in research and more limited adoption for routine feed analyses (Givens *et al.* 2000). The possibilities for use in plant breeding were quickly realized and Cooper *et al.* (1962) published values for the heritability of *in vitro* digestibility for ryegrass and cocksfoot. Casler & Vogel (1999) concluded that the use of this technique had facilitated improvement in digestibility by 0·7–2·5% per generation. The *in vitro* technique suffers from the requirement for a source of rumen liquor and, because of the number of manipulations involved, it is rather expensive for routine analysis.

The next breakthrough in this area came from the development of near infra-red spectroscopy (NIRS). This technique can be used with fresh and dried samples and involves measurement of the absorption properties of the sample across the NIR region. The absorption patterns can be related either to distinct chemical entities or to more aggregated expressions of nutritive value. The technique was first used for determining moisture content of grain (Norris & Hart 1965) and was then developed for use with forages (Norris *et al.* 1976). With appropriate calibration, NIRS can accurately predict a wide range of specific organic components in grasses and *in vivo* digestibility can be predicted by NIRS with precision similar to that achieved with *in vitro* techniques (Barber *et al.* 1990; Park *et al.* 2005). The possible development of NIRS for use on a forage harvester for in-line prediction of feeding value is being studied by Paul *et al.* (2000) and has great potential.

Little attention was paid during the early 1900s to the voluntary intake of grassland feeds, although subsequent studies collated by Mertens (1994) showed that DM intake accounted for 0·6–0·9 of the variation in digestible energy intake by ruminants and a high proportion of variation in rate of animal production. Concepts of control of voluntary intake have been dominated by the bulk hypothesis. Lehmann (1941) first suggested that intake in the ruminant was limited by the bulk of ingesta in the rumen. This concept was further developed by Balch & Campling (1962) who proposed that the intake of forage was limited by the rate at which it was removed from the rumen by either digestion or by the flow of undigested particles from the rumen. Whilst this concept continues to provide a good framework, it is now realized that intake of high quality forages may be limited by (a) the metabolic demands of the animal (Conrad *et al.* 1964) (b) other components of the feed, particularly in silages (Wilkins *et al.* 1971) and (c) in grazing conditions by sward structure, as it affects ease of prehension of herbage (Penning *et al.* 1991).

The analytical scheme of Van Soest was a key development in understanding the nutritive value of forages (Van Soest 1963; Van Soest & Wine 1967). The essential separation was between a fibre fraction resistant to neutral detergent (NDF) that represented the cell walls of the forage, whilst the remainder, soluble in neutral detergent, represented the cell contents (CC). The scheme also determined acid detergent fibre (ADF), comprising cellulose and lignin, and acid-detergent lignin (ADL). The CC fraction is digested rapidly and almost completely in the rumen, whilst NDF is either indigestible or requires microbial action for digestion. Van Soest showed a general negative correlation between the digestibility of NDF and the ratio of ADL to ADF. This scheme provided a much more functional insight to forage composition than the Weende scheme, in which part of the cell wall was included in the crude fibre fraction and part in the nitrogen-free extract. This scheme could be used to predict digestibility, although with less precision than possible with *in vitro* digestibility. More importantly, it provided a framework for consideration of forage intake. The fall in intake of grasses as they mature is associated both with increases in content of NDF and reduction in the digestibility of NDF, resulting in a close positive relationship between intake and digestibility within a grass species. However, when grasses and legumes are compared at similar levels of digestibility, intake is higher for the legume. This was shown to be due to the legume having a higher content of CC (rapidly removed from the rumen) and a lower content of NDF (slowly removed from the rumen) than the grass. Thus, consideration of NDF as well as digestibility was shown to improve the prediction of intake (Van Soest 1965). Subsequent work by Minson (1990) showed that intake was also influenced by leaf proportion and bulk density of the forage, with all of these factors being in accord with the hypothesis of bulk limitation to intake. More recently, NIRS has been used for intake prediction, with Steen *et al.* (1998), Gordon *et al.* (1998) and Offer *et al.* (1998) all demonstrating good prediction of silage intake from NIR spectra.

