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Running Title: Grassland Research: Key developments from North Wyke Research Station

Chapter title: The importance of sustained grassland and environmental research: a case study from North Wyke Research Station, UK, 1982-2017.

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Abstract

This paper reviews contributions made to agricultural and environmental science and practice from research on temperate grassland carried out from 1982 to present at Rothamsted Research's North Wyke Research Station, Devon, UK. It describes the evolution of the research programme and demonstrates the importance of sustained, interdisciplinary and collaborative research. North Wyke has maintained a clear research focus, alongside an ability to adapt to changing grassland and environmental research needs and funding sources, and despite having changed affiliations on several occasions. The substantial contribution to agricultural and environmental science arising from the research station has influenced, and continues to influence farm practice, research and policy nationally and internationally. Some key topics have included nutrient cycling, farm waste management, gaseous emissions, biodiversity, grazing management, animal production (meat and milk), and forage quality. Currently, North Wyke Research Station is leading the way on taking increasingly holistic approaches to researching more efficient, sustainable approaches to grazing-livestock agricultural production. This involves the use of world-leading, facilities such as the North Wyke Farm Platform, comprising three farmlets, designed to test the productivity and environmental sustainability of contrasting temperate grassland beef and sheep systems. Future perspectives highlight key challenges facing the agricultural industry including climate change mitigation and adaptation, and the growing world population. Opportunities exist to tackle these challenges through technological advances, but also through increased integration of agricultural, environmental, economic and social research. North Wyke Research Station provides an example of a research facility where such challenges can be addressed.

Keywords: Agronomy, livestock production, ruminant grazing behaviour, environmental research, legumes, nutrient cycling, soil organic matter, greenhouse gases, biodiversity, sustainable intensification.

Contents

1. Introduction

1.1. Background

More than 50% of the UK is covered by grassland, used primarily for the rearing of livestock for meat and dairy production, providing £8 billion per annum to the UK economy (Orr et al., 2016). Despite this large value and extent, grassland has received relatively little attention in terms of research, with only a few specialist research centres being dedicated to understanding and enhancing their functioning and productivity. This paper reviews contributions made to science and practice from research on grassland carried out from 1982 to present at North Wyke Research Station, now part of Rothamsted Research. Our aim is to describe the evolution of the research programme and to demonstrate the importance of long-term, interdisciplinary and collaborative research.

North Wyke is located in Devon, England (50°46’10”N, 3°54’05”W), in a cool, temperate area with annual rainfall averaging 1050 mm and mean annual temperature of 9.3^{o}C. Most of the soils are ‘heavy’ with impeded drainage, making conditions representative of much of the permanent grassland area in western Britain and indeed North-West Europe.

The research station at North Wyke and the context of the early programme is described by Wilkins et al. (2009). Briefly, North Wyke was acquired by the then Grassland Research Institute (GRI) in 1981 to provide the base for a new research programme on long-term or permanent grassland production and utilization. The GRI was one of a family of Institutes parented by the then Agricultural and Food Research Council (AFRC) and funded principally by the Research Council and the then Ministry of Agriculture, Fisheries and Food (MAFF). The GRI’s base at Hurley was in an area of low rainfall, not representative of the main grassland areas in the country. This new programme was required because grassland research in England and Wales had been concentrated on sown, short-term grassland, despite most grassland in the country being permanent or only occasionally re-sown (Green, 1982). A National Farm Study (Forbes et al., 1980) had highlighted the generally small, but highly variable, levels of utilized output from farms with large proportions of permanent grassland. There were important unanswered questions on the productivity and management of such swards, particularly in conditions of high rainfall and impeded drainage.

Proposals were developed for a programme to better understand the productivity and response to management of permanent grassland and to develop improved systems for animal production from such swards, including emphasis on the use of forage legumes, particularly white clover (*Trifolium repens* L.), and problems resulting from wet conditions. This programme also encompassed research to better quantify both herbage production and utilization on farms. The acquisition of North Wyke was a key factor in the delivery of this programme. North Wyke had been an experimental farm for Fisons Ltd. from 1955, so that when the GRI acquired the site in 1981 some of the infrastructure for field research on grassland was already established. At the same time, part of an adjoining farm, Rowden, was acquired to increase the area to 250 ha of grassland. Subsequently, additional areas were rented for specific experiments and parts of the programme have been carried out on commercial farms. An important recent addition was the purchase in 2017 of 100 ha of land at Whiddon Down, some 6 km from North Wyke, to facilitate a breeding programme to establish a closed herd of elite beef cattle as a leading genetic resource to support livestock sustainability research.

The initial programme was developed by staff transferred from GRI at Hurley and by some new staff appointments. Much of the research was carried out in collaboration with scientists still based at Hurley and with staff from the Agricultural Development and Advisory Service (ADAS). Whilst the programme at North Wyke has continued to be concerned mainly with long-term grassland, there have been major changes in emphasis over the years, associated with new scientific opportunities, changing parent organisations (four changes over 36 years), changing policies of funding bodies and changes in the structure and organisation of research. Table 1 details the changes in structures. Some of the more significant changes in the research programme over the years have been (a) the move from emphasis on grassland solely for animal production to consideration of grassland in a multi-functional context and (b) the addition of more strategic and fundamental research to the initial focus on applied research.

Insert Table 1 here

Table 1. Grassland Research at North Wyke (1981-2017): key events and evolution of research

1.2. Grassland in a multi-functional context

Whilst there has always been close integration of soil, plant and animal components in the research programmes, the case for the acquisition of North Wyke was driven entirely by concerns to increase production and contribute to a Government policy to increase national food self-sufficiency (Ministry of Agriculture, Fisheries and Food, 1975). It was only in the mid-1980s that concern for possible adverse effects of intensive grassland farming on the environment increased along with the need for relevant research. Thus, the emphasis on pollution of waters and the atmosphere, greenhouse gases (GHGs) and climate change and biodiversity increased. At the same time, funding for more applied production-oriented research declined, particularly with the introduction in 1987 of the UK Government policy to withdraw funding from ‘near-market’ research. Although this change led to a major reduction in funding for animal production research at North Wyke, the research station was well equipped to develop programmes on environmental aspects of grassland.

A key to this was the establishment in 1982 of the Rowden Drainage Facility (Fig. 1.a and b) for research on the effects of drainage on the production and utilization of grassland. This unique facility provided 12 (and subsequently 14) grazed, hydrologically-isolated plots each of 1 ha, with half being drained and half undrained. Whilst the early emphasis was on the effect of drainage on herbage and animal output, the installation facilitated unique studies on nutrient transformations and movements and water quality and is still a key facility at North Wyke. Rowden has also been key to studies on carbon sequestration and emissions of greenhouse gases (GHGs) from contrasting grassland managements and provided the basis for early integrated scaled-farm (farmlet) studies. The ability to consider whole animal production systems was further enhanced by the establishment of the North Wyke Farm Platform (NWFP) in 2010 with three farmlets, each of 22 ha, with three contrasting grassland systems, supporting beef and sheep production. There has been major investment in instrumentation for the monitoring of many characteristics of soil, water and atmosphere in addition to plant and animal production, use of labour and economics.

Insert Figure 1 here

Figure 1.a. Photograph of Rowden Drainage Facility showing the 1 ha hydrologically isolated plots. (Photo: Google Earth)

Figure 1.b. Photograph of weirs for monitoring runoff on a drained plot. One weir measures discharge from surface runoff, the other from soil drains. (Photo: S. Jarvis)

One of the key features that has contributed to the success of North Wyke as a grassland research station has been its proximity to contrasting soils in the region. Most of the land-based studies at NW have been conducted on two similar, inherently poorly drained soils of the Hallsworth or Halstow series (Harrod and Hogan, 2008). These soils vary in their hydrological characteristics, but both have poor water storage capacity and are slowly permeable down to 30 cm soil depth, where they have a clay-rich layer with very poor hydraulic conductivities. These soils are typical of much of the intensively managed grassland areas in the western UK and typically used for livestock production where annual rainfall averages >1000mm. These soils have much potential to ‘poach’ and become compacted (Scholefield, 1986; Scholefield and Hall, 1986) and consequently have large propensities to produce anaerobic conditions. Importantly for many of the studies and platforms developed at North Wyke, these soils facilitate the measurement and sampling of runoff in what are effectively lysimeters because of the impermeability of the clay layer. This feature is the principle upon which the Rowden experiment, NWFP and many other important studies involving soil block or small plot experimental set-ups have been developed. North Wyke is, however, close to the more freely draining neighbouring soil of the Crediton series, and this has enabled comparative studies between the two contrasting soil types and predominant land uses of grassland (Hallsworth/Halstow) and arable (Crediton).

1.3. Type of research

Through the 1980s the research at North Wyke was field-based, with only minimal laboratory facilities on site. There was reliance on Hurley for analytical services and many programmes were developed in collaboration with scientists based at Hurley. A major change occurred in 1990 following the decision to close the Hurley site and for programmes relating to soils, farm wastes, plant-animal relations and grassland pests and diseases to be re-located to North Wyke. There was substantial capital investment at North Wyke, particularly for laboratory facilities. These changes increased both the breadth and depth of research based at North Wyke and the ability to carry out holistic programmes on soil, plant, animal and environmental aspects of grassland production. This also led to a wider funding base with increase in funding from Research Councils and less reliance on MAFF and its successor organisation the Department for Environment, Food and Rural Affairs (Defra).

It has been a strong feature of research that many projects have involved collaboration with other scientists both in the UK and overseas, with the facilities at Rowden and the NWFP being key to attracting such collaborations. North Wyke was a partner with Rothamsted in the Biotechnology and Biological Sciences Research Council’s (BBSRC) first formal integration of research between Institutes with the formation of the Soil Cross Institute Programme in 2005. There have been formal associations between North Wyke and the Universities of Bristol, Exeter, Plymouth and Reading and post-graduate students registered with many UK Universities have carried out their research at North Wyke. Staff from the National Soil Resources Institute, AgResearch (New Zealand), Royal Holloway University of London and the Universities of Exeter and Liverpool have been based at North Wyke, increasing the size and the range of skills of the academic community on site. International collaboration has been fostered through the personal contacts of scientists and Memoranda of Understanding with many Universities and Institutes worldwide and North Wyke has hosted a multitude of visiting scientists from all parts of the world to further contribute to the diversity of activities.

As demonstrated by the large body of work described here, a key feature of the research has been to cross scientific and physical boundaries to integrate questions and solutions required of complex systems, across disciplines and scales (spatial and temporal) and within and beyond grassland farming practices with fundamental, strategic and applied research. The various interactions between the different types of research and influencing factors through the years are summarised in Fig. 2.

Insert Figure 2 here

Figure 2. Interaction of factors influencing nature of research on grassland components and systems undertaken at North Wyke (Adapted from Jarvis et al., 2012).

2. Agronomy

The main thrusts in agronomic research at North Wyke have concerned the production potential and management of permanent grassland, with a focus on forage legumes, particularly white clover.

2.1. Permanent grassland

Research at North Wyke during the 1980s examined the production potential of permanent grassland, in particular its response to fertilizer nitrogen (N), and its performance and feed value relative to that of sown grassland. This was achieved through a combination of multi-site small-plot cutting trials, grazing experiments and on-farm studies of grassland utilization. The programme had its origins in a GRI-led study of factors affecting the productivity of permanent grassland farms, conducted in the mid-1970s as the “National Farm Study” (Forbes et al., 1980). Data collected from 502 farms (450 of which were monitored intensively) over two years allowed the calculation of farm-scale Utilized Metabolizable Energy (UME) output from home grown grass and forage, which was related to measured inputs and environmental factors. Forage production was not recorded, but the range in UME output was far greater than would be expected from that based on likely variation in grassland production rates. The main factors affecting UME were stocking rate and fertilizer N inputs. Reseeding of permanent grassland to perennial ryegrass (*Lolium perenne*)-based leys was widely practiced because of perceived increases in responses to fertilizers and improved feed value, but the study found only weak correlations between UME output and sward age.

Although much information was available for sown ryegrass (*Lolium spp.*) leys, there was a knowledge gap for longer-term grassland. In 1983 a series of field experiments was established (with ADAS) at North Wyke and 15 other sites across England and Wales to compare existing permanent swards with newly reseeded perennial ryegrass (Hopkins et al., 1990). The sites represented varied elevation, rainfall and soil type: the existing swards had no recent history of reseeding and perennial ryegrass was either absent or a minor component. Results from the first four years (1983-86) provided strong evidence of large production potentials of the permanent grassland. Amounts of dry matter (DM) yield varied between sites, unsurprisingly given the range of elevations (7 to 400 m above sea level) and soil types, herbage DM response to N was significant for all the N-fertilizer treatments (0, 150, 300, 450 kg N ha^{-1}).

Results from across the range of sites were relatively consistent. In the establishment phase of year one (1983) there was, as expected, less annual DM production from the sown sward, but this was compensated for by greater yields of the reseeded sward in year two, typically by about 40% more than the permanent swards. This production advantage was not maintained in years three and four, and over four years, across all sites, mean annual DM production was almost identical between the two sward types for all the N-fertilizer treatments. At eight sites there were additional treatments for the same full range of N treatments but under an 8-weekly cutting (three cuts per year) rather than a four-weekly regime. Total DM yields were greater than for the four-weekly regime and there was a small but significant production advantage to the permanent swards. At the same eight sites, a series of plots was established to determine the impact of pests and diseases on the herbage yield of the swards. These plots were treated with insecticide + molluscicide, a fungicide or a nematicide. Yields were increased by 11% on average across all sites treated with the insecticide + molluscicide treatment, showing that pests and diseases commonly reduced the yield of permanent swards (Clements et al., 1990). These experiments, though, clearly showed that permanent grassland swards were capable of high levels of production and response to fertilizer N. However, herbage of the sown ryegrass was of superior feeding value as indicated by lower concentrations of modified acid detergent fibre (MADF) especially under the eight-weekly cutting management (Hopkins et al., 1990). There was a change in botanical composition in many of the permanent swards, with perennial ryegrass, where it was present, increasing in response to inputs of N-fertilizer.

The large potential of permanent swards was confirmed in terms of animal production in grazing experiments at North Wyke. Replicated drained and undrained plots of a permanent sward receiving 400 kg N ha^{-1} were compared with a reseeded perennial ryegrass sward receiving 400 kg N ha^{-1} over a period of five years with grazing to a controlled sward height by beef cattle (Tyson et al., 1992). Levels of individual animal performance were similar between the sward type despite the higher concentration of MADF noted above. Liveweight gain per ha for the undrained treatments were very similar at 840 kg for the re-seed and 860 kg for the permanent sward, whilst with drainage, liveweight gain ha^{-1} was slightly greater for the reseed at 1010 kg compared with 900 kg for the permanent sward (Table 2). The effects of these treatments on nitrate (NO_3^-) leaching are discussed in a later section.

Insert Table 2 here

Table 2 Liveweight gain (kg ha^{-1}) by beef cattle and nitrate (NO_3^-) leaching (kg N ha^{-1}) for grazed, drained and undrained permanent swards and perennial ryegrass re-seeds receiving 200 and 400 kg fertilizer N ha^{-1} (from Tyson et al., 1992). # Figures in parentheses are means for the period 1983-87

Investigations were also made at the multi-site experiments of differences and changes in a range of herbage minerals (Hopkins et al, 1994). There was little information previously on the likely consequences of management intensification of permanent grassland, though some reported evidence of fertilizer N use affecting ratios of N/sulphur (S) and potassium (K)/(calcium (Ca)+magnesium (Mg)), and of reseeding affecting herbage copper (Cu). Herbage samples from 0 and 300 kg N ha^{-1} treatments from spring and summer harvests were analyzed. Results showed that permanent and reseeded swards reacted similarly to fertilizer N. Reseeding, probably because of cultivation, led to increased mean concentrations of Ca, Mg, S, sodium (Na) and cobalt (Co), but reduced the Cu, molybdenum (Mo) and zinc (Zn). Nitrogen fertilization led to further increases in Na and Mg, and reduced Mo: this was the most pronounced effect of changing from extensive permanent grassland to intensive reseeded grassland. This remains the most comprehensive information on herbage mineral concentrations for contrasting sward types with consistent managements.

