9

White Clover Supported Pasture-based Systems in North-west Europe

James Humphreys,[1]* Paul Phelan,[2] Dejun Li,[3] William Burchill,[4] Jørgen Eriksen,[5] Imelda Casey,[6] Daniel Enríquez-Hidalgo[7] and Karen Søegaard[5]

[1]Animal and Grassland Research Innovation Centre, Teagasc, Fermoy, Ireland; [2]Animal and Grassland Research Innovation Centre, Teagasc, Dunsay, Ireland; [3]Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, China; [4]Johnstown Castle Environment Research Centre, Teagasc, Co. Wexford, Ireland; [5]Aarhus University, Tjele, Denmark; [6]Waterford Institute of Technology, Waterford, Ireland; [7]Universidad Católica de Chile, Santiago, Chile

Abstract

White clover (WC) (*Trifolium repens* L.) is a useful component of European grasslands due to: (i) its capacity to convert dinitrogen (N_2) gas to plant-available nitrogen (N) in the soil via biological nitrogen fixation (BNF); (ii) its tolerance of grazing; and (iii) its high nutritive value for ruminant livestock. Its relative importance has declined in recent decades in line with the intensification of ruminant production systems that increasingly rely on maize silage and intensively fertilized grass leys. There are many challenges in managing WC on farms. These include: (i) maintaining the ideal balance between the grass and WC in grassland; (ii) low and inconsistent dry matter (DM) productivity; (iii) difficulties with ensilage due to the low herbage DM and sugar concentrations; and (iv) increased risk of bloat. However, the cost of fertilizer N has increased substantially since the late 1990s, particularly relative to the farm-gate price received for milk, beef and sheep meat. This price:cost squeeze has generated renewed interest in the use of WC on farms. Furthermore, under legislation stemming from the Nitrates Directive, permissible stocking densities and rates of fertilizer N input are lower than previously in many European countries, and the lower productivity of WC-rich grassland is not as much of an obstacle to adoption on farms as it has been in the past. As well as the capacity that WC has to improve herbage nutritive value, the main advantage of WC-based systems stems from the replacement or reduction of fertilizer N input by BNF and the contribution that this makes to farm profitability and

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*james.humphreys@teagasc.ie

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environmental performance. Although WC-rich grassland has lower productivity, lower fertilizer N costs can largely close the gap in farm profitability between WC-based and more intensively managed systems. There is generally less N circulating within lower stocked WC-based systems, resulting in lower N losses to water and lower ammonia and methane emissions to the atmosphere; losses that are often closely related to stocking density. WC has additional advantages when it comes to the other greenhouse gases: nitrous oxide and carbon dioxide. Direct emissions of nitrous oxide are lower from WC-rich grassland than from N-fertilized grassland at the same level of productivity and substantially lower than intensively fertilized grassland. Emissions of carbon dioxide associated with the manufacture, transport and application of nitrogenous fertilizers are avoided by the use of WC. Using life cycle assessment, studies have shown that WC-based systems have between 11% and 26% lower carbon footprint per litre of milk than N fertilized systems; the largest difference was with more intensive systems reliant on high input of fertilizer N. Escalating fertilizer N costs have improved the profitability of using WC in pasture-based systems in recent years. From the perspective of the overall future sustainability of pasture-based ruminant production, WC-based systems offer economic competitiveness, lower energy dependency and lower environmental impact.

Introduction

White clover (WC) (*Trifolium repens* L.) is a useful component of European grasslands due to: (i) its capacity to convert dinitrogen (N_2) gas to plant-available nitrogen (N) in the soil via biological nitrogen fixation (BNF); (ii) its suitability for grazing; and (iii) its high nutritive value for ruminant livestock. It is most commonly grown in association with perennial ryegrass (PRG) (*Lolium perenne* L.) where it can improve sward crude protein, organic matter digestibility, herbage production and herbage intake by ruminants. However, the use of WC has declined in recent decades in line with the intensification of ruminant production systems that increasingly rely on maize silage and intensively fertilized grass leys (Peyraud *et al.*, 2009). There are many challenges to WC management on farms, such as: (i) maintaining the ideal balance between grass and WC in pastures; (ii) low and inconsistent productivity; (iii) increased risk of bloat in grazing livestock; and (iv) difficulties with ensilage.