It is well recognized that grassland feeds provide a large proportion of the protein supplied to ruminants. During the early part of the 20th century, protein value of forages was evaluated as either crude protein content (Kjeldahl $N \times 6{\cdot}25$) or as digestible crude protein. However, it was increasingly realized that forages contained one fraction that is degraded in the rumen (ruminally degradable protein, RDP) and a second fraction that passes through the rumen undigested (ruminally undegradable protein, UDP). A proportion of the RDP would be used for synthesis of microbial protein in the rumen. Burroughs *et al.* (1967) and Miller (1973) proposed protein-rationing schemes that were based on the need to satisfy animal requirements for amino acids and used information on RDP, UDP and factors for the conversion of RDP to microbial protein and for the digestion of these fractions in the small intestine to calculate amino acid supply to the animal (Agricultural Research Council 1980). Most systems for determining protein supply and requirements are now based on these principles.

Most grassland feeds have a high proportion of RDP, but the conversion to microbial protein may be limited, particularly in silages which have undergone extensive fermentation in the silo, because of shortage of energy for microbial growth (discussed by Beever & Mould 2000). The presence of tannins in some legumes such as *Lotus* spp. and *Onobrychis* spp. may reversibly bind with protein and increase UDP (Jones & Mangan 1977; Waghorn *et al.* 1987). In some instances, extremely high tannin levels may limit feed protein value by reducing the intestinal digestibility of protein (Waghorn *et al.* 1994). There is a need for further improvement in techniques for fractionating the N constituents in forages and for predicting the efficiency of conversion of RDP to microbial protein, as discussed in Givens *et al.* (2000).

Grassland feeds also make major contributions to mineral and vitamin supply. These aspects are discussed in Givens *et al.* (2000) and will not be reviewed here. Anti-nutritional factors that may severely limit nutritive value, particularly in forages grown in stress conditions, are reviewed by Reed *et al.* (2000) and Barry *et al.* (2001).

At the end of the 20th century, new aspects of the quality of grassland feeds emerged in relation to effects on product composition and human health. Dietary levels of conjugated linoleic acid (CLA) and the ratio of n-6 to n-3 polyunsaturated fatty acids (PUFA) were associated with anti-carcinogenic effects and susceptibility to coronary heart disease, respectively. Timmen & Patton (1988) showed beneficial effects of feeding fresh pasture on PUFA and CLA in milk fat and Enser *et al.* (1998) demonstrated effects on PUFA in meat. These observations have now been confirmed in many experiments (see Scollan *et al.* 2005) and open up possibilities for further exploiting grassland products in feeding systems and for new objectives in forage breeding and management. Effects of ensiling on PUFA have already been studied (Dewhurst & King 1998) and variation between grass varieties and species in content of PUFA and in susceptibility to biohydrogenation in the rumen have been identified (Dewhurst *et al.* 2001; Elgersma *et al.* 2003).

Grazing

Important progress in grazing research did not occur until the middle of the 20th century. Indeed little research effort had been directed specifically to grazing until that time, with the notable exception of the work of Jones (1933*a*, *b*; 1937), who showed dramatic effects of grazing on sward composition, with the timing and severity having major effects on the contents of legumes and weeds in pastures; treatments involving light stocking in the spring severely depressed clover content. It became widely accepted that production from grassland would be increased by the adoption of some form of rotational grazing involving significant rest periods (Stapledon 1937). This approach was stressed by Voisin (1959), who advocated systems in which (a) duration of grazing was short to prevent re-grazing of new herbage growth and (b) rest periods were sufficiently long for replenishment of carbohydrate reserves and for the grass to experience a period of particularly rapid growth. It was subsequently realized that these concepts, derived from experiments with cut grasses, were not necessarily applicable to grazed swards, because even in continuously stocked pastures there may be very large variation in the frequency with which individual tillers are defoliated. McMeekan (1952) stressed that selection of the number of stock to be carried was the first essential to achieving efficient utilization of grazed swards. He followed this with experiments in which stocking rate was shown to have major effects on animal production from grazed swards. The use of controlled rotational grazing resulted in only a slight increase in production compared with set stocking, with the response only occurring at high stocking rates (McMeekan 1961). This conclusion was confirmed in subsequent reviews (e.g. Ernst *et al.* 1980).

The importance of stocking rate was further emphasized by Mott (1961) who presented generalized curves relating stocking rate to animal output per head and per unit area. These demonstrated that at low stocking rates, whilst output per head may be maximized, the proportion of the sward that is utilized will be low, limiting animal output per unit area. As stocking rate increases sward utilization improves, but at the cost of lowered output per head, because of grazing severity restricting animal intake. Output per unit area is maximized at intermediate stocking rates. Thus, a strong case was made for grazing experiments to be carried out at a range of stocking rates in order to establish rigorous responses to variables such as sward type, grazing method and fertilizer application. Examination of such data led Jones & Sandland (1974) to suggest that the relationship between stocking rate and individual animal performance was linear over a wide range of stocking rates.