Because most grass-to-grass reseeding on farms was of ageing or deteriorated sown swards, rather than of older permanent swards, a subsequent three-year study at eight different sites focused on the response of ageing ryegrass sown swards to reseeding, under a range of fertilizer N rates (Hopkins et al., 1995). This study took place on sites with a history of intensive management. Production responses to N were large, and greater, on average, on the newly reseeded grassland than the ageing ryegrass leys, although this pattern was not consistent. While there were gains in herbage DM yield from reseeding, at least for the high-N treatments on some sites, it was concluded that the gains obtained might not necessarily cover the costs involved, at least in the short term.

The above multi-site experiments greatly improved our understanding of grassland production as measured under the precise management of small-plot experiments: parallel research was also conducted on commercial farms to measure herbage production and its utilization (Peel et al., 1988a, b). The National Farm Study (Forbes et al., 1980) had revealed a wide range in farm level UME outputs and for many farms with below average UME it seemed likely that grassland utilization was less than might have been expected. However, herbage production and UME output had not been recorded at the farm scale. Peel et al. (1988a, b) found that on five farms in SW England, (a) farm-scale herbage production agreed with predictions based on plot experiments, taking account of fertilizer use and site conditions, and (b) utilization on farms was variable and in some cases below potential. The reasons for herbage production not being converted to UME included losses in silage making (average efficiency of utilization 64%), and in grazing (mean of 67% utilization efficiency, with a wide range between farms). The need for greater grazing pressure and more flexible management, and improvements in silage making and feeding, have since been widely recognized and adopted in practice.

The whole programme produced convincing evidence that high levels of both herbage production and animal production can be attained from permanent swards receiving appropriate inputs and management. The results much increased the confidence of farmers that high levels of production and utilization can be attained from permanent swards by improving management, without recourse to reseeding.

2.2. **Forage legumes**

Research on the agronomy and utilization of forage legumes, particularly white clover grown in association with grass, at North Wyke built on previous research at the GRI (Gibb and Treacher, 1984; Orr et al., 1990), which had shown the potential for grass-legume diets to support high levels of animal production. The work on production potential of mixed swards, the introduction of white clover into permanent swards, its maintenance through the control of pests and understanding and modelling changes in sward composition has been conducted in the context of long-term grassland.

2.2.1. Herbage production

Evidence of the herbage production potential of sown perennial ryegrass-white clover on different sites was provided by the 16-site study of permanent and reseeded grassland (see earlier) which gave direct comparisons between grass-clover and N-fertilized grass (Hopkins et al., 1990). Averaged across sites and years, annual DM production from sown grass-white clover (at 0-N fertilizer and with clover contributing about 20% of the herbage) was around 70-80% that of sown grass receiving 150 kg N ha^{-1}.

2.2.2. Clover introduction and maintenance

Surveys (Green, 1982) had shown that most old swards had little clover, despite receiving low applications of fertilizer N. The programme on clover introduction at North Wyke led to the following recommendations (Sheldrick et al, 1987; Sheldrick, 2004): (a) before introduction, rectify deficiencies of P and K and lower sward density by band spraying with a grass-sensitive herbicide or by taking a heavy cut for silage, (b) at introduction using, for instance, a rotary strip seeder the seed needs to be in contact with mineral soil, (c) use chemicals to control slugs and *Sitona* weevils, (d) periodic light grazing after sowing using cattle or, in winter, sheep to reduce grass competition. Similar principles can be applied for management to increase clover content without seed introduction, but for success there must already be a reasonable network of clover stolons present before treatment (Sheldrick et al., 1993).

2.2.3. Pest and disease control

White clover is prone to attack by a range of pests and diseases (Clements, 1997; Clements and Cook, 1998). Work at North Wyke identified the clover root weevil (CRW; *Sitona obsoletus* Gmelin.= *S. lepidus*) as probably the most injurious pest (Clements and Murray, 1991). This led to a major programme on the relationship between CRW and clover.

The adult CRW feeds on the leaves, creating characteristic ‘U-shaped’ notches on leaf margins and the larvae feed on the N-fixing nodules and roots of the plant. Root feeding significantly reduced the N-fixation and general vigour of the plant, putting it at a competitive disadvantage with the companion grasses (Murray and Clements, 1998; Murray et al., 2002). The specific nodule feeding habit of CRW raised questions about how the damage might facilitate short-term transfer of N from clover to grasses. Using stable isotope techniques Murray and Hatch (1994) showed that, under controlled conditions, ryegrass plants grown with infested clover plants had greater biomass and N-content than those growing with un-infested control plants, thus further increasing the competitive advantage of the grass, at least in the short term. More detailed work (with the Université de Caen, France) showed that exudation and subsequent uptake of free amino acids were important in N transfer (Murray et al, 1996; Cliquet et al., 1997; Paynel et al., 2001). Collaborations with the Universities of Reading and Abertay focused on the mechanisms by which CRW larvae were attracted to nodules and identified an isoflavenoid (formononetin), produced by roots, as being particularly attractive. In 1996 CRW was found in, and was rapidly spreading throughout, New Zealand with devastating effects on white clover and consequently on New Zealand's economy. Because of existing links and expertise at North Wyke, New Zealand's AgResearch based a team there to search for possible natural enemies and developed a successful biocontrol programme to combat the pest in New Zealand (Goldson et al., 2004). One of the reasons for the rapid establishment of CRW in New Zealand was the impact of temperature on the phenology of the weevil. In Europe CRW is univoltine, but in New Zealand it has two generations per year. Recent estimates on the grass /clover swards of the NWFP have shown significant damage (Murray et al., 2017). Modelling with temperature data has indicated that conditions have been favourable in two of the last three years for two generations to be present at North Wyke. As climate change occurs there may be significant pest outbreaks in the UK which could be especially severe now that suitable pesticides have been withdrawn from use.

The interest in the use of stable isotopes to determine the effects of root feeding has led to novel techniques to better understand other trophic interactions and soil food webs. Murray et al. (2009) injected isotopically labelled bacteria into soils and traced the movement of both C and N through different soil arthropods to determine feeding preferences. Crotty et al. (2014) subsequently used the natural abundance of stable isotopes and community-wide metrics to determine that plants are top-down drivers of soil invertebrate community functioning and that land management impacts on the whole soil faunal community.

2.2.4. Modelling changes in composition of mixed swards

Change in compostion of grass-clover swards with time has been considered a major impediment to their use in practice. Schwinning and Parsons (1996a, b) provided a much-improved understanding of the dynamics of the relationships between grass and white clover. Using ecological and physiological principles, they developed models that predicted spatial and temporal changes in the balance between grass and clover using a cellular automaton approach with the simulated pasture comprising up to 90,000 interlocking hexagonal cells. The model highlighted the importance of soil N, affected both by the extent of N fixation by clover and by localized additions of N by urination of grazing animals. In areas with high soil N, there is a competitive advantage for the grass, but soil N will then become depleted because of reduced clover presence and reduced N fixation. This shifts the competitive advantage to the N-fixing clover, leading to increases in clover content, but the cycle will be repeated giving continued oscillations in sward composition, particularly at the patch scale. They simulated the short- and long-term effects of selective grazing, random deposition of urine, fertilizer inputs, seasonal disturbances and the dispersal ability of the clover, enabling better understanding of the cyclical nature of clover contribution to mixed swards.

2.2.5. White clover as a companion crop

Research by Clements and his colleagues followed up earlier work at Hurley (Jones and Clements, 1993) on sowing wheat or barley into a permanent sward of white clover (Clements and Asteraki, 1993; Clements and Hopkins, 1994; Clements et al., 1996; Clements et al., 1997). The white clover growth recovered after the cereal crop was harvested for silage or as grain and contributed N to the system. Furthermore, damage to the cereal crop from pests and diseases was reduced. This was attributed to reduced aphid numbers resulting from the large populations of predatory invertebrates harboured by the clover understorey and a reduced incidence of splash-borne diseases by the high ground cover. A reduction in soil erosion that occurred during winter was noted and attributed to the network of clover stolons restricting soil movement. However, the adoption of these systems in practice has been limited by the difficulty in predicting and controlling the balance between the different species, highlighting the need for further research. Companion or 'intercropping' with legumes and other crops still features in the North Wyke research portfolio, although the emphasis has shifted towards improving phosphorus (P) use efficiency via the complementary production of root exudates by different species (Darch et al., 2017).

2.2.6. Other legumes

The potential of legumes including birdsfoot trefoil (*Lotus corniculatus*, L.and *L. pedunculatus*, Cav.), red clover (*Trifolium repens* L.) and lucerne (*Medicago sativa*, L.) have been investigated in experiments at North Wyke. Birdsfoot trefoil is of interest because of its high feed quality linked to condensed tannin content and its ability to tolerate low-input, poor nutrient status soils that would be sub-optimal for white clover. Initial experiments at North Wyke and other UK sites showed promising levels of herbage production from grass-birdsfoot trefoil swards, (Hopkins et al., 1996).

While the advantages of forage legumes, notably their high feed value and role in N fixation, had been shown to have potential practical and economic advantages (Doyle et al., 1987), their integration into farm practice required evidence on their use as silage crops or for grazing. By the 1990s there was a considerable amount of knowledge about white clover, though much less information about other temperate legumes. Further developments came in the late 1990s with two international projects led by North Wyke and involving collaborators at other UK sites and in several European countries, supported with EU funding (LEGSIL - Low-input animal production based on forage legumes for silage, and LEGGRAZE - the use of legume based swards in low input grazing systems). Both these projects had multiple objectives, but for legume forage production some important findings from LEGSIL were: (a) high performance of red clover across most sites, (b) the highest-yielding grass-legume mixtures were comparable to grass swards receiving 200 kg N ha^{-1} at most sites, and (c) yields from other tested legumes, including lucerne and birdsfoot trefoil, were variable (Halling et al, 2001). The LEGGRAZE project also included several alternative legumes, depending on the site, and revealed greater intake and animal performance from condensed-tannin-containing legumes, including birdsfoot trefoil, and that these alternative legumes showed clear potential for use in low-input grazing situations (Sölter et al 2007; Molle et al, 2008). In the last decade there has been considerable increase in the use on farms of alternative legumes, particularly red clover in organic systems. Slow establishment and poor persistence limit the use of birdsfoot trefoil and stresses the need for a breeding programme to produce better adapted varieties.

3. Grazing

Grazing has been a major focus of research at North Wyke since the site was acquired by the GRI in 1981, with eight grazing experiments being established in the first year. The programme initially had an applied focus, seeking to exploit in the context of permanent grassland the results from more basic research on grazing behaviour and plant:animal interactions that had been carried out elsewhere, particularly at Hurley. The effort was broadened and strengthened in 1994 with the re-location of more basic research from Hurley to North Wyke.

This section is in two parts. Firstly, research on grazing behaviour is outlined. Innovative techniques facilitated new understanding of ruminant behaviour and preference and these findings led to new approaches for grazing and sward management. The second part describes research on the animal production responses to variation in grazing management and the use of swards comprising mixtures of grasses and legumes.

3.1. Grazing behaviour

Grazed grass can be one of the cheapest sources of nutrients for ruminant animals, but animal performance may be limited by the quantity of herbage that the animal is able to consume. Daily DM intake is a function of the time spent grazing grazing (mins) and intake rate (IR) (g DM per minute grazing). Research has been directed towards increasing understanding of these factors. Important contributions were made to improve techniques to measure and analyse the behaviour of grazing animals. A review by Penning (1983) concluded that of the various techniques previously used to record grazing behaviour through measurements of head position, head movement, or jaw movements, none were wholly satisfactory. Refinement of earlier behaviour recorder designs for grazing animals led to the production of more robust and reliable solid-state equipment (Rutter et al., 1997a) to replace the earlier tape-recorder devices. The development of improved interactive software (Rutter, 1999) enabled the detailed recording of jaw movements and subsequent semi-automated analysis of temporal patterns of grazing and ruminating activity, the identification of individual biting and non-biting grazing jaw movements, and ruminative mastications. Identification of concentrate consumption and drinking could also be recognized by experienced operators. Subsequently, additional sensors and modifications of the dedicated software allowed recording of lying-down, walking and standing activity (Champion et al. 1997) and animal location (Rutter et al. 1997b). Such detailed analysis of behaviour, together with the proven technique of measuring short-term herbage IR at pasture (Penning and Hooper, 1985), provided the means for much of the research at North Wyke. Although many of the solid-state recorders were constructed in-house, the subsequent patenting of the dedicated software (GB Patent 9610740.4) and the manufacture of recorders under commercial license allowed researchers elsewhere (e.g. Argentina, Brazil, Uruguay, China) to acquire recorders to investigate grazing behaviour by various classes of livestock (including dairy cows, dairy and beef heifers, yaks and horses).

Studies of grazing behaviour by sheep and dairy cows demonstrated the constraint imposed by sward height and structure on bite mass, and in turn bite rate and short-term IR. In conditions where IR was reduced or where a greater intake was required to meet physiological demand, the major strategy employed by animals was to increase total grazing time over the day (Penning et al. 1995; Gibb et al., 1999). Investigation of the effect of time of day on bite mass, bite rate and IR showed similar diurnal variations in sheep (Orr et al., 1997) and dairy cows (Gibb et al., 1998). Dry matter IR was greatest in the late afternoon and evening, because of increased bite mass, even when bite rate declined. Throughout a series of experiments conducted with dairy cows grazing ryegrass pastures maintained under continuous variable stocking management, and where times of milking were standardized, a distinctive temporal pattern of grazing meals was found, irrespective of any treatment effects on total grazing activity (Gibb et al., 1997, 2000, 2002a, 2002b). Most notably, following return to pasture after afternoon milking, cows performed one or two grazing meals lasting in total for more than five hours. With the largest herbage DM IR occurring during the late afternoon and evening, coinciding with this major period of grazing activity, more than 50% of their daily intake of herbage was consumed following afternoon milking (Fig. 3). Possible exploitation of this pattern of grazing behaviour was examined by Orr et al. (2001a). In many dairy cow enterprises operating a daily paddock stocking regime, it was common practice to move cows to their fresh allocation of pasture after morning milking. However, with the major grazing activity occurring during the late afternoon and evening when the sugar content of the grass is highest, moving cows to fresh clean pasture following afternoon milking was expected to prove advantageous. A test of this hypothesis showed that after an initial adjustment period of four weeks, the greater intakes achieved by cows provided their fresh allocation of pasture in the afternoon, resulted in a 5% increase in milk yield.

Insert Figure 3 here

Figure 3. Mean number of minutes per hour spent grazing either grass or clover over the course of the day for cows grazing adjacent monocultures of 75% grass and 25% clover (by ground area) (Rutter et al., 1998).

Experiments with sheep, cattle and goats provided valuable insights into their behaviour regarding grass and clover swards. Study of ingestive behaviour by non-lactating ewes continuously stocked on monocultures of perennial ryegrass or white clover showed that whilst daily intakes were similar, there were notable differences in grazing and ruminating behaviour on the two swards (Penning et al. 1991). Although bite rate and ingestive and ruminative mastication rates were similar on both swards, ewes grazing clover achieved greater bite masses and IR, and spent less time grazing and ruminating than those on ryegrass. In addition, marked differences were observed in the temporal patterns of grazing and ruminating activity between ewes grazing grass and clover swards. In contrast, with their increased physiological requirements, lactating ewes achieved larger daily intakes on a clover than on a grass sward, because of greater IR on clover swards, resulting in greater lamb growth rates (Penning et al. 1995).

Investigations into dietary preference and selection showed that sheep (Penning et al., 1991, 1995), dairy heifers (Rutter et al., 2004a) and lactating cows (Rutter et al., 2004b) offered a choice between perennial ryegrass and white clover exhibited a partial preference for a diet containing 60 to 70% clover: in contrast, goats selected a diet containing 52% clover (Penning et al. 1997). In addition, these studies demonstrated a pronounced preference for grazing clover during the morning and ryegrass during the afternoon and evening. The preference for grass, with a greater fibre content than clover, later in the day, was thought to be a behavioural strategy to maintain rumen function during the night, avoiding the necessity of night-time grazing (Rutter, 2006). Examination of the effect of spatial scale of heterogeneity of grass and clover on behaviour and intake were studied with lactating ewes offered monocultures of perennial ryegrass or white clover, adjacent equal-sized monocultures of ryegrass and clover, or a mixed sward of grass and clover (Champion et al., 2004). Results showed that offering separate monocultures of grass and clover can benefit the grazing animal, through a reduction in the time spent searching for clover and the greater IR.

In the light of such results, alternative management practices were suggested to make greater use of grazed clover in the diet of dairy cows. With the perceived difficulty of maintaining swards sufficiently rich in clover to meet the partial preference for the legume, and the greater ease of controlling weed invasion in all-grass and all-clover swards, an experiment was conducted to examine whether advantage could be taken from these diurnal patterns of preference for grass and clover. The behaviour and performance of cows grazing a monoculture of clover following morning milking and a monoculture of ryegrass following afternoon milking, were compared with cows offered fresh areas of a mixed grass/clover sward twice-daily after milking (Rutter et al. 2003). Grazing grass and clover in separate swards under rotational stocking management increased total herbage intake and milk yield. Implications of this research on dietary preference by grazing sheep and cattle were discussed in a review by Rutter (2006).

Understanding of the factors determining selection and preference by grazing animals was extended in a joint programme with Oxford University, with much of the work centred on grass and white clover. It was shown that when provided access to monocultures of the two species sheep demonstrated a partial preference for clover (always consuming some grass), but the proportion of time spent grazing white clover was influenced by previous dietary experience, fasting and the physiological state of the animal, with the diurnal changes in preference noted earlier being confirmed (Newman et al., 1992; Newman et al., 1994; Parsons et al., 1994a). Experiments in which sheep were provided contrasting feeds in an array of bowls distributed on an area of bare earth, demonstrated that sheep would return to eat at sites at which their preferred feed was previously located, thus spatial memory had a role in foraging decisions (Edwards et al., 1994, 1996).

This information was embedded in deterministic and stochastic dynamic models combining information on the energetics of eating with concepts from ecological and foraging theory (Parsons et al., 1994b; Thornley et al., 1994; Edwards et al., 1995; Newman et al., 1995). The effects of herbage availability and the spatial distribution of sward components on components of grazing behaviour (preference, biting rate, handling time, bite size and dimensions, grazing time) and thus on net daily energy balance were considered, as were dynamic effects, such as the depletion in availability of the initially preferred species resulting in a switch to a diet containing a greater proportion of the alternatives.

Important insights into the characteristics of different perennial ryegrass varieties was achieved during an evaluation of 15 varieties undertaken with grazing ewes and their lambs on swards maintained under continuous stocking management (Orr et al., 2003). Results demonstrated large differences in daily DM intake by ewes between grass varieties, with the larger intakes per ewe and ha being achieved with two tetraploid hybrid varieties than with those grazing nine diploid and four tetraploid varieties. Daily intakes were correlated with short-term IR, but not with eating time; the animals being unable to increase their grazing time sufficiently to compensate for smaller IR. Intake rate was not correlated with green-leaf mass, tillers m^{-2} or water-soluble carbohydrate content of leaves from the grazed horizon, but a large IR was achieved by sheep grazing the much-tillered diploid varieties and the tetraploid hybrids with fewer tillers m^{-2}. Comparison of ranking of varieties based on grazing yield calculated from daily stocking rate carried and herbage intake per ewe with that measured using eight cuts each season from ungrazed plots showed no correlation between the two methods (Orr et al. 2001b), thus indicating that evaluation of grass varieties by simple cutting trials may not be representative of their performance under continuous stocking regimes.

In view of the large effect of IR on DM intake noted above, a technique for the rapid screening of bite mass was developed using micro-swards established in large trays and grazed briefly by beef heifers (Orr et al., 2005). The ranking of perennial ryegrass varieties using this technique was similar to that obtained in the field with rotationally-stocked swards. This micro-sward methodology can provide a low cost and rapid method for screening the intake potential of grasses in breeding programmes and variety assessment trials.

3.2. Animal production with grazing

3.2.1. Grazing management

Research in the 1970s, particularly at Hurley, highlighted the conflicts between achieving efficient utilization of herbage grown and high rates of performance by individual grazing animals. Severe grazing will utilize a large proportion of the herbage present, but at the expense of intake and production per animal. Research on continuously-stocked sown ryegrass swards indicated the best sward height to achieve efficient utilization with little sacrifice in animal performance. The optimal height was greater for animals such as ewes in early lactation with a large demand for nutrients (and need for large individual intake rates) than for those with a smaller demand for nutrients (e.g. dry sheep) when grazing can be more severe to increase utilization whilst accepting smaller intakes per animal (Parsons, 1984: Hodgson et al., 1986). Research at North Wyke showed that the general relationships were similar for permanent swards to those previously established with sown swards. Liveweight gain per ha with growing beef cattle was greater for swards continuously stocked to maintain a compressed sward height of 58 mm (equivalent to a sward surface height of about 75 mm), compared with either more severe or laxer grazing (Wilkins et al., 1987). With lactating dairy cows, organic matter intake per cow was greater for swards continuously stocked to maintain a sward surface height of 70 mm than with either 50 or 90 mm (Gibb et al., 1997), with IR being greatest with the intermediate grazing severity. With rotational grazing, Mayne et al. (1987) concluded that the best compromise between sward utilization and animal performance was achieved by grazing to maintain a residual sward surface height of about 80 mm.

Several approaches were explored to improve the balance between utilization and individual animal performance. Rotational grazing lends itself to the adoption of leader-follower grazing systems, with preferred stock of high performance potential grazing in advance of lower-performing stock and thus giving the more responsive stock the advantage of a lax grazing regime. Adopting this approach with spring-calving dairy cows gave a large increase in production by the leader group (comprising the cows with higher initial milk yields) compared with the performance attained by cows with similar initial yields but grazing in a single group. There was a penalty in the yield of the followers, but an increase of 9% in overall milk production ha^{-1} (Mayne et al. 1988). This approach would be even more attractive if used with animals having greater contrast in their requirements (e.g. cows in early lactation as leaders and dry cows as followers).

A second possibility to improve sward utilization is to graze severely and endeavour to maintain production by the provision of additional feed as silage or as concentrate. Research at North Wyke indicated that even with grazing to a low residual sward height, the provision of supplementary grass silage resulted in a substantial reduction in grazing intake, with no improvement in animal performance (Mayne et al., 1987). Later experiments found large effects of variation in the quantity and composition of concentrates and their method of feeding on the grazing behaviour and performance of continuously stocked cows (Gibb et al., 2002a, b). Particularly favourable results were obtained with supplements having a large content of digestible fibre.

The opportunities and problems produced by the combination of mild autumn and winter conditions, typical of much grassland in western Britain provided another research focus. This gives a long season of growth, but high rainfall and heavy soils present difficulties in utilizing this herbage. An approach that is widely practiced is to integrate sheep grazing during autumn and winter with cutting or grazing by dairy cows during spring and summer, with the sheep presumed to be less likely to cause poaching damage during winter grazing. A series of experiments established relationships between the duration and intensity of grazing by sheep in winter and subsequent silage yields. The results indicated considerable opportunities for increasing overall utilization by this approach, particularly if the swards were rotationally grazed during winter with new areas being offered every two days (Laws and Newton, 1987). It was shown that grazing in winter in this way did not affect milk production the following summer by grazing lactating heifers compared with that from swards not grazed in winter (Newton et al. 1986), so that the winter grazing was a complete addition to annual utilized output.

3.2.2. White clover

In addition to the research on the behaviour of animals presented with grass and clover swards referred to earlier, experiments at North Wyke have explored the use of mixed swards of grass and white clover with sheep, beef cattle and dairy cows. Systems of lamb production based on mixed swards grazed rotationally with sheep using forward creep grazing were successfully developed. Rotational grazing gave greater clover contents in the sward than set stocking, with beneficial effects on lamb growth rates. Advantages were demonstrated for the use of six rather than three paddocks and for movement between paddocks based on residual sward height rather than using fixed intervals between grazings (Newton et al., 1989; Laws and Newton, 1992).

Research with beef cattle established the effects of fertilizer N inputs in spring and of grazing management and severity on clover persistence and animal output (Yarrow and Penning, 1993; Johnson and Morrison, 1997). Animal liveweight gain increased with sward clover proportion up to 0.3, the largest proportion examined (Yarrow and Penning, 2001). This research provided the guidelines for an 18-month beef production system involving extremely small inputs of fertilizer and supplementary feed. This was tested at North Wyke (Peel et al., 1987; Hopkins et al., 2005) and demonstrated to give smaller N surpluses than systems based on pure grass swards (Laws et al., 2000). The system was developed on farms in conjunction with the UK Meat and Livestock Commission.

Research with spring-calving dairy cows continuously grazing mixed grass-white clover swards demonstrated that milk yield per cow fell as grazing severity was increased to give residual compressed sward heights below 6 cm (Rook et al., 1994). Milk yields per cow increased with sward clover proportion up to 0.25, the largest proportion examined (Dumont, 1990; Wilkins et al, 1994), with responses to concentrate feeding tending to be smaller for swards with the greater clover contents. In all, this research, together with economic assessments by Doyle and Topp (2001), produced a persuasive case for the use of white clover in production systems and these mixed swards play an important part in the NWFP programme described later.

4. Nutrient Cycling

4.1. Nitrogen cycling

As noted earlier, the controls over forage production are many but supply of N from soil, fertilizer or manures is critical. Therefore, a heavy emphasis has been placed at North Wyke in understanding the flows of N through grassland systems with the aims of reducing losses and maximizing the efficiency of N use from all sources. This need was reinforced by the concern over NO_3^- leaching into waters: other facets of losses of N are also important and these are covered in the section on gases. North Wyke was in the unique position of having the large-scale (1-ha) grazed, hydrologically isolated plots on the Rowden facility, designed to characterise the effects of drainage on production and water movement (Tyson et al., 1992). These provided the opportunity to examine the effects of fertilizer input and drainage on losses of NO_3^- over time (Table 2). Scholefield et al. (1993) monitored drainage water at V-notch weirs and sampled daily for the analysis of NO_3^--N. On drained plots, a large proportion of the rainfall was routed preferentially down large pores to mole drains, whilst on undrained plots, drainage was mainly by surface runoff. Large, but differing according to management, annual losses of NO_3^--N were recorded: 38.5, 133.8 and 55.7 kg N ha^{-1} from old swards that received 200 and 400 kg N ha^{-1}, and from a reseeded pasture that received 400 kg N ha^{-1} fertilizer, respectively. Ploughing and reseeding resulted in a two-fold reduction in leaching, except during the first winter after ploughing, and twice as much leaching occurred after a hot, dry summer as after a cool, wet one. Tyson et al. (1997) also used the Rowden facility to show the differences between white clover-based and fertilized swards with smaller losses being recorded from the smaller-input clover system. The impact of using clover swards is complex and not only integrates effects of N fixation inputs and returns through the animal, but also the impact of clover roots on enhancing soil structure and water flow through the soil (Holtham et al., 2007). It became clear that simplified approaches to understanding water and chemical transport could not describe field behaviour adequately, as demonstrated elegantly in a series of experiments following breakthrough patterns and preferential pathways of flow in large blocks (5.4 x 3.4 x 1.2 m) of undisturbed soil (Williams et al., 2003).

These and other leaching studies from, for example, reseeded grassland (Shepherd et al., 2001) showed that the impact of cultivating and reseeding grassland was short-lived when compared with the annual effect of arable cultivations. Prediction of the impact of leaching loads on peak river NO_3^- concentrations (Scholefield et al., 1996) highlighted the complexity of controls over losses and flows into waterways. Findings on leaching from grassland were summarised by Jarvis (2000) and highlighted the need to understand or develop (a) effects of management on leaching *per se*, (b) that as mitigations were developed, an appreciation of other flows and losses was important to avoid pollution swapping, (c) complete systems, (d) improved advice for N supplies from all sources and (e) improved predictive models.

The other major components of N loss are discussed later but it was clear that supply of mineral N from the soil was a key feature for the N cycle and required improved understanding to maximise N use efficiency (Scholefield and Titchen, 1995). It was also clear that better estimates of supplies from organic sources were required. Thus, techniques with cores incubated in the field in sealed containers with acetylene to inhibit nitrification and thereby minimize losses of N through denitrification were developed (Hatch et al., 1990; Jarvis et al., 2001). Mineralization rates on previously long-term grazed pastures on the silty clay loam soil which had background managements of +/− drainage and +/− fertilizer (200 kg N ha^{-1} y^{-1}) (Gill et al.,1995) were large and ranged from 1.01 to 3.19 kg N ha^{-1} day^{-1} and there was substantial net release of N through the winter period, representing, on average, 27% of the annual release. Clough et al. (1998) showed the potential of using the relationships between soil thermal units, net N mineralization and dry matter production in pastures to advise farmers on N mineralization from soil organic matter and modelling of N transformations in pasture systems.

Patra et al. (1999) measured field rates of mineralization to greater depth and determined potential mineralization rates of sand, silt and clay sized particles and macro-organic matter fractions of different sizes in the laboratory. This demonstrated the importance of the topsoil and macro-organic matter particles in contributing to the mineral N pool. Differences between fertilized grass and mixed grass/legume swards and the additional effects of dung were examined by Antil et al. (2001): dung addition increased mineralization rate by up to two times. Various studies of short term fluxes using ^{15}N labelling (*e.g*. Ledgard et al., 1998; Hatch et al., 2000; 2002) all demonstrated the rapidity of transfer of N between different soil pools and the large dependency on the background managements and soil conditions.

One of the major contributors to the soil organic matter pool and consequently to the mineral N pool is that from animal excreta and manures and North Wyke has contributed much to the understanding of factors controlling N release from a range of organic sources. For example, in a laboratory experiment, Chadwick et al. (2000b) demonstrated that the C:organic N ratio could be used to indicate the rate of NH_4^+ release from NH_3-stripped livestock manures. This was then verified in the field at multiple sites, where the rate of organic-N mineralization was again shown to be related to the C:organic N ratio and cumulative day degrees (Bhogal *et al*., 2016). These experiments showed that organic N is mineralised more rapidly from pig slurry and poultry manures than cattle slurry and cattle farm-yard manure (FYM), and these relationships underpin the MANNER-NPK decision support tool (Nicholson *et al*., 2013), and hence the manure N availability tables in the UK's Fertiliser Manual (Defra, 2010).

From an early stage, it was obvious that understanding whole systems was key to optimising N efficiency and an initial attempt to do this was the integration of manure returns from cattle housed in experimental polytunnel housing to the 1 ha grazed Rowden lysimeters to provide self-contained farmlets (Laws et al., 2000). This provided a replicated means of quantifying different managements on different soil types. North Wyke was instrumental in assessing the role of management strategies on emissions not only at different stages, but for the whole of the manure management chain for NH_3 (Webb and Misselbrook, 2004) and for GHGs (Chadwick et al., 2011). This was based on experiments on commercial farms, and in the experimental cattle housing and manure storage facilities developed at North Wyke (see section on NH_3). Thus, measuring emissions of NH_3 and nitrous oxide (N_2O) at each stage of the manure management chain (livestock housing, manure storage and spreading to land), showed that straw-bedded systems for beef cattle gave less NH_3 but greater N_2O emissions than systems based on slurry (Thorman et al., 2003). Covering and compacting solid manure heaps were also effective at reducing N (and K) losses (Chadwick, 2005).

The development of the manure management chain facilities and experience from the large-scale drainage experiment were the precursors of the NWFP that operates today, with its replicated livestock housing, manure storage and land application treatments, and where the grazing animal is included (Orr et al., 2016). A direct consequence of improved information was the ability to undertake desk studies/synthesis using mass balance approaches to demonstrate the impacts of managements on N flows, budgets and losses (Jarvis et al., 1996) for typical grassland farms and subsequently to demonstrate changes in management either on hypothetical cases, or on real farming systems (Cuttle and Jarvis, 2005). To provide better prediction, mathematical models have been formulated. NCYCLE, developed by Scholefield et al. (1991), simulated the cycling of N in grassland systems grazed by beef cattle and predicted annual amounts of N in liveweight gain, and that lost through NH_3 volatilization, denitrification and leaching, based on fertilizer application and soil and site characteristics. NGAUGE (Brown et al, 2005) was developed from this and provided a new decision support system for fertilizer management for British grassland. Outputs included field- and target-specific N fertilizer recommendations with farm- and field-based N budgets, comprising amounts of N in both production and losses and identification of possible pollution swapping. Because multiple demands are placed on farming systems from economic, food quality, affordability, healthy environment, animal welfare, biodiversity etc., $SIMS_{DAIRY}$, a farm-scale model, was developed and used to explore this complexity for dairy farms (del Prado et al., 2008; 2009).