It was progressively realized that greater understanding of the physiology of the grazed sward and factors determining animal intake and response was required to develop management guidelines for grazed swards. Parsons *et al.* (1983) quantified the balance between photosynthesis, gross tissue production, herbage intake and death in swards continuously stocked by sheep with grazing controlled in different treatments to maintain a wide range of sward states characterized by differences in leaf area index. Total herbage intake by sheep was equated with net tissue accumulation and was shown to be extremely low with either very lax or very severe grazing (as suggested by the earlier work of Mott) but was maximized with an LAI of 2. These conclusions were supported by the work of Bircham & Hodgson (1983). Subsequent research indicated that sward height could be used as a proxy for LAI and physiologically based models were produced in which net herbage growth was related to sward height for different variants of continuous and rotational grazing (Parsons *et al.* 1988). These models confirmed the dominant effect of intensity of grazing on net herbage growth, but indicated circumstances in which an advantage of up to 20% could result from rotational grazing.

In a parallel work, Penning *et al.* (1991) related eating rate, grazing time and total herbage intake by sheep to sward height. This, and similar but less detailed research with beef cattle and dairy cows (Mayne *et al.* 2000), provided a sound basis for grazing management based on maintaining target sward heights that could be readily applied on the farm. The optimum sward height was identified as being higher for larger animals and those with high nutrient demands. Parsons (1984) and Hodgson *et al.* (1986) list target sward heights for different classes of stock. It is notable that control of management in rotational systems according to sward height before and after grazing had been suggested previously by Brougham (1958).

Even with the use of sward height guidelines, grazing management remains a compromise between maximizing individual animal production and achieving efficient sward utilization. A number of approaches to manipulate this relationship have been suggested such as leader-follower grazing (Blaser *et al.* 1959; Mayne *et al.* 1988) or the alternation between grazing and cutting (Holmes *et al.* 1972; Wilkins 1990), but they have not been widely adopted. The leader-follower concept remains a particularly attractive option. It involves rotational grazing with the leaders being animals with a high physiological demand for nutrients, allowed to graze a paddock first and achieve high levels of individual intake, whilst followers, stock that have lower nutrient demands, are used to graze second and achieve efficient sward utilization.

There is a promise that further increases in the efficiency of grazing systems will result from research using techniques to measure herbage intake at pasture through the use of n-alkanes (Dove & Mayes 1991) and from animal behaviour recording devices to measure time and record spatial position and dietary choice of grazing animals (Orr *et al.* 2004).

Grass conservation

The predominance of hay making during most of the 20th century has already been noted. Despite improvements in the design and capacity of machinery, hay making remains a method of conservation that is prone to high levels of loss in humid temperate regions, because of the requirement for long spells of dry weather to accomplish drying. Losses may occur through continued plant respiration after cutting and from the physical loss of fragile leaf components during the latter stages of drying. It is perverse that the increased power input with tedding, turning and baling machinery has probably increased physical losses compared with hand methods and machinery operating at lower speeds. Also, during the early part of the period it was more common to put partly dried hay on wires or tripods in the field to finish drying without mechanical disturbance. Research on hay making during the 20th century centred on techniques to reduce the drying period required in the field. Consideration was given to techniques to increase drying rate by either physical or chemical treatments to reduce the resistance to water loss (Dernedde 1980; Jones & Harris 1980) and to the removal of hay from the field at higher moisture contents for either barn drying or storage with chemical or biological additives. This whole area was recently reviewed by McCartney (2005). Barn drying enabled the production of high quality hay, but had high costs for capital, labour and fuel. The approach was fairly widespread from 1950–80, but is now little used, apart from in areas in which silage making is prohibited because of concerns for microbial contamination of milk for cheese making. Whilst preservatives such as propionic acid and ammonia gave good results in laboratory conditions, effects in practice were variable and there has been little application of these approaches.

Technical limitations to both haymaking and silage making led to the search in the 1920s and 30s for new approaches to grass conservation. The first steps to grass drying had been made in Germany in 1905 (Oehring 1973), but there had been little commercial application. Woodman used high-temperature drying in his research on the nutritive value of grasses from 1925. He saw possibilities for the commercial production of dried grass, with grass of high quality cut and dried at high temperature either directly or after a short period of field wilting. He demonstrated that the nutritive value of the dried grass was similar to that of the grass prior to drying and showed that the product could be used as either a complete ration or used to substitute for concentrate feeds (Woodman 1937). A range of types of drier were marketed with 39 plants in operation in the UK in 1936 and 1200 plants in 1951 producing 500 000 t.