Despite these N cycling models being able to show the potential for unintended consequences ('pollution swapping') of management practices to mitigate a specific form of N pollution, funding programmes tended to be 'pollutant-centric'. It was not until the late 1990's-early 2000's that North Wyke researchers started to combine measurements of different loss pathways on the same experiments. For example, Chadwick et al. (2011) demonstrated that despite being extremely successful at mitigating NH_3 volatilization, shallow injection resulted in significantly greater N_2O fluxes than surface broadcasting. A 'win-win' strategy (i.e. reduced NH_3 volatilization and reduced N_2O emission) was achieved in the field with what was a new nitrification inhibitor at the time, dimethylpyrazolphosphate (DMPP). Using ^{15}N-labelled slurry, Dittert et al. (2001) showed that the slurry-derived N_2O emission after shallow injection could be reduced by >30% when mixed with DMPP. A more recent example of 'pollution swapping' associated with shallow injection (Hodgson et al., 2016), illustrated how shallow injection of slurry (to reduce NH_3 volatilization) could increase the survival of faecal indicator organisms in the injection slot, when compared with surface-broadcast slurry. The concept of moving from a 'pollutant-centric' approach to mitigation to a 'measure-centric' approach that could identify potential win-win's as well as unintended consequences was recognised as important to the UK Defra, and resulted in the development of a user manual (Newell-Price et al., 2011) aimed at catchment sensitive farming officers, and the publication by Cuttle et al. (2016).

The contribution of North Wyke research to national fertilizer recommendations for grassland (Defra, 2010) has already been noted and the research also contributed practically to wider advice. Thus, the EU INTERREG Green Dairy project (Green Dairy, 2006) provided an opportunity to bring together researchers and experts, results from experimental farms, and involvement of commercial farms and their managers from 11 regions along the western Atlantic seaboard of the EU. This provided an improved platform to make progress with better understanding of the complex controls over nutrient flows in a very diverse range of farming practices, climates and soils, opportunities to improve nutrient use at the farm scale, and better understanding of the impact of dairy farming on water quality. Another European-wide project again used North Wyke expertise to contribute to an early assessment of nutrient management and associated legislation in the EU (De Clerque et al., 2001).

Nitrogen management has impact not only on N flows *per se*, but also interacts with other essential elements. Thus, the effect of S application on the efficiency of N use was investigated in cut plot experiments on two contrasting soil types. The application of S improved efficiency of N use for a permeable soil receiving large additions of N, resulting in a large reduction in NO_3^- leaching and its associated environmental impact (Brown et al., 2000). Alfaro et al. (2003) demonstrated that N fertilizer application and drainage increased K uptake by the grass and, with it, the efficiency of K used. It also depleted easily available soil K, which could be associated with smaller K losses by leaching.

4.2. Phosphorus

The important role that P has in grassland production systems has long been recognised but its wider impacts on the environment came to the fore in the early 1990s, and it became an important component of the research portfolio at North Wyke. Two strong concepts surrounding P dynamics and cycling at that time were that: (a) it did not leach from soils and (b) organic P was not bioavailable, and therefore not environmentally significant. The programme at North Wyke on P cycling made important and significant contributions to re-thinking these tenets of the global P research community.

It was increasingly accepted that agriculture was a major contributor to diffuse pollution (primarily nutrients) causing eutrophication of surface waters, and while the contribution of grasslands to N fluxes was well understood (see previous section on N), their role in P pollution in surface waters was not. Grasslands were identified as significant sources of P inputs to surface waters in a series of studies using the Rowden grazed lysimeters (Hawkins and Scholefield, 1996; Haygarth and Jarvis, 1997; Haygarth et al., 1998a), complemented by leaching experiments using intact soil lysimeters (0.8 m wide and 1.5 m deep), (Turner and Haygarth, 1999; 2001a). These studies showed that significant quantities of P can be leached from grassland systems, especially in dissolved organic forms: previous conventional wisdom indicated that losses from pasture-based systems were likely to be small. Other studies highlighted the potential incidental transfer of large quantities of P in particulate forms as well as dissolved forms in relation to different management techniques such as reseeding (Butler and Haygarth, 2007) and incidental losses of P associated with slurry spreading (Preedy et al., 2001). The quantification of P budgets for grassland farms (Haygarth et al., 1998b) demonstrated the accumulation of P applied as fertilizers or in organic substrates in topsoil, especially in dairy farms, and highlighted the need to better understand the mechanisms controlling the transfer of this large pool to surface waters. Some of these studies were carried out in collaboration with staff from the National Soil Resources Institute (NSRI) based at North Wyke, focussing on hydrological mechanisms (Fraser et al., 1998) and pathways (Fraser et al., 2000) of transfer.

It became apparent that there was considerable ambiguity in much of the terminology that was used, often causing confusion. Importantly, publications from North Wyke were instrumental in standardising and classifying terminology used in the description of chemical forms, processes, pathways and operationally defined forms of P cycling (Haygarth, 1997; Haygarth and Sharpley, 2000). This was followed by a convergence of the scientific concepts and knowledge on the transfer of P from agricultural land to surface waters through the development of a conceptual framework referred to as ‘the phosphorus transfer continuum’ (Haygarth et al. 2005). Subsequent catchment scale work based on small local headwater rivers and streams elucidated the relative roles of point and diffuse agricultural sources of P (Wood et al., 2005; Haygarth et al., 2005; Bilotta et al., 2010) and saw the development of the ‘critical source area’ concept for identifying areas most likely to be sources of P transfer to surface waters (Page et al., 2005). The further development of these approaches is described in later sections.

Early P research at North Wyke focused on methodological developments, particularly laboratory analysis techniques for quantifying concentrations of phosphate (PO_4^{3-}) in soil extractions and natural waters (Rowland and Haygarth, 1997) and sample storage (Haygarth et al., 1995; Denison et al., 1998), from which protocols were developed which persist today. Another key methodological discovery at North Wyke was that one of the standard approaches to preparing soils for analysis, that of air-drying, may be fundamentally flawed causing over-estimation of the availability of P and other nutrients. Turner and Haygarth (2001b) demonstrated a significant positive correlation between water-soluble P and soil microbial biomass (SMB), indicating that upon drying, significant quantities of microbial P were released, predominantly in organic form (Fig. 4). This raised fundamental questions about the methods employed in P research, which had largely been developed for arable soils, usually with little SMB and large inorganic P contents, but which may not be appropriate for other systems such as grasslands. This highlighted the potential importance of patterns of soil drying and rewetting on P cycling and potential losses to surface waters, spawning a series of projects which found that changing rainfall patterns under predicted climate change scenarios could result in increased losses of P from soils to surface waters (Blackwell et al, 2009; 2010).

Insert Figure 4 here

Figure 4. Increase in water-soluble organic P after soil drying as a function of soil microbial P (Turner and Haygarth, 2001b).

Up until the late 1990s there was general acceptance that organic P was unavailable to plants, and hence not environmentally problematic in terms of causing eutrophication, but building on this study and many before it, a paradigm shift occurred in the way P cycling and dynamics was viewed and researched. Today, the soil organic P pool, which can comprise up to 80% of the soil total, is not considered as an unavailable pool, but a source for plants that must be exploited to improve P-use efficiency. This is particularly important given the concerns that exist over P fertilizer security in the future, which is at the heart of both global food security issues and the sustainable intensification of agriculture. Recent work at North Wyke has focused on methods of optimising the utilization of organic P in soils by plants through root exudation of organic acids and phosphatase enzymes (Darch et al., 2016; Darch et al., 2017) along with method development to facilitate this research (Darch et al., 2016). Alongside this, studies using ^{31}P-NMR for the assessment of controls on organic P cycling (Blackwell and Turner, 2013) and more recently the development of novel use of the stable isotopes of oxygen in PO_4^{3-} ($\delta^{18}O$- PO_4^{3-}) have facilitated the investigation of P cycling. This latter technique has developed because P has only one stable isotope, and although P dynamics can be traced using radioisotopes, their use is restricted in the environment. North Wyke is one of only a few research centres worldwide that is utilizing the $\delta^{18}O$-PO_4^{3-} approach, applying it for the source identification of PO_4^{3-} in surface waters (Granger et al., 2017a) and P cycling in soils (Granger et al., 2017b). Future studies will focus on the development of this technique for identification of specific enzymatic P transformation processes.

4.3. Soil organic matter and carbon

Soil organic matter (SOM) has multi-functional roles in controlling nutrient (see earlier) and water storage, influencing structure and other aspects of soil quality, and acting as a major global depository of C. Pasture soils are especially important in all these respects and studies of SOM and C have featured widely in North Wyke activities, initially as a component defining soil properties, then as an important controller of nutrient availability, understanding its forms and their function and impact, and more latterly in its role as a regulator of climate change. The systems on the Rowden Experiment have provided the base resource for many studies of SOM cycling, again demonstrating the importance of long-term treatments in defining and understanding change. For example, there is strong evidence that management influences the quantity of C and its distribution down the profile with drainage, for example, decreasing C significantly (Fig. 5) after 15 years. These data also demonstrate the importance of the sub-soil, which although containing smaller concentrations of SOM, holds a large reservoir of C. Patra et al. (1999) showed that quality, with respect to net N mineralisation rate of macro-SOM was much enhanced in the upper 10 cm by cultivation and reseeding (10 years previously) when compared with a much longer-term sward. Other studies (Bhogal et al., 2000) have underlined the importance of organic N as an important N pool in grassland soils and cultivation has a significant impact on its release, the fate of which is dependent on soil type: comparison of soils showed considerably more movement to deeper layers in the profile of a silty clay loam (30% clay) than in a clay loam (49% clay). Similarly, the importance of SOM as a source of P in soils is now acknowledged (Stutter et al., 2015; Menezes-Blackburn et al., 2017). SOM content increases with sward age with a concurrent increase in capacity to supply N (Shepherd et al., 1999). Patterns in the nature of SOM were seen with increasing natural abundance of $\delta^{15}N$ enrichment with depth which corresponded well with visible soil horizons and showed an inverse relationship with total soil N (Kerley and Jarvis, 1997). ^{15}N enrichment was mirrored by the enrichment in organic materials down the profile and also corresponded with an increasing chemical complexity.

Insert Figure 5 here

Figure 5. Effects of long-term (15 years) drainage on soil organic matter content in grazed pasture soils under high N management on the Rowden Experiment (McTeirnan et al., 2001).

Soil microbial biomass (SMB) is a key agent of change in SOM influencing flows of C (and other nutrients). Most studies of SMB activity at North Wyke have necessarily been related to specific management scenarios, but the long-term provenance of the soils at Rowden have made them attractive for studying the role of soil microorganisms in permanent grasslands in global C cycling and climate change (e.g. Weijers et al., 2011; Karhu et al., 2012; Auffret et al., 2016). In the field over the long-term, SMB C and N were substantially greater in previously unfertilized than in fertilized treatments (Lovell et al., 1995). There was also a substantial difference in the numbers of culturable bacteria with over four times fewer being present in soils without previous N application, in contrast to total biomass contents. Important differences in microbial activity of unculturable organisms (bacteria and fungi) in response to short-term management changes which may influence C and N cycling have been investigated using a variety of analytical approaches at North Wyke (e.g. phospholipid fatty acids (PLFAs)). A multivariate study (Clegg et al., 2003) of the impact of long-term grassland management regimes on microbial community structure in soils provided evidence that grassland management practices affected the community composition of specific soil microbial groups. There were significant impacts of N fertilizer on the eubacterial and actinomycete community structure, and drainage had a significant impact on the community structures of actinomycetes and pseudomonads. Specific effects on selected functional groups of organisms have been demonstrated by analysis of clone libraries and denaturing gradient gel electrophoresis of 16S rRNA gene fragments. A study of nitrite (NO_2^-)-oxidizing bacteria in grassland soil demonstrated that N management practices on Rowden soils influenced the diversity of NO_2^--oxidizing bacteria (Freitag et al., 2005) with implications therefore for N cycling and loss processes, e.g. denitrification.

The interaction between added organic materials (excreta) and soil biology is an essential component of SOM storage and function in grassland soils. In grazed pastures return of dung is a key means of organic matter return, however, addition of dung (Lovell and Jarvis, 1996) had little effect in the short term on SMB. Natural abundance ^{13}C isotope labelling has been used extensively at North Wyke to explore the fate of excretal carbon into different soils pools (Bol et al., 2002; 2003; 2004). The raw materials (urine, dung and slurries) used as ^{13}C-labelled substrates for application to soil are easy to produce by switching livestock diets to maize, a widely-grown forage crop with a C4 photosynthetic physiology that has naturally increased abundance of ^{13}C in its biomass. This approach enabled the rates of turnover of major organic compounds such as carbohydrates (Dungait et al., 2009), lignin (Dungait et al., 2008) and lipids (Dungait et al., 2010) from cow dung in soil to be calculated contributing new information on the cycling of carbon in grassland soils important for our understanding of the potential for increasing carbon sequestration. The heavy stable isotope of nitrogen (^{15}N) is also increased in excretal products so that dual bulk ^{13}C and ^{15}N stable isotope analysis of soils that have been treated with maize-dung is useful for revealing the interaction of the C and N cycles in soils. For example, Glaser et al. (2001) examined short-term dynamics of slurry-derived C and N in North Wyke grassland soils using natural abundance ^{13}C and ^{15}N stable isotopes; within 12 hours of application more than one-third of the applied slurry C was in the uppermost 0-2 cm layer, decreasing to 18% after 2 days, but subsequently increasing to 36% after two weeks.

Dissolved organic matter is fundamental to many biogeochemical processes in soils and natural waters. Dissolved organic C discharged from grazed Rowden plots was determined over two months (McTiernan et al., 2001) and export varied from 42 to 118 kg C $ha^{-1,}$ and there was a significant positive correlation between export and rates of N application for treatments without drainage. Soluble C export was significantly reduced by drainage. Vascular plant-derived phenols in dissolved organic matter are important as markers in understanding and estimating C flux from soils. However, land under different uses (grazing, forestry and moorland) in SW England, UK, exported similar amounts of lignin per unit weight of organic carbon to the drainage water (Williams et al., 2016), adding to the increasing evidence that lignin is not necessarily recalcitrant in soils as previously assumed.

Land application of animal wastes from intensive grassland farming has caused environmental problems including transfer of materials to waters. Lloyd et al. (2012) partitioned components of animal manure organic matter in soil and identified specific inorganic and organic biomarkers that could be used to trace the movement of dissolved fractions. Faecal biomarker lipids called 5β-Stanols (that are only formed in the gut of rumens) were good tracers of soil-bound manure organic matter which remained at the top of a soil column even after intense leaching, whilst NH_4^+ and proteinaceous material were good tracers of dissolved manurial products. Experimental slopes (Lloyd et al., 2016) were used to show that rainfall producing ‘flashy’ hydrological responses resulted in large volumes of surface runoff, and were likely to move sediment and flush dissolved components of slurry-derived organic matter from the slope, increasing the contamination risk. Rainfall which produced slower hydrological responses were dominated by vertical percolated flows removing less sediment-associated organic matter, but produced leachate which could contaminate deeper soil layers, and potentially groundwater, over a longer period. This has implications for investigations of sources of faecal contamination of water courses and the redistribution of soil-associated manure-organic matter by erosion of surface soil layers.

Recent emphasis on SOC has centred on its role as a major global C store and research at North Wyke has made a substantial contribution to quantifying the importance of grassland soils to this. Readily available climate, soils and plant survey data have been effective in making local field to landscape-scale (field-1-100 000 km^{-2}) SOC stock predictions (Manning et al., 2015). Ward et al. (2016) estimated grassland SOC in Great Britain to be 2097 Tg C to a depth of 1 m, with ~60% of this being below 30 cm, being greatest under less intensively managed systems. These findings highlight the existence of substantial SOC stocks at depth in grassland soils that are sensitive to management. This is of great relevance globally, when the extent of land cover and large stocks of SOC held in temperate managed grasslands are considered. They also have implications for global C models which do not currently account for changes in SOC to depth with management.

The detailed studies of C and organic materials in grassland soils at North Wyke have added enormously to understanding of controls over the storage and functionality of SOC in a dominant global land use. Advances in quantitative analytical techniques applied to the soils at North Wyke have re-defined the new understanding of SOM dynamics and influenced development and application of new modelling approaches. Emerging analytical technologies, especially stable isotope labelling, which better characterise forms and bioavailability and improve the quantification of the complex relationships between soil constituents at the molecular scale, are further augmenting this knowledge by revealing underlying processes (Dungait et al., 2012a). It is now understood that long-term mesotrophic grasslands may have reached C saturation, and their value in C sequestration is the maintenance of this status (Dungait et al., 2012b), or their enhancement through the potential offered by grasses with deep-rooting traits to increase C storage in sub-soil horizons (Marshall et al., 2016). Many of the assumptions about SOM stability and the potential for carbon sequestration have been challenged by new technologies that allow fundamental organic matter cycling processes to be understood, and this calls for modelling approaches that consider the role of grasslands in global C budgets to be reconfigured (e.g. Li et al., 2017), to assist in the development of sustainable strategies for SOM/C management in grasslands.

One of the key challenges for the future highlighted by the research carried out at North Wyke is to determine the relationships between the dynamics of C and other nutrients across scales, which will require both new modelling approaches and integrated approaches to elemental cycling. Feedback mechanisms need to be considered: rising global temperatures may increase the rates of SOM decomposition, potentially accelerating climate change further by releasing additional CO_2. Auffret et al. (2016) used molecular approaches to show that SMB temperature sensitivity was at least partly related to community structure. Such findings emphasise the key importance of SMB responses for feedbacks to global change, and highlight important areas where our understanding of C remains limited and models are therefore imperfect.

4.4. Gaseous emissions

It is well known that agriculture is one of the major sources of important environmentally active gases, especially from livestock-based systems. In the case of NH_3, emissions from agricultural sources, predominantly arising from the excreta from livestock and from urea- and NH_4^+-based mineral N fertilizers, have long been recognised as an important loss of plant available N from the system (Potts, 1807). From the latter half of the 20th century, NH_3 was increasingly being recognised for its role in eutrophication and acidification of natural ecosystems, indirect GHG emission and, more recently, fine particulate formation with the associated impacts on human health. Nitrous oxide emission not only represents a major loss pathway for N, but importantly it contributes powerfully to global warming, as does CH_4, the main agricultural source of the latter being from digestive processes of ruminant livestock.

4.4.1. Ammonia

North Wyke scientists have been at the forefront of the development, assessment and application of NH_3 emission measurement techniques, in particular the modification of the system of small wind tunnels of Lockyer (1984) for comparative measurements at the small plot scale, widely used and adopted worldwide, and, as further developed by

Ross and Jarvis (2001a), at the laboratory scale. North Wyke scientists have collaborated widely in the evaluation of techniques (van der Weerden et al., 1996; Misselbrook et al., 2005a; Sommer and Misselbrook, 2016) and in the training and adoption of their use in countries developing NH_3 research programmes (Pereira et al., 2010; Powell et al., 2011; Salazar et al., 2014; Sanz et al., 2010).

Quantification of NH_3 losses is important for N budgeting at the field or farm scale, but has become increasingly important at the national scale because of international reporting requirements under the Gothenburg Protocol and the EU National Emissions Ceilings Directive (NECD). Early estimates of emissions from cattle and sheep grazing (see Jarvis et al., 1991b) and manure applications to land (Pain and Misselbrook, 1997) were combined with estimates from livestock housing and manure storage to provide the first national scale estimate of NH_3 volatilization from agricultural land (Jarvis and Pain, 1990). A review of 'bottom up' and 'top down' approaches to estimating total NH_3 emission from the UK concluded that the two approaches were in broad agreement, with agricultural sources accounting for >90% of total emissions and cattle representing the most important sector. A more structured model for national emission reporting for agricultural sources was developed by Pain et al. (1998) with emission factors across the range of agricultural sources and practices being compiled by Misselbrook et al. (2000). The inclusion of emissions from outdoor yards used by cattle was a significant addition (Misselbrook et al., 1998a; 2006) which brought the 'top down' and 'bottom up' estimates into closer agreement. The model for livestock sources was further improved by Webb and Misselbrook (2004) by introducing a mass-consistent N flow approach which has since become the recommended approach in the guidelines for national inventory compilation (European Environment Agency, EEA) and adopted by a number of European countries (Reidy et al., 2008; 2009). Similarly, the model for emissions from N fertilizer applications to land (Misselbrook et al., 2004) was also recommended in the guidelines as an example of a detailed national approach.

Cattle housing, including outdoor yards, and manure applications to land were identified as major emission sources and therefore key targets for mitigation. Significant work was undertaken in assessing potential mitigation approaches for slurry applications to grassland, including acidification (Pain et al., 1994), and application techniques (Smith et al., 2000; Misselbrook et al., 2002). Mitigating emissions from cattle housing still represents a major challenge, although the methods around frequency and method of cleaning yards (Misselbrook et al., 2006) may also be applicable to concrete cattle-house floors. Targeted straw use in deep litter systems also offers some potential (Gilhespy et al., 2009). Polytunnel housing experiments demonstrated greater NH_3 emissions from cattle housed in a slurry-based system than a straw-based system and that there was an optimal straw usage to reduce NH_3 volatilisation (Gilhespy et al., 2009). The dependence on the time livestock spent indoors on NH_3 emissions from slurry-based housing was also demonstrated (Gilhespy et al., 2006). Other research assessed options for manure storage, where covering (for slurry stores and farmyard manure heaps) and acidification (for slurry stores) offer the greatest potential (Chadwick, 2005; Misselbrook et al., 2016). Misselbrook et al. (2005b) showed that reducing the crude protein content of the cattle diet leads to less N excretion (particularly urinary N) and smaller NH_3 emissions from subsequent manure management. The formulation of balanced forage-based diets remains a key research aim in this context.

In addition to national scale inventory models, field- and farm-scale emission models have also been developed for scenario assessment and development of recommendations. Much of the emissions research at North Wyke was used in the development of the MANNER model (Nicholson et al., 2013). This predicts NH_3 emissions following manure application events with the aim of informing field nutrient management plans. The farm-scale dairy farm model of Hutchings et al. (1996) highlighted the influence of slurry management practices in overall emissions and the importance of an integrated, whole farm assessment of any potential control measures to avoid misleading messages. Finally, the importance of coupling emission and deposition was recognised and showed that a substantial proportion of NH_3 emitted from land sources can be re-deposited locally (Ross and Jarvis, 2001a; 2001b; Hill, 2000), with important implications regarding the spatial distribution of emission sources and sensitive habitats.

4.4.2. Nitrous oxide

Studies at North Wyke concentrated initially on quantifying the contribution that denitrification made to the overall N loss from poorly drained grassland soils and used field methods developed by Ryden et al. (1987) by incubating soil cores in sealed jars or measuring emissions from under surface enclosures (Jarvis et al., 1991a), both with acetylene present to block the denitrification process continuing through to N_2 production. An improved field method, based on square-section soil cores enclosed in an incubation box (Jarvis et al., 2001) demonstrated rates that were consistently less than with the established method on poorly-drained soil, in the short- and longer-terms. Such measurements under a range of management conditions (Hatch et al., 1998) enabled early prediction of denitrification losses at field and farm scales to be used in North Wyke models such as NCYCLE (Scholefield et al., 1991) and farm balances (Jarvis, 1993). Attention soon turned to emissions of N_2O *per se* because of needs to: (a) quantify emission factors and (b) understand controls in order to develop mitigation strategies. Pastures contain multiple sources of N_2O (fertilizer, managed excreta and direct dung and urine returns) and NW research pioneered quantification of contributions from these components. Allen et al. (1996) determined emissions from cow dung and urine patches: rates were much larger during autumn-winter than during spring-summer. On well-drained soil, rates were substantial for both excreta types (207 mg N_2O-N kg^{-1} of deposited dung and 197 mg N_2O-N kg^{-1} of urine in autumn-winter). The respective values on poorly-drained soil for dung and urine were 0.2 and 148 mg N_2O-N kg^{-1} suggesting that production occurred during both nitrification and denitrification processes. Emission rates of up to ~1590 μg N_2O-N h^{-1} m^{-2} occurred in the field: small deposition rates were occasionally observed. Other factors such as compaction had important effects, increasing emissions by up to 3.5 times (Yamulki and Jarvis, 2002). One of the major problems encountered is that of spatial variability. Velthoff et al. (1996) measured fluxes in mown and intensively-grazed plots on slightly-sloping, poorly-drained soil at North Wyke, using 144 flux chambers over four days. Fluxes from grazed grassland were larger than those from mown grassland. Weak relationships existed between flux and moisture, NH_4^+, NO_3^- and C contents, but with less than 15% of the variance accounted for. Spatial variability was large both at a small (<6 m) and larger (10-100 m) scales and was greater on mown than on grazed grassland. Geostatistics showed that even techniques integrating fluxes over large areas may be restricted by large spatial variability. Velthoff et al. (2000) also demonstrated temporal as well as spatial variability, but spatial effects were much greater than temporal variability over four days with topography playing a major role.

At greater spatial scale, Matthews et al. (2010) demonstrated that up to 14% of the total annual farm N_2O flux was from the 'unmanaged', small-scale features of beef and dairy farms (areas around drinking and feeding troughs, gateways, ditches and seepage areas around FYM heaps and not necessarily accounted for in inventory estimates), and soil NO_3^- concentration was a key control of fluxes from these 'hot-spot' areas. Allen et al. (1996) noted that emissions were dependent on soil N in a poorly drained silty clay loam, but that soil moisture, rate of plant growth and carbon availability all played important roles on sandy and stony loams. The results of all these studies indicated that estimates of the N_2O flux from livestock farms using the traditional IPCC Tier 1/ Tier 2 Inventory approach have poor accuracy.

To overcome temporal variability, automated chambers for continuous measurement with minimum disturbance to the soil were developed (Yamulki and Jarvis, 1999; Chadwick et al., 2000a). Clear temporal and diurnal changes in fluxes were demonstrated from urine and dung patches (Yamulki et al., 2000) with maximum fluxes generally occurring in late afternoon or early morning, but generally not in phase with soil temperature changes. The N_2O isotopic content of N^{15} and O^{18} followed a similar trend to that of flux indicating that denitrification was the major process involved. After heavy precipitation, the larger $\delta^{15}N$ and $\delta^{18}O$ values suggested consumption of N_2O by total denitrification.

The complexity of N_2O emissions required better understanding under controlled conditions. Clough et al. (1999) showed that leached NO_3^-, potentially a groundwater contaminant, could be denitrified at depth by following the fate of ^{15}N-labelled NO_3^- injected into the subsoil (80 cm) of intact soil columns with added C. Gas flux from the surface and concentrations down the profile were monitored. On average, after 38 days, only 13% of the labelled N was present in the column as NO_3^-, with immobilization (54%), entrapment in pores (7%), dissolution in water (2%), fluxes from the surface (N_2O < 1%, N_2 1.8%) and unaccounted for ^{15}N (20%) making up the remainder. For a poorly drained soil, the potential of subsoil to denitrify NO_3^- was small under optimal anaerobic conditions in a laboratory-based incubation with a range of C substrates of increasing recalcitrance and only simple carbohydrates were used readily by the resident microorganisms (Murray et al., 2004).

Another short-term (12-day) laboratory study (Williams et al., 1998) investigated effects of applying urine, fertilizer (NH_4NO_3) and fertilizer + urine on NO and N_2O emissions. There was also a complementary 24-day field study on pasture. Application of urine to the field soil at a rate equivalent to 930 kg N ha^{-1} increased the amount of mineral and microbial N in the soil which increased NO and N_2O emissions. Molar NO-N:N_2O-N ratios were very small indicating that denitrification was the main process during the first 12 days after application. In the laboratory, urine inhibited nitrification during the first seven days, but was clearly underway afterwards, and denitrification was still the dominant process. Effects of fertilizer and grazing on NO and N_2O emissions were less obvious in the field than in the laboratory and fluxes returned to background rates within four days. This was attributed to plant uptake and leaching reducing mineral N, processes not occurring in the laboratory.

Chadwick et al. (2000a) demonstrated temporal fluctuations in N_2O fluxes after pig and dairy slurry applications to grassland, and that even though the applications were at the same NH_4^+-N loading rates, the dairy slurry resulted in a two times greater cumulative N_2O flux, possibly because of differences in C availability and particle sizes between the two slurry types, with finer dairy slurry particles blocking soil pores causing greater soil anaerobicity.

The dynamics of mineral N species involved in denitrification were studied in the laboratory (Dendooven et al., 1994) to test a mechanistic model linking C mineralization and denitrification, using competitive Michaelis-Menten type enzyme kinetics. It was concluded that poor affinity for N_2O compared with the large affinity for NO_2^- could lead to large losses of N_2O in the field even if only small quantities of NO_3^- were available. Further understanding of the complexity of the processes and their controls required the development of an automated flow-through laboratory system which allowed even greater precision over conditions and measurement from intact soil cores in an N_2-free atmosphere (DENitrification System, DENIS, Fig. 6.a) (Scholefield et al., 1970; Cardenas et al., 2003). Studies showed that emissions of N_2O and N_2 were short-lived and appeared immediately after application of mineral N and C. Full denitrification was promoted less when the soil was dry prior to application suggesting that the enzyme for N_2O reduction had a lag in synthesis in dry conditions (Bergstermann et al., 2011). More complex materials such as slurry produced longer, and often multiple, emission peaks showing the potential for the use of different pools of N. Other studies have used isotopomers of N_2O to apportion the N_2O produced to a particular source and/or process (Koster et al., 2011) and suggest that a succession of nitrification and denitrification might occur. A major advantage of DENIS is that it allows measurement of N_2, (confirming that N_2O reduction occurs), although it does not exclude the potential for other processes to occur. Further development of DENIS has incorporated measurement of NO, CO_2 and CH_4 (Fig. 6.b). Isotopic enrichment of the N_2O emitted has shown that of the measured N_2O produced in wet soils, about 85% came from added N and the rest from soil N (Loick et al., 2016). This, however, does not provide information on whether prior transformations of the added N (if as NH_4^+ for example) would have contributed as additional sources of N_2O, so quantification of these transformations are required to determine whether nitrification could have contributed too. The system has an important use in assessing the effectiveness of mitigation measures under controlled conditions such as the use of nitrification inhibitors (Nis) (Hatch et al., 2005); acidification of slurry fraction combined with NIs showed that acidification had a stronger effect in reducing N_2O (Owusu-Twum et al., 2017).

Insert Figure 6a and 6b here

Figure 6.a. The DENIS system showing soil incubation vessels and gas flow apparatus (foreground) and continuous gas measurement equipment (background). (Photo: Rothamsted Research)
Figure 6.b. Example of data output from the DENIS system: gaseous emissions over time from a poorly drained grassland soil amended with NO_3^- and glucose (from Loick et al., 2016)

Future improvements to the system include measurement of $^{13}CO_2$ from applied ^{13}C and the inclusion of plants, in order to separate soil and plant effects on emissions, and to study the role of root exudates in soil processes and the competition with microbes for nutrients.
The accumulation of information and understanding has meant that North Wyke has taken a lead role in developing models and constructing national inventories for N_2O. Models include mechanistic approaches developed specifically for UK conditions (Brown et al., 2002) as well as more empirical approaches for overall N prediction (Scholefield et al., 1991; Jarvis, 1983). A cost curve analysis of the potential of mitigation options identified improved fertilizer practice, general improvement in grassland agronomy and better manure/slurry management as key ways forward (IGER, 2001). Initially based on IPCC default methodology, international demands for more accurate methods as well as national targets have required an improved inventory for better estimates of emissions for the UK agriculture sector. A large programme of research funded by Defra and based on literature data (Buckingham et al., 2014), experimental results (Chadwick et al., 2014; Cardenas et al., 2016) and modelling (Fitton et al., 2014), has provided information for developing a UK country-specific inventory of N_2O emissions. New factors have been derived for emissions from soils and manure management; better activity data are used and new tools for making the calculations of emissions have been developed.

4.4.3. Methane

Much of the agricultural emission of CH_4 is derived from ruminant enteric fermentation. Early studies at North Wyke developed a novel approach to determine the emissions from grazing animals by placing them in a large 'enclosure' (Lockyer and Jarvis, 1995) under near-natural grazing conditions. Rates measured were consistently less than those determined with open circuit respiration chambers. However, tests confirmed that both methods gave good quantitative recovery of added CH_4, and can therefore be assumed to provide reliable estimates of emissions from animals, but perhaps pointed to different behaviours under the two systems (Murray et al., 1999). Continuous measurements of emissions from sheep showed strong diurnal patterns of emission with peak emissions between 15:00 and 17:00 h and rates gradually falling throughout the night before starting to rise at around 08:00 h (Murray et al., 2001). Later studies (Lockyer and Champion, 2001) confirmed a strong behavioural pattern with peak emission rates corresponding to peaks in eating activity.