The interest in the UK declined from about 1950 with renewed availability of imported high-protein concentrate feeds, but with low prices for oil and progress in mechanization there was a resurgence of interest in grass drying and processing from about 1965, as discussed by Wilkins (1974*a*). However, increased fuel prices from the 1970s led to reduced focus on this method of grass conservation in temperate regions, although there is still some production particularly in Spain and France, helped by support from the European Union. It is most unlikely that there will be any future major expansion in grass drying.

The slow adoption of silage making in the UK has already been noted and was mirrored in other countries in the temperate zone. Widespread adoption did not occur until technology was available which would produce silage of high feeding value with low levels of loss and at a reasonable price. At the beginning of the 20th century, it was realized that air needed to be excluded and that in some situations the addition of molasses improved silage quality, but the essential fermentation pathways and sources of loss were not known and techniques to prevent air ingress during storage were not available. Consequently, most silage was poorly made involving high losses and a product with much lower feeding value than the grass prior to ensiling. The first breakthrough was the development of the AIV process in Finland (Virtanen 1933). He applied a mixture of sulphuric and hydrochloric acids to arrest enzymic and bacterial action in the silo and produced a silage with composition similar to the unensiled grass, but with low pH. Although reasonably well accepted by stock, subsequent experiments showed that intake was restricted through problems with the metabolism of the added mineral acids (Saue 1968; L'Estrange & MacNamara 1975). Nevertheless, this was an important demonstration of the possibility of achieving efficient preservation as silage. The process was widely adapted in Nordic countries, despite the hazards of handling corrosive acids and problems of animal metabolism.

Research on the ensiling process continued at several centres. The major fermentation pathways were elucidated and sources of loss identified (Langston *et al.* 1958; McDonald & Whittenbury 1967; Zimmer 1969). Weissbach *et al.* (1974) in Germany established that it was possible to predict the course of fermentation in the silo from knowledge of the crop DM content and the ratio of water-soluble carbohydrate content to buffering capacity. These developments provided a sound basis for considering ways of manipulating the ensiling process to minimize the risks of clostridial fermentation and for evolving practical systems for effective silage making. At the same time, the throughput rates and efficiencies of forage harvesters were improved, polythene sheeting became available to seal silos effectively and formic acid was marketed as an effective additive with a simple and efficient application system. These developments provided the package of advances required for a system attractive to farming and rapid adoption followed, as discussed by Brassley (1996). The subsequent development of systems for making big-bale silage, often by contractors, led to further expansion of silage making to small farms without the need for large investments in machinery and silos (Wilkins 2005).

In the early 1970s, there was still major uncertainty on the factors determining the feeding value of silages, with reductions in voluntary intake and in the efficiency of N utilization being commonly reported (Wilkins 1974*b*). Research at the Grassland Research Institute, Hurley, UK showed that the intake of silage was reduced when there was extensive breakdown of protein to simple N compounds, but also where there was excessive production of lactic acid (McLeod *et al.* 1970; Wilkins *et al.* 1971). Limiting the extent of fermentation by heavy wilting prior to ensiling or by the use of high rates of formic acid were shown in a series of experiments in Finland to result in silages with intakes and protein utilization closely similar to that of the unensiled grass (Huhtanen 2002; Huhtanen & Shingfield 2005).

ENVIRONMENTAL IMPLICATIONS

Nutrient management

Throughout most of the 20th century, fertilizers and organic manures were considered as sources of nutrients to promote plant growth; increased applications did much to increase grass production, as noted earlier. There was remarkably little attention to the fate of applied nutrients, although Mulder (1952) had referred to the need for close examination of the fate of unabsorbed fertilizer N applied to grassland. By the 1970s, concerns were expressed about the possibility of grassland contributing to nitrate pollution of rivers and aquifers, but experiments carried out with cut grass indicated that in favourable growing conditions little N is lost by leaching, even with fertilizer N applications up to 400 kg/ha (Garwood & Tyson 1973; Prins *et al.* 1988). The possibility of higher losses with grazing had been demonstrated in New Zealand (Walker 1962) but the issue only gained prominence following the work of Ryden *et al.* (1984), which showed leaching losses of 29 kg/ha from cut swards receiving 420 kg/ha of fertilizer N were increased to 162 kg/ha from grazed swards with the same fertilizer input.