Methane is also emitted from the excretal returns of animals, both directly at grazing and from the stored slurry or manures returned to land. Various studies quantified CH_4 emissions from dung and urine patches (Jarvis et al., 1995) and from application of manures (Chadwick et al., 2000a). Yamulki et al. (1999) demonstrated that there was uptake as well as emission on some occasions after dung or urine was applied. Laboratory studies determined the effect of soil and slurry type on CH_4 emissions and showed that they were influenced by soil type only when the slurries applied had low DM contents and that most of the CH_4 emitted was derived from the slurry itself and not from the soil (Chadwick and Pain, 1997). Dietary composition had an important impact on subsequent CH_4 release from the resultant applied slurries (Misselbrook et al., 1988b) with less emission from slurry from animals with a reduced crude protein diet. The initial C:N ratio and DM content of stored FYM were the most important factors affecting emissions although its storage temperature was also influential (Yamulki, 2006). Maximising the generation of CH_4 is, of course, a prerequisite for anaerobic digestion systems and Ward et al. (2008) reviewed and identified the conditions which optimised output from agricultural resources. At the more detailed level, analysis of microbial populations at all the various stages of the digestor process showed clear differentiation between of the community structure (Hobbs et al., 2008): biogas systems that supported a greater microbial density utilized twice the input material and doubled the biogas output.

5. Agro-ecological research at North Wyke

The management and productivity of agricultural grassland was transformed across the UK after the 1940s, largely through greater fertilizer inputs, changes in stocking practices, increases in silage production replacing hay meadows, a greater emphasis on optimizing yields of nutrients rather than DM *per se*, and development of new harvesting techniques (Chamberlain et al., 2000; Vickery et al., 2001). These changes have had a major impact on biodiversity within the agricultural landscape (Vickery et al., 2001; Hodgson et al., 2014). Research at North Wyke on agro-ecological issues began primarily because of conflict between farmers and nature conservationists over the designation of Sites of Special Scientific Interest (SSSIs) on the Somerset Levels in the UK. The conflict highlighted fundamental gaps in knowledge over likely impacts of modest increases in fertilizer input on the botanical diversity of meadows. The Tadham project (1986–1993) was initiated and designed to improve our understanding of what constituted ecologically sustainable amounts of fertilizer to allow grassland botanical diversity to be maintained on a species-rich hay meadow on a peat soil on the Somerset Moors in SW England. Advancing understanding of abiotic and biotic constraints to the restoration or creation of botanically diverse grasslands has continued to be a major research theme at North Wyke.

The Tadham project was the start of an era that put North Wyke at the forefront of agri-environmental research in the UK. It provided empirical evidence of critical fertilizer inputs and cutting date to maintain or restore high species diversity in UK meadows and the agronomic consequences of imposing such constraints (Mountford et al., 1993; Kirkham and Wilkins, 1994a, b; Kirkham and Tallowin, 1995; Tallowin, 1996). The Tadham project indicated that soil P content was an important factor influencing grassland botanical diversity (Kirkham et al., 1996) and this was confirmed on a wider basis within other grasslands in a European-wide project co-ordinated by North Wyke (Janssens et al., 1998). Grasslands of strong botanical diversity containing ecological specialist plant species were only present where soil P amount was <5 mg extractable P 100 g^{-1} dry soil (Fig. 7.a). A subsequent survey of farms in southern England showed a strong general relationship between grassland botanical diversity and total N input (Fig. 7.b) (Tallowin et al., 2005). Empirical refinement of critical fertilizer N inputs to less than 15 kg ha^{-1} per annum was achieved in a subsequent project on upland and lowland botanically diverse meadows (Kirkham et al., 2008; Kirkham et al., 2014).

Insert Figure 7 here

Figure 7. Impacts of nutrients on plant species diversity: a) impact of soil total P, b) impact of applied N (from Janssens et al., 1998).

Achieving very poor soil P availability was demonstrated to be key to the development of fen-meadow communities, such as *Cirsio-Molinietae,* together with the need to introduce species that do not have a persistent soil seed bank and the need to create specific germination and establishment niches (Tallowin and Smith, 2001; Isselstein et al., 2002). Practical methods for restoring grassland botanical diversity were demonstrated (Pywell et al., 2007), which have continued to be refined by research with other groups (Wagner et al., 2016). The widespread loss of ecological specialist plant and butterfly species from the agricultural landscape (Hodgson et al., 2014) focussed research attention on identifying constraints to their re-establishment. Fry et al. (2017) identified that soil type, poor soil P status and the early introduction of ecological specialist species prior to more generalist species (which are widely sown) are essential and that the introduction of the hemi-parasitic *Rhinanthus minor* L. has little, if any, benefit.

Our collaborative research has significantly improved understanding of the drivers that influence below-ground microbial communities. More bacterial-dominated microbial communities were associated with exploitative plant traits than in fungal-dominated communities with resource-conservative traits, thus demonstrating that plant functional traits and soil microbial communities are closely related at the landscape scale (de Vries et al., 2012). The wider value of improved botanical structural diversity in agricultural grassland for invertebrate assemblages, particularly pollinator guilds, has been clearly shown by our research (Woodcock et al., 2007; Potts et al., 2009; Blake et al., 2011; Woodcock et al., 2012). Where soil fertility is too great for a rich botanical diversity to be established, a practical option has been identified by research at North Wyke. in such cases, establishment of a modestly diverse grassland containing a mixture of legume and non-legume herb species together with agricultural grass varieties has wide ecosystem service benefits (Woodcock et al., 2014). This research led directly to an agri-environment option for livestock farmers within the UK Countryside Stewardship Scheme, which by 2016 had over 150 agreements covering over 1600 ha within the UK (Natural England, 2016 pers. com.).

The biodiversity research at North Wyke has also made a significant contribution to quantifying the agronomic constraints of managing the UK's semi-natural grasslands in terms of productivity and nutritional value to livestock (Tallowin, 1997; Tallowin & Jefferson, 1999). Grazing semi-natural grasslands may enhance their wildlife floral and faunal diversity and abundance through modifying plant species composition by exploiting the dietary choices of domestic livestock. Impacts of grazing management were reviewed by Tallowin et al. (2005). This indicated that, for species-rich grassland, lenient grazing pressure maintained botanical diversity and abundance of positive indicator species over a five-year period and also enhanced faunal diversity and abundance reflecting improvements in spatial, architectural and temporal structure. However, there was no enhancement in positive indicator species and there was also an increase in pernicious weeds suggesting that grazing alone may not deliver all the biodiversity goals and that additional management interventions may be required. For species-poor grassland, distinctive differences in structure can lead to differences in faunal diversity. Orr et al. (2012) investigated the impact of diet selection of beef cattle in semi-natural pastures, grazed at moderate stocking or lenient stocking, using GPS to track their foraging paths. This study demonstrated that GPS tracking of livestock foraging paths could be combined with vegetation mapping and automatic grazing behaviour measurements to investigate diet preference in complex, heterogeneous swards.

Research at North Wyke has also highlighted the need to improve understanding of how grassland management affects faunal diversity, such as farmland bird population dynamics, in the agricultural landscape, (Vickery et al., 2001). North Wyke scientists also made important contributions to understanding the range of synergies and trade-offs between ecosystem services, the dependence of service provision on time and location of land management, and the dependence of service benefit on the number, locations and preferences of human beneficiaries (Bradbury et al., 2010).

6. Platforms and Networks

6.1. Environmental Change Network

The UK Environmental Change Network (ECN), a national, long-term observation network to provide quantitative data on multiple driving and response variables, was launched in 1992 as a response to concerns about biodiversity loss, widespread air and water pollution and climate change. It comprises a broad range of ecosystems and physical, chemical and biological measurements made according to standard published protocols (Sykes and Lane, 1996). It is a collaborative multi-agency initiative currently consisting of 11 terrestrial and 45 freshwater sites and is linked to other international long-term networks. North Wyke was one of the original sites and core measurements are centred on poorly drained, long-term low input grassland forming part of the Rowden Experiment. Several of the monitoring protocols are shared with other UK monitoring networks (insects, butterflies, NH_3) enabling data to inform on change at a more extensive scale. A robust set of quality controlled data stored in a central database is openly available (http://www.ecn.ac.uk/data) and a series of eighteen datasets (between 1993-2012) of continuous monitoring at terrestrial sites has been published (Rennie and Sherin, 2017).

In general, climate trends at North Wyke follow those at other sites, showing a warming trend and increase in annual precipitation across the whole terrestrial network during the first 15 years (Morecroft et al., 2009). However, between 1993-2012 neither average monthly air temperature nor total monthly precipitation changed significantly at North Wyke or most ECN sites (Monteith et al., 2016). These differing climate trends depending on the period studied demonstrate the importance of long-term monitoring to distinguish between inter-annual variability and long-term trends.

Atmospheric deposition indicators including precipitation chemistry showed that national and international legislation to reduce air pollutants had been effective (Monteith et al., 2016). At North Wyke, concentrations of SO_4^{2-} and NO_3^- in precipitation and soil solution water have declined leading to increased pH in soil solution water, indicating that the soil was recovering from acidification. Data from ECN sites have been used to inform environmental policy, e.g. soil solution chemistry changes linked to atmospheric emission controls have been reported (RoTAP, 2012). This change resulted in plant species numbers increasing across most sites including North Wyke, especially those preferring less acid soils indicating a recovery from acidification (Rose et al., 2016). Data from ECN sites highlight the need for further investigations on the relative and interactive effects of atmospheric eutrophication and acidification on plant diversity.

Beaumont et al. (2016) noted that North Wyke has also recorded an increase in plant species associated with wetter conditions in improved grasslands possibly reflecting a trend towards wetter summers. They also note that cessation of artificial fertilizer applications in localised areas resulted in increased plant species richness and benefitted several butterfly species. Between 1994-2008, carabid beetle abundance declined over the whole network but with inconsistencies in the trends between regions and habitats highlighting the importance of localised land management as well as climate change (Brooks et al., 2012). The total abundance of macro-moths declined at North Wyke (Morecroft et al., 2009; Beaumont., 2016); the cause of this is unclear, particularly as during the first 15 years, North Wyke was the only ECN site where a decline in the total number of individual macro-moths was observed (Morecroft et al., 2009). Monitoring also provides new information on the distribution of species: thus a specimen of *Pterostichus cristatus*, Dufour, 1820, a nationally rare carabid beetle which had never been recorded in South West England, was discovered in August 2012: this new record is thought to represent a previously unknown relict indigenous population (Corbett & Whitehead, 2017).

The first two decades of ECN have revealed marked environmental changes at North Wyke and network-wide. The data, with expert local knowledge, have been used to assess the validity and applicability of a Millennium Ecosystem Assessment as a framework to gauge and compare ecosystem service delivery from ECN sites (Dick et al., 2011) and identified challenges and limitations. The potential consequences of environmental change arising from climate, pollution and land management pressures on ecosystems continue to be of major concern. High-quality, long-term datasets are essential for quantifying changes, to develop tools to forecast environmental changes and assess likely impact on key ecosystem services and how ecosystem components recover after implementation of new policies and management practices. ECN's datasets will become increasingly valuable resources as they continue to lengthen.

6.2. North Wyke Farm Platform (NWFP)

One of the most important recent developments and largest investments in infrastructure that has taken place at North Wyke is the establishment of the NWFP (www.rothamstedresearch/farmplatform). Funded by BBSRC as a National Capability the NWFP was constructed in 2010 (Orr et al., 2011). The platform (Fig. 8) comprises three scaled farms or farmlets which were designed to test the productivity and environmental sustainability of contrasting temperate grassland beef and sheep systems at the farm system scale. Each of the three farmlets (each of approximately 22 ha) was further divided into five catchments (15 in total) with each catchment being hydrologically isolated through a combination of topography and a network of French drains at their edges. These drains channel drainage/runoff water to monitoring sites, as described in Griffith et al. (2013). Over two years from April 2011, beef and sheep production systems were managed under the same guidelines on the three farmlets to measure baseline productivity on the existing permanent pasture (Orr et al., 2016). After April 2013, two of the farmlets entered a phase to move progressively towards new treatments with either use legumes targeting 30% ground cover by white clover or with a programme of planned regular reseeding to maximise the potential of new grass germplasm through targeted breeding programmes with our partners at the Institute of Biological, Environmental and Rural Sciences (IBERS) in Aberystwyth.

Insert Figure 8 here

Figure 8. A schematic plan of the North Wyke Farm Platform

The NWFP provides a means to research, understand and deliver sustainable grazing livestock systems through developing a detailed understanding of sustainability metrics and trade-offs (e.g. productivity, nutritional quality, biodiversity and emissions). The aim is to deliver optimised production of high value animal products from land not suitable for crop production at the same time as harnessing and protecting other ecosystem services and minimising environmental pollution (Orr et al. 2016). The NWFP experiment along with others like it (e,g. those of the Global Farm Platform network that encompass different climatic and eco-regions, see www.globalfarmplatform.org), can address the true position and role of livestock products in sustainable agricultural production and global food security. Sustainable livestock production can produce multiple social, economic and environmental benefits by not only improving productivity but also reducing the ecological footprint and generate diversity of ecosystem services such as improved water, air and soil quality and reduced erosion, sedimentation and GHG emissions.

Significantly, the NWFP provides a facility where all the preceding research themes and strands at North Wyke, including production, environmental and sustainability aspects, are drawn together in a single experimental platform. It builds on the legacy of the depth and breadth of research expertise that has evolved at North Wyke, enabling the potential of all-forage beef finishing systems using Life Cycle Analysis. The approach will elucidate the impact and value of pasture based beef production through mapping animal performance, product quality (including nutrition provision per area of land, hedonics and shelf life), environmental impact, labour cost and economic returns using primary data sets which can only be collected at the NWFP. In addition, as a National Capability, all core input and output data collected from across the NWFP is made publicly available via a Data Portal (https://nwfp.rothamsted.ac.uk/). In the future, the treatments can be evolved or changed as advances in plant breeding and systems understanding develop.

6.3. Working across scales: from laboratory to landscape

One of the key factors that has contributed to the success and impact of the research carried out at North Wyke has been the ability to work across a range of scales, from laboratory to landscape studies, and via modelling expertise, even to national scale. This, in part, is due to the proximity of North Wyke to the agricultural environment for which it was established to research. Working across scales is fundamental to agricultural and environmental research, with the need to carry out empirical, small scale reductionist studies in the laboratory to understand fundamental mechanisms that are often part of a complex set of interacting processes in the field, catchment or landscape. It is essential to see how well the basic understanding of individual processes translates to, and scales within, the real world, via observation of the agricultural and natural environment, especially since process scaling has important implications for the efficient management of farming. Examples of how this has been done at North Wyke are numerous, but are well exemplified by the work on P dynamics and the development of 'the phosphorus transfer continuum' concept (Haygarth et al., 2005), which brings together work on P dynamics across a range of scales into a widely applied conceptual framework, enabling the fundamental understanding of factors controlling the transfer of P from agricultural systems to water bodies. It built on an earlier conceptual framework (Lemunyon and Gilbert, 1993) plus a substantial body of work explaining P dynamics at different scales and through different processes (e.g. Turner and Haygarth, 2001; Haygarth et al., 1999). Subsequently it contributed towards the development of policy and guidelines for the management of diffuse agricultural pollution (including P) in the form of the Defra mitigation methods user guide (Newell-Price et al., 2011; Cuttle et al., 2016). Such multi-scaled approaches are urgently required to integrate different disciplines and provide a platform to develop mechanistic modelling frameworks, collect new data and identify critical research questions. Other examples of work across scales from North Wyke already noted include the incorporation of improved understanding of the N cycle and its component parts (especially NH_3 and N_2O) into models which can be applied across the range of scales for scientific or practical purposes.

Recently, an increasingly important component of research at North Wyke has involved integrated experimental and modelling work to characterise grazing farm systems and their environmental impacts at a national scale, across England and Wales. For example, work funded by Defra as part of the Demonstration Test Catchment (DTC) programme (McGonigle et al., 2014) has been concerned with estimating pollutant emissions to air and water under business-as-usual (current) uptake of on-farm mitigation measures and projecting the technically feasible impacts of alternative futures for grazing livestock farmers, built around understanding farmer receptiveness and attitudes towards on-farm diffuse pollution mitigation measures. On this basis, a national modelling framework was used to simulate agricultural pollutant emissions to water and air under business-as-usual and the policy scenario embodying increased uptake (95%) of 29 farmer-preferred measures. The simulations (Collins et al., 2016) suggested that median reductions in business-as-usual emissions of sediment, P and NO_3 to water in areas of England and Wales dominated by lowland grazing livestock farms were 28%, 28% and 12%, respectively, whereas corresponding median reductions in gaseous emissions could be in the order of 23% (NH_3), 7% (N_2O) and 16% (CH_4). These results have been used to contribute to ongoing policy discussions following the decision of the UK to exit the European Union.