Van der Meer (1983) drew attention to the importance of whole-farm nutrient budgets. With intensive dairy systems common in the Netherlands at that time only some 0·16 of the N input was recovered in animal products, with some 450 kg N/ha not accounted for. Some would have been retained in the soil, but most would be lost to the environment by leaching or to the atmosphere as ammonia, nitrous oxide or dinitrogen. The contribution of nitrate to water pollution is well recognized, whilst nitrous oxide is a greenhouse gas and ammonia contributes to soil acidification and atmospheric N deposition, putting fragile habitats at risk, as discussed by Jarvis & Pain (1997).

Progress was made in identifying the processes determining the different sources of loss from grassland systems and models constructed for calculation of losses in defined circumstances (Scholefield *et al.* 1991). These were used by Jarvis *et al.* (1996) to explore the impact on the different sources of loss of different approaches for improving N efficiency, including tactical applications of fertilizer, the use of white clover and the integration of maize within the system. Models were further developed to indicate appropriate fertilizer rates and application strategies to satisfy economic and environmental targets (Brown *et al.* 2004).

The risks of 'pollution swapping' became more obvious, with some techniques such as drainage reducing losses of nitrous oxide, whilst increasing leaching losses (Scholefield *et al.* 1988). This stressed the importance of considering the system as a whole and the range of emissions and losses from the system. The focus returned to whole-farm nutrient budgets and ways in which overall N efficiency could be increased. If this could be done, then animal output could be maintained with lower levels of N input and lower N losses to the environment. Jarvis & Aarts (2000) indicated possibilities for major increases in system efficiency by improving (a) the transfer of N from the soil to the harvestable crop, (b) the transfer from harvestable crop to feed intake, (c) conversion in the animal from feed to milk and meat and (d) transfer for excreta to soil. Legislation in the Netherlands, and now in other European Union countries, incorporates the whole-farm nutrient balance approach and limits the permissible N surplus in order to reduce pollution risks (de Clercq *et al.* 2001).

Intensification of grassland use has caused problems in relation to P as well as N, with the major issues being eutrophication and damage to aquatic ecosystems through movement of either soil particulate P or leached P to water. Losses that are agronomically insignificant can have major environmental effects. Pathways and processes are discussed by Haygarth & Jarvis (1999). The whole-farm budget approach is being used for P as well as N (Jarvis & Aarts 2000) and limits are being imposed on P surpluses. Attention also needs to be paid to reducing the risks of soil transfer and losses that occur when heavy rain follows application of either fertilizer or organic manures.

Biodiversity

In the first half of the 20th century, a high proportion of the grassland area supported swards whose botanical composition had evolved in response to local geology, soil type and centuries of traditional management practices. Most grassland that was mown was used for late-cut hay rather than silage, and grazing stocking densities and inputs of manures or fertilizers were comparatively low. As land returned to grass, e.g. following a period under arable crops, swards were frequently established using botanically complex seed mixtures, hayloft sweepings or even allowed to regenerate naturally from the seed bank in the soil. Botanically diverse grasslands were therefore widespread and many existed almost by default, and provided habitats for a varied flora and other wildlife. Conversely, the area occupied by agriculturally improved swards and sown ryegrass leys was comparatively small, as evidenced by the first surveys of the grasslands of England and Wales conducted in the 1930s (Davies 1941; Ordnance Survey 1945; Fuller 1987). The need for increased agricultural production during the 1939–45 wartime emergency, and subsequent policies to improve farm output and national self sufficiency (HMSO 1975) led to a range of powerful governmental support measures to farmers to plough up or otherwise improve the agricultural production of permanent grasslands. This was to lead to widespread changes in the botanical composition and structure of grassland swards with major consequences for wildlife value in the wider countryside (Duffey *et al.* 1974; Hopkins *et al.* 2000).

Policy changes to encourage management to support biodiversity and conservation objectives have increased progressively in recent years. These have arisen partly in response to pressures to halt habitat and species losses resulting from agricultural intensification, from the need to address overproduction of some agricultural commodities, and to comply with international agreements such as the 1992 UN Global Convention on Biological Diversity. In the UK, organizations and legislative support for wildlife protection were firmly established by the start of the 20th century, and the designation of nature reserves from 1915 was further strengthened with the establishment of the Nature Conservancy in 1949 (Evans 1992). The major change since the mid-1980s has been the extension of measures to encourage conservation not just in nature reserves and designated Sites of Special Scientific Interest, but in the wider countryside that is predominantly under agricultural management, with a recognition that biodiversity has a role as part of a multi-functional land management (Hopkins & Holz 2005; Partel *et al.* 2005). Agri-environment schemes that reward or compensate farmers to maintain or introduce management that helps deliver biodiversity and other environmental objectives were introduced in the UK in 1987, following local UK pilot schemes and experience elsewhere in Europe. The approach was broadened into revisions of the EU Common Agricultural Policy from 2005. There is also recognition that biodiversity can contribute to rural economies, both through its influence on the landscape and contribution to rural tourism, and increasingly through links between sward botanical composition and food product quality (Rubino *et al.* 2006). These changing objectives pose a number of challenges and opportunities for both grassland scientists and grassland managers, not only in terms of managing the remaining areas of species-rich swards but in restoring and enhancing the biodiversity value of agriculturally improved grassland (Hofmann & Isselstein 2005).

FUTURE PERSPECTIVES

The importance of grassland as the basis for the ruminant livestock industries in the temperate zones of Europe and other regions seems likely to continue for the foreseeable future, despite competing demands for land use. However, the trend towards multifunctionality, with agricultural grassland contributing to environmental objectives such as landscape and biodiversity protection, water catchment protection, soil erosion control and carbon sequestration is also likely to increase. Research is already indicating approaches to satisfy these requirements. The changed situation presents new income opportunities and technical challenges to grassland farmers, while at the same time providing a basis for the continuation and adaptation of grassland management that goes beyond agricultural production. However, in areas that are economically marginal for agriculture there are uncertainties as to whether grassland farming can continue, unless special measures are implemented to retain grassland management that delivers the objectives that society requires.

Whether the trend towards extensification of management continues in the longer term will depend on the overall pressures on national and global food production. Increases in world populations, particularly in urban areas, and increases in demand for milk and meat in developing countries (Delgado 2005) will increase the pressure on land. In addition, many of the world's livestock farming areas, particularly the semi-arid zones, face uncertainties linked to the impacts of climate change and their ability to maintain production. Temperate oceanic grassland zones, based on scenarios to the 2050s, appear likely to be more resilient to the anticipated changes than zones that already experience stress from high temperatures and low summer rainfall (Hopkins & Del Prado 2006). Nevertheless, a number of responses to climate change, both in terms of adapting to its effects and in helping offset its causes, will need to be considered in the temperate zones. In the somewhat drier areas, maize, lucerne and other cereal crops might be expected to replace grassland, though this is less likely in the more humid Atlantic Arc areas of Europe and in New Zealand. Further pressure will arise if substantial areas of land, including grassland, are converted to biomass or other industrial crop production. Whilst there are many uncertainties, it appears likely that there will be a requirement to increase the output of food and feed from grassland and that this will put particular pressures on low-input systems that currently combine production with environmental objectives.

There is already a trend in some countries for intensive production on limited areas, with the focus on food production rather than on delivery of environmental services other than as required by legislation, such as controlling nutrient emissions. Dairy farming in parts of the UK and the Netherlands, and in the USA, has been moving in this direction, driven by demands to cut production costs for basic commodity production. In the future, improved nutrient efficiency is likely to be the major challenge for such systems (Wachendorf & Golinski 2006). Greater knowledge will facilitate much better control of fertilizer inputs and precision management.

It was noted earlier in the present review that cultivar improvement has led to improved forage production potential but the rate of progress in breeding for production has been modest (Humphreys 2005; Abberton & Marshall 2005). Whilst some further production potential improvement of cultivars is possible, considerable opportunities exist for improvement in forage quality, including PUFAs, WSC and protein quality. The application of new technological approaches such as introgression, gene mapping and marker-assisted selection provides the means to improve varieties for a range of nutritional and other targets such as rumen efficiency, lipid composition and drought tolerance (Pollock *et al.* 2005). There may be an increased role for many of the lesser used grass species for particular environments and for contributing dietary components that lead to enhanced quality in meat or milk products, and for biodiverse swards that contribute to products of distinctive quality. At least in the medium term, there is also likely to be an increased role for forage legumes across a range of grassland production systems because of (a) their high nutritive value, both as sole feeds and in mixtures, leading to high intake and (in the case of legumes containing condensed tannins) to improved N utilization; (b) the low input requirements and low production costs compared with N-fertilized grass and therefore reduced fossil energy use; and (c) their place in organic systems. Some expansion of legume use would be consistent with achieving goals of environmental policy and meeting consumer expectations (Peeters *et al.* 2006).

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