7. Conclusions and future perspectives

North Wyke Research Station has developed into an international centre of excellence for grassland research, having carried out pioneering studies into fundamental, agronomic, environmental and livestock performance aspects of grassland production. Historically, research has been carried out in specific themes, such as nutrient cycling, farm waste management, gaseous emissions, grazing management, animal production (meat and milk) and forage quality. The research themes developed and reacted to changes in the requirements of policy and funding, yet also influenced and guided the research agenda. Currently, North Wyke Research Station is leading the way on taking increasingly holistic research approaches to land and landscape management with a focus on sustainable grazing-livestock production, driven by optimised nutrient use efficiency. Such ground breaking holistic research is made possible through the North Wyke Farm Platform, a farm scale laboratory essential to an integrated Rothamsted Research programme around sustainable agriculture.

We are at a critical juncture for global agriculture, when the need to secure global food security is challenged by competing requirements for maximal production and minimal pollution. This has led to the concept of 'sustainable intensification' at a time when the earth's planetary boundaries have been exceeded for many nutrients including N and P (Steffen et al. 2015), as well as impending climate change. Any intensification of agriculture and particularly livestock agriculture, has significant environmental risks such as water and air pollution, carbon emissions and deposition, soil degradation and erosion, as well as issues affecting production efficiency, product quality and consumer acceptability, such as reduced animal fertility, health and welfare. National and international socio-political changes, such as those likely to result from the UK's exit from the EU, will impact on future land management and this will require novel approaches based on sound science. These challenges necessitate multidisciplinary solutions that are best tested and researched in real-world production systems such as the North Wyke Farm Platform (Eisler et al., 2014; Orr et al., 2016). Moreover, Dumont et al. (2014) recently highlighted a need to 'redesign' livestock systems incorporating the integration of crops and livestock. To this end, Rothamsted Research and the North Wyke Research Station have an important role to play in developing farming systems that will enable the world to produce 'more food of higher quality from the same amount of land without detriment to the environment'. Furthermore, a decline in the nutritional quality of food, especially in terms of micronutrients, has recently been highlighted (e.g. Eggersdorfer et al., 2016), and reflects deficiencies throughout the food chain. Methods for tackling this include the development and formulation of novel fertilisers, but much remains to be learnt about the cycling and uptake of micronutrients in soils, plants, animals and humans. Another key aspect, looking forward, is the threat of climate change and the need to quantify not only the potential causes and impacts related to grassland systems, but also how best to adapt to the inevitable changes that will occur. There are many opportunities that can facilitate addressing these challenges, including:

- Increasing technological ability to gather extensive data sets with high temporal and spatial resolution on all components of grassland systems, from soils, waters, plants, livestock and the atmosphere. These include not only ever-increasing capability to identify and quantify key components at the elemental/molecular scale but also remote sensing technology via satellites and drones, development of sensors for real time environmental monitoring of soil, water and atmospheric properties as well as crop and livestock health.

- Improved understanding of genetic resources and traits in plants and livestock, enabling breeding for desired phenotypes with greater resilience to biotic and abiotic stress in the face of climate change and other pressures on land use.
- The availability of large amounts of metagenomic information describing the functioning of soil microbe-plant (rhizosphere) interactions and the pan-genome of plant-gut microbes and livestock host.
- The ability to work across temporal and physical scales from the soil and gut microbiomes, through field scale to farm scale and beyond via a continuum of experimental studies, observations and modelling. This is a key research approach adopted over decades at North Wyke, and crucial to the successful development of solutions to the sustainable intensification of agriculture.
- Reducing waste at all points of the agricultural value chain including improved crop and animal health globally, extended shelf life of products, changing consumption patterns and improved recycling of waste within the food chain from farm to consumer.

In addition to the opportunities above, there are several developing opportunities which should be exploited and will further assist with tackling the global challenges currently faced:

- Making best use of 'big data': we can deploy increasingly advanced and complex technology to capture and interrogate data that describe the systems we are investigating, but the challenge remains to successfully and usefully process and interpret these data sets, converting them to useful metrics which, for example, can help us to quantify the performance of agricultural systems in terms of sustainability. Developing appropriate statistical approaches alongside ever more complex but robust models are key to the success of this.
- Developing appropriate precision farming techniques in relation to the remotely sensed, real time datasets, improving efficiency in agricultural production.
- Integration of agricultural, environmental, economic and social sciences, enabling comprehensive Life Cycle Analysis of different farming strategies to enable identification of truly sustainable systems. The NWFP has a key role to play in the development not only of the farming systems that can deliver this, but also the mechanisms of investigation and integration of the science.

A vital aspect of any research programme to optimise the impact of the scientific opportunities is a well-primed knowledge exchange programme for both land managers and the wider public communities. The importance of this is now much better recognised and improved efforts and finances are steered towards 'knowledge exchange and commercialisation' of research, complementing traditional approaches such as open days and stakeholder workshops with social media and improved mobile technology, e.g. mobile phone apps.

Quantification of sustainability based on metrics such as nutrient loss and nutrient provision (human nutrition) per land area within Rothamsted Research programmes and within temperate grassland systems at North Wyke are critical steps towards food security. However, it must be recognised that agricultural practices globally are diverse, with those for livestock ranging from feedlot and intensive total mixed ration systems through to rangeland extensive grazing and nomadic herding systems. To this end, a network of 'farm platforms' has been established across different climatic and eco-regions as a global resource for optimising and exemplifying research on the contribution of sustainable ruminant livestock production to global food security (www.globalfarmplatform.org). The global farm platform network will develop future innovations, as exemplified for temperate grassland at North Wyke, across the diverse range of livestock production practices globally to secure the sustainable future of livestock production and its contribution towards global food security.

North Wyke has, without doubt, had research longevity and scientific impact during its 35 years and this resilience perhaps is in part due to the relatively small size of the research station which engenders intimate collaborations amongst a diverse range of scientific experts. This diversity of expertise at North Wyke, complemented by many national and international collaborations, has undoubtedly contributed towards the high impact the work carried out there has had on academic, environmental and agricultural communities. With over 1000 peer reviewed publications to date attributable to work carried out by scientists at North Wyke, the substantial contribution to agricultural and environmental science arising from the research station has influenced, and continues to influence research and policy nationally and internationally.

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Tables

Table 1. Grassland Research at North Wyke (1981-2017): key events and evolution of research (after Jarvis et al., 2012)

Date	Institute	Key events	Research
1981	**Grassland Research Institute (GRI)** (HQ	Purchase of North Wyke by Crown Estates and 25-year lease to Research Council. Transfer and	Improved pasture production: strategic and

	Hurley)	recruitment of staff. Infrastructure work and start research	applied
1985	GRI amalgamated with parts of the National Institute of Dairying to form the **Animal and Grassland Research Institute (AGRI)** (HQ Hurley)		Improved pasture production: strategic and applied
1986	AGRI amalgamated with the Welsh Plant Breeding Station and part of the Poultry Research Centre to form the **Institute for Grassland and Animal Production (IGAP)** (HQ Hurley)		Continued emphasis on improved pasture production but development of programmes on agroecology and nutrient utilisation
1987-1990		Government withdraws funding for near-market research with loss of 30% of income for North Wyke	Reduction in research on animal production from grassland
1990-1992	IGAP re-formed as **Institute for Grassland and Environmental Research (IGER)** with transfer of poultry research and closure of the Hurley site in 1992 (HQ Aberystwyth)	Closure of Hurley site announced with programmes and staff concerned with soils and nutrients, farm wastes, plant-animal relations, grassland pests and diseases and animal modelling transferred to North Wyke over a 2-year period. Major investment at North Wyke with new laboratory and glasshouse facilities.	Policy driven strategic research for environmentally sound grassland production and utilisation
2002		North Wyke estate purchased by BBSRC from Crown Estate	Basic and strategic research to underpin environmental policies for grassland production
2004		Disposal of dairy herd	
2005		Formation of Soil Cross Institute Programme (SoilCIP) led by Rothamsted and North Wyke	
2006		Closure of strategic research programme on grazing and plant animal interactions	
2008	IGER closed and North Wyke merged with **Rothamsted Research** (HQ Harpenden)	Integration of grassland and arable research	
2009		Major investment at North Wyke to establish fully instrumented facilities for North Wyke Farm Platform	Increase in holistic research at systems level
2016		Purchase by Rothamsted Research of 100 ha land at Whiddon Down	Increased support for livestock research at North Wyke

Table 2 Liveweight gain (kg ha^{-1}) by beef cattle and nitrate (NO_3^-) leaching (kg N ha^{-1}) for grazed drained and undrained permanent swards and perennial ryegrass re-seeds receiving 200 and 400 kg fertilizer N ha^{-1} (from Tyson et al., 1992).

	Liveweight gain (kg ha^{-1})		NO_3^- leached (kg N ha^{-1})	
	Undrained	Drained	Undrained	Drained
Permanent swards (1983-92):				
200 kg N ha^{-1}	860	920	16	56

400 kg N ha^{-1}#	930 (860)	990 (900)	74	194
Ryegrass re-seed (1983-87)				
400 kg N ha^{-1}	840	1010	27	85

Figures in parentheses are means for the period 1983-87

Figure Legends

Figure 1.a. Photograph of Rowden Drainage Facility showing the 1 ha hydrologically isolated plots. (Photo: Google Earth)

Figure 1.b. Photograph of weirs for monitoring runoff on a drained plot. One weir measures discharge from surface runoff, the other from soil drains. (Photo: S.Jarvis)

Figure 2. Interaction of factors influencing nature of research on grassland components and systems undertaken at North Wyke (Adapted from Jarvis et al., 2012)

Figure 3. Mean number of minutes per hour spent grazing either grass or clover over the course of the day for cows grazing adjacent monocultures of 75% grass and 25% clover (by ground area) (Rutter et al., 1998).

Figure 4. Increase in water-soluble organic P after soil drying as a function of soil microbial P (Turner and Haygarth, 2001b).

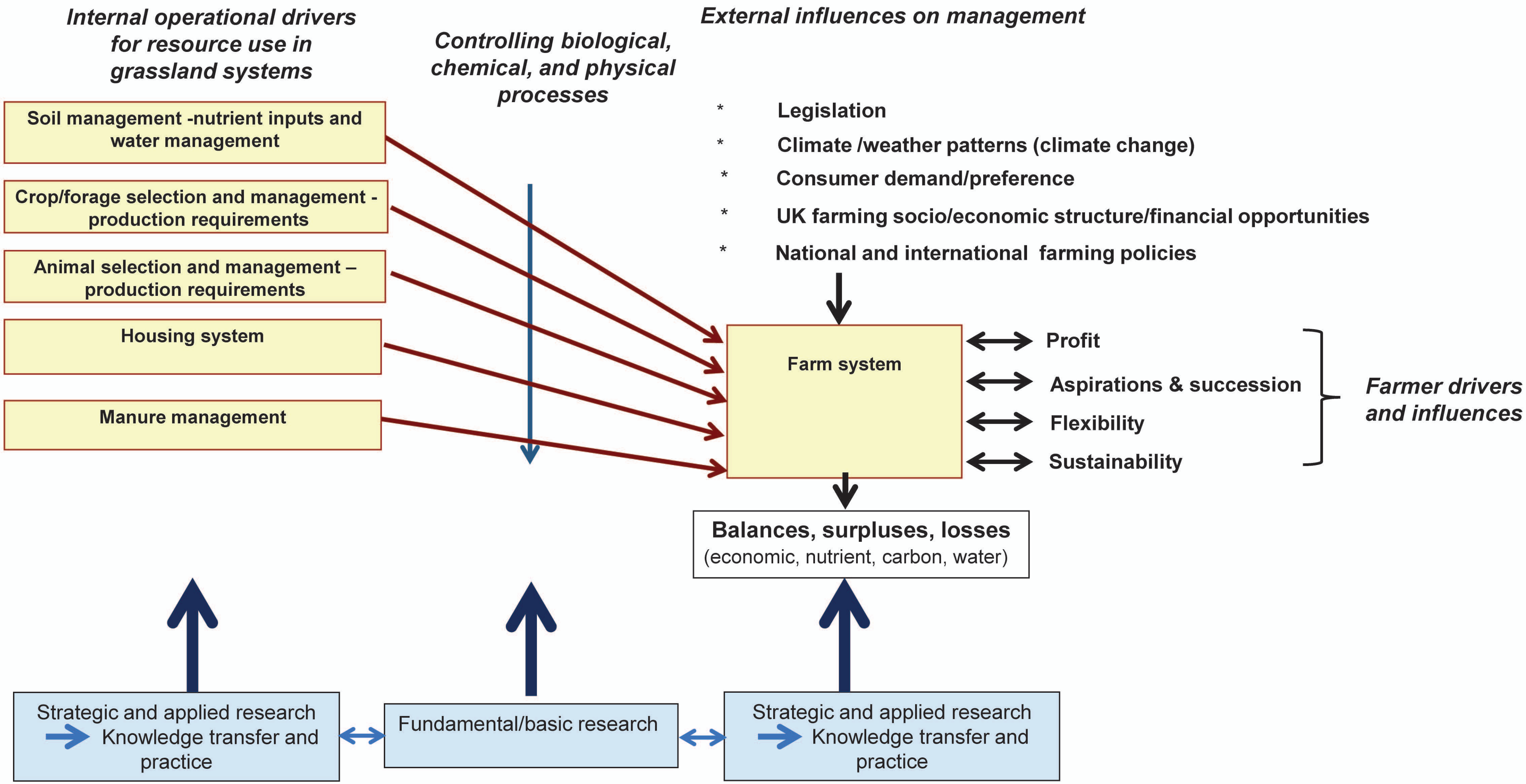
Figure 5. Effects of long-term (15 years) drainage on soil organic matter content in grazed pasture soils under high N management on the Rowden Experiment (McTeirnan et al., 2001).

Figure 6.a. The DENIS system showing soil incubation vessels and gas flow apparatus (foreground) and continuous gas measurement equipment (background). (Photo: Rothamsted Research)

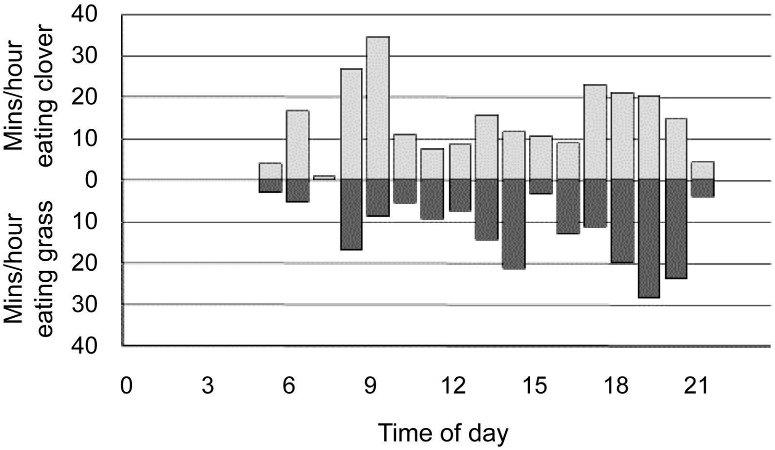
Figure 6.b. Example of data output from the DENIS system: gaseous emissions over time from a poorly drained grassland soil amended with NO_3^- and glucose (from Loick et al., 2016).

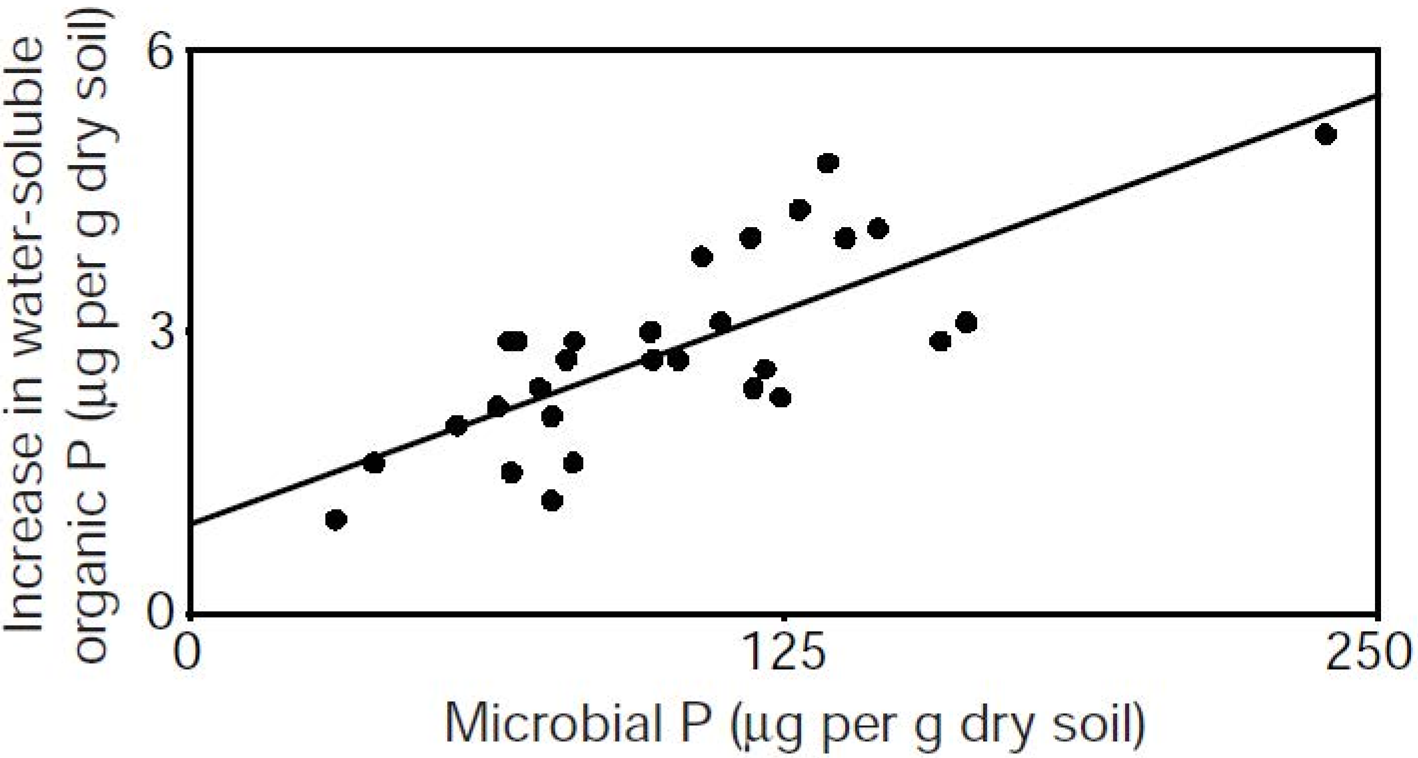
Figure 7. Impacts of nutrients on plant species diversity: a) impact of soil total P, b) impact of applied N (from Janssens et al., 1998).

Figure 8. A schematic plan of the North Wyke Farm Platform

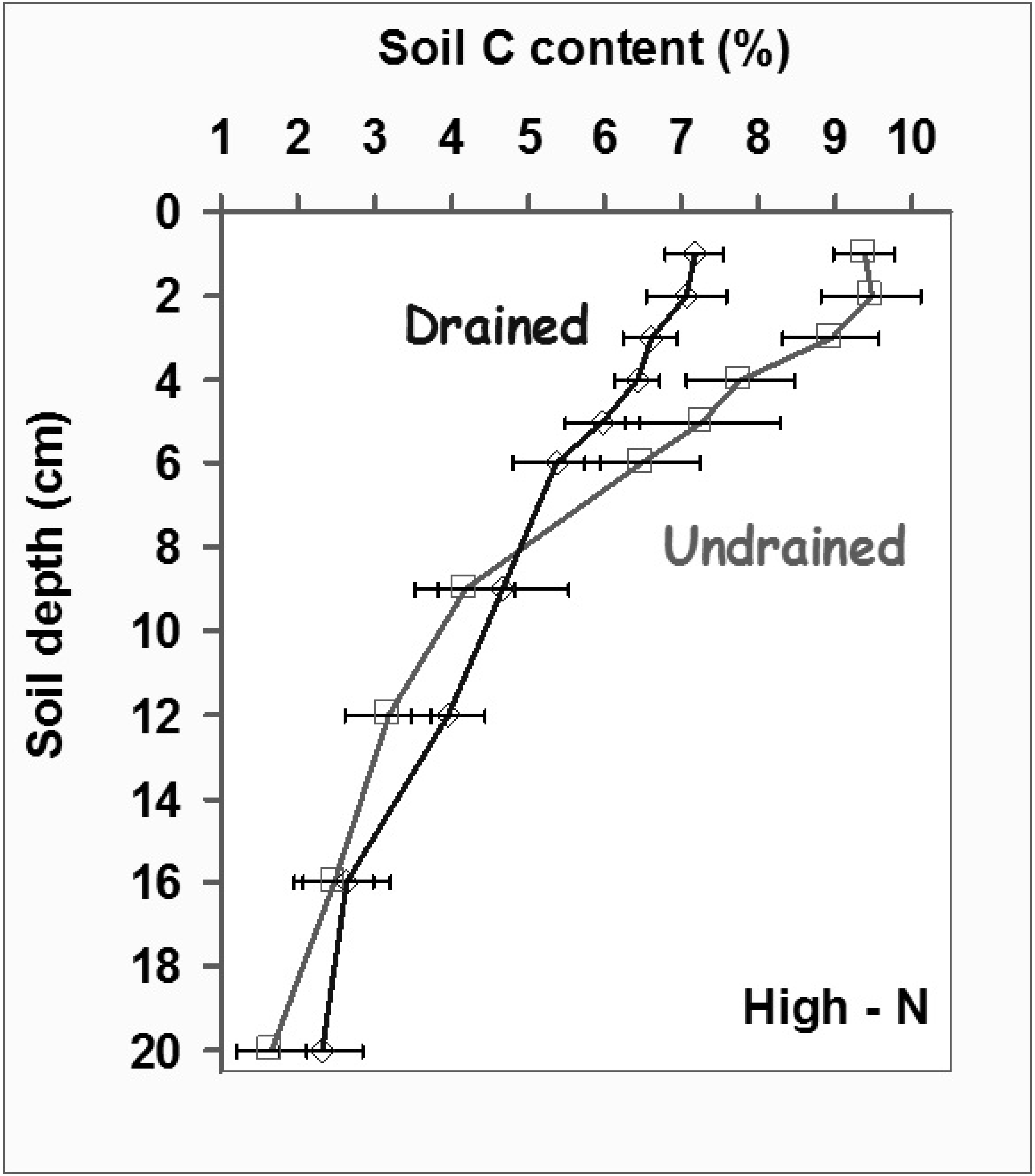

Internal operational drivers for resource use in grassland systems
Controlling biological, chemical, and physical processes
External influences on management
Soil management -nutrient inputs and water management
Crop/forage selection and management - production requirements
Animal selection and management – production requirements
Housing system
Manure management
* Legislation
* Climate /weather patterns (climate change)
* Consumer demand/preference
* UK farming socio/economic structure/financial opportunities
* National and international farming policies
Farm system
Profit
Aspirations & succession
Flexibility
Sustainability
Farmer drivers and influences
Balances, surpluses, losses
(economic, nutrient, carbon, water)
Strategic and applied research Knowledge transfer and practice
Fundamental/basic research
Strategic and applied research Knowledge transfer and practice

Diurnal pattern of preference



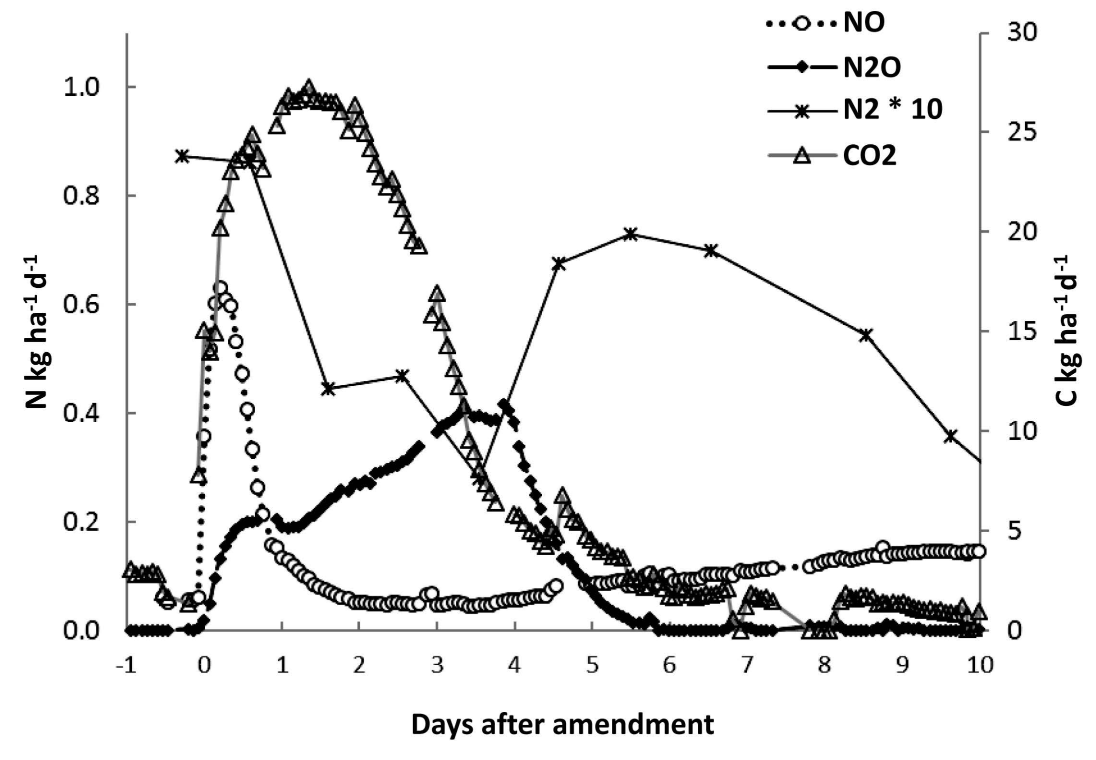


Increase in water-soluble organic P (µg per g dry soil)
6
3
0
0
125
250
Microbial P (µg per g dry soil)

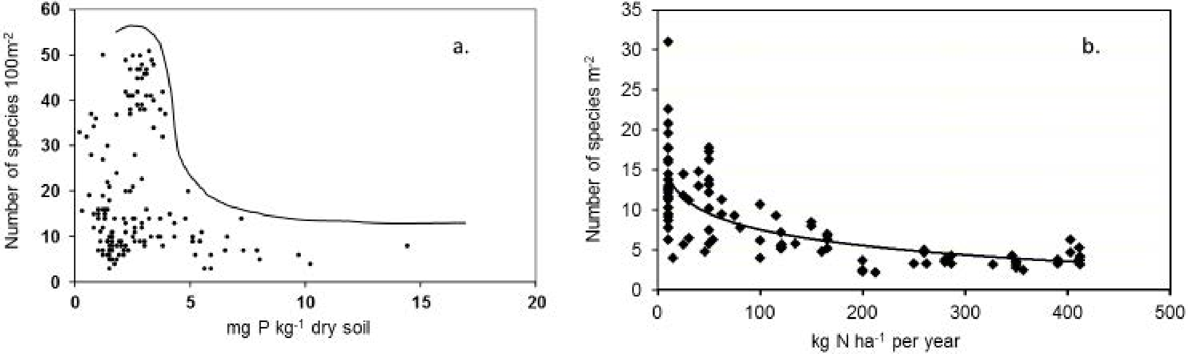


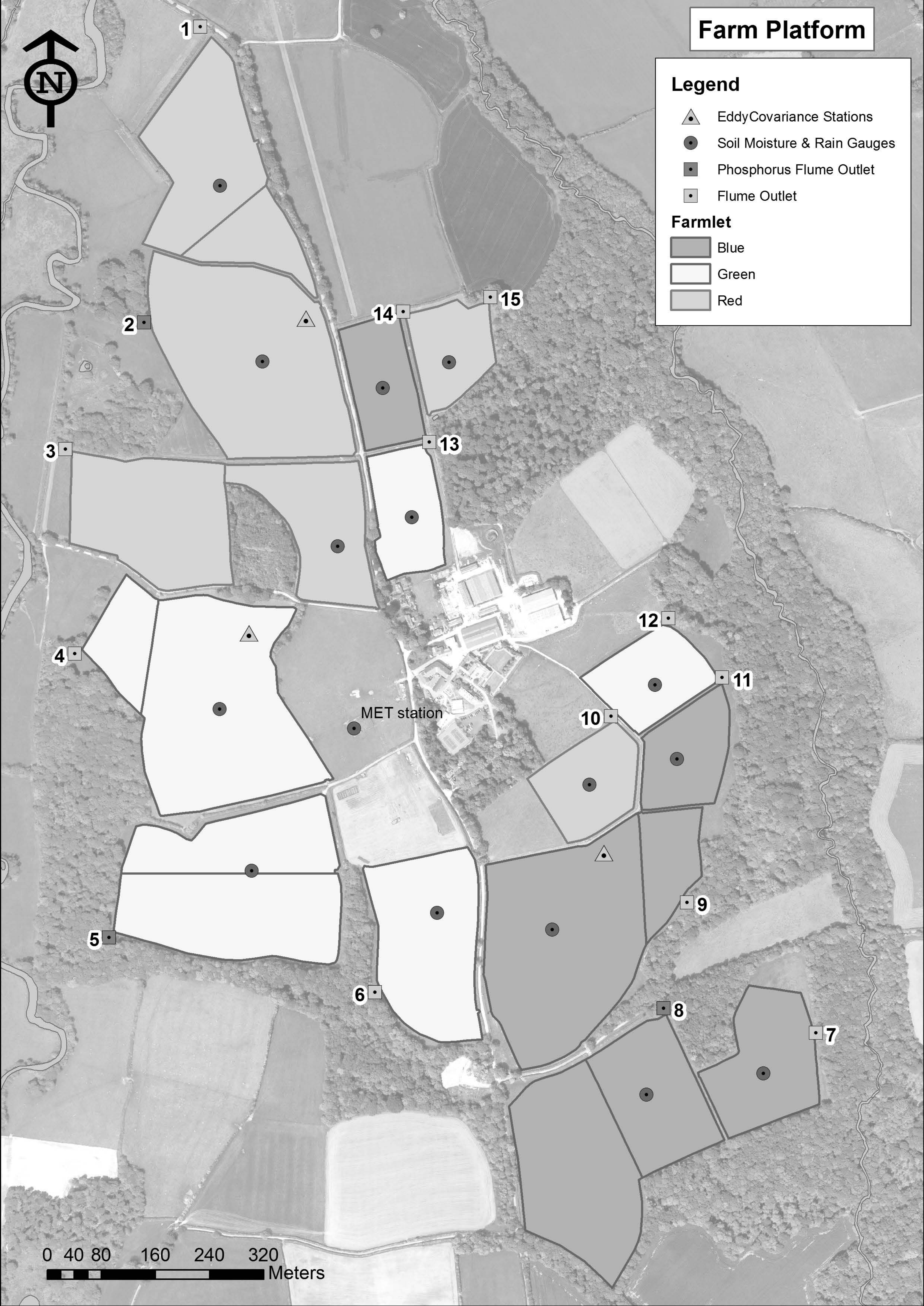
Soil C content (%)
1
2
3
4
5
6
7
8
9
10
Soil depth (cm)
0
2
4
6
8
10
12
14
16
18
20
Drained
Undrained
High - N


121
131
141
151
161



NO
N2O
N2 * 10
CO2
N kg ha-1 d-1
C kg ha-1 d-1
Days after amendment
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
-1
0
1
2
3
4
5
6
7
8
9
10


60
50
40
30
20
10
0
0
5
10
15
20
Number of species 100m-2
mg P kg-1 dry soil
a.
35
30
25
20
15
10
5
0
0
100
200
300
400
500
Number of species m-2
kg N ha-1 per year
b.



Farm Platform
Legend
EddyCovariance Stations
Soil Moisture & Rain Gauges
Phosphorus Flume Outlet
Flume Outlet
Farmlet
Blue
Green
Red
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
MET station
0 40 80 160 240 320
Meters