The productivity of WC-rich grassland that does not receive fertilizer N in pasture-based dairy systems has generally been found to be 70–90% of that of intensively N-fertilized PRG-based grassland (hereafter referred to as grass-only) receiving annual applications of up to 415 kg/ha of fertilizer N (Humphreys *et al.*, 2009; Andrews *et al.*, 2007; Table 9.1). In many countries in the north-west of Europe, these very high rates of fertilizer N input and associated stocking densities are no longer permissible due to regulations under the Nitrates Directive (European Council, 1991). Furthermore, since the late 1990s, the farm-gate cost of fertilizer N has increased at an annual rate of around 5%. Hence, there has been a strong increase in the cost of fertilizer N relative to the farm-gate price received for milk (Fig. 9.1). These trends have negative impacts on the profitability of pasture-based systems of dairy production that rely on high inputs of fertilizer N. At the same time, there has been more regulatory pressure to lower N losses to water and to the atmosphere. These include various national regulations stemming from the

Table 9.1. The number of years that comparisons took place, stocking densities of dairy cows, annual fertilizer N input, concentrates fed to cows, annual herbage production and milk production in systems-scale comparisons of milk production from white clover (WC)-based and N-fertilized grassland.

No. years	Stocking density (LU/ha)	Fertilizer N input (kg/ha)	WC content of herbage (g/kg DM)	Concentrates fed		Herbage production (t DM/ha)	Milk production		References
				(kg/cow)	(kg/ha)		(kg/cow)	(t/ha)	
1	3.86	0	270	211	815	16.25	3468	13.39	Bryant *et al*. (1982)[a]
	3.86	86	270	211	815	16.11	3500	13.51	
1	4.09	0	230	245	1002	16.97	3196	13.07	Bryant *et al*. (1982)[a]
	4.09	137	195	245	1002	18.08	3377	13.81	
6	na[b]	0	150	na	na	na	na	8.56	Weissbach and Ernst (1994)[c]
	na	308	na	na	na	na	na	14.20	
5	2.52	122	385	600	1512	na	4224	10.64	Ryan (1986, 1989)[d]
	3.20	361	< 50	600	1920	na	4068	13.02	
3	4.5	0	580	890	4007	8.8	3914	17.61	Aaes and Kristensen (1994)[e]
	5.1	240	260	890	4539	12.1	3965	20.22	
5	3.30	0	152	na	na	16.38	3953	12.96	Ledgard *et al*. (1998, 1999, 2001)[f]
	3.30	215	107	na	na	18.45	4735	15.52	
	3.30	413	49	na	na	20.58	4858	15.92	
3	1.90	17	290	1847	3509	10.10	8294	15.75	Schils *et al*. (2000a, b)[g]
	2.20	208	<50	1828	4022	10.80	8095	17.80	
3	4.7	0	504	1008	4738	9.0	4039	18.98	Søegaard *et al*. (2001)[e]
	4.8	300	0	1008	4838	11.1	4055	19.46	
1	1.90	0	253	1096	2082	9.24	5719	10.87	Leach *et al*. (2000)[h]
	2.40	350	9	1412	3389	10.35	5724	13.74	
2	1.75	80	240	535	936	10.57	6550	11.46	Humphreys *et al*. (2008)[i]
	2.10	180	39	535	1124	10.75	6275	13.18	
	2.50	248	20	535	1338	12.06	6242	15.61	
	2.50	353	7	535	1338	13.26	6375	15.94	
4	2.15	90	219	531	1142	11.51	6521	14.02	Humphreys *et al*. (2009)[i]
	2.15	226	60	520	1118	12.45	6526	14.03	

Continued

Table 9.1. Continued.

No. years	Stocking density (LU/ha)	Fertilizer N input (kg/ha)	WC content of herbage (g/kg DM)	Concentrates fed (kg/cow)	Concentrates fed (kg/ha)	Herbage production (t DM/ha)	Milk production (kg/cow)	Milk production (t/ha)	References
2	1.6	0	240	539	857	8.80	6388	10.20	Keogh *et al*. (2010)[i]
2	2.12	100	180	575	1218	10.10	6273	13.30	
3	2.12	100	210	496	1052	11.10	6137	13.01	Phelan *et al*. (2013b)[i]
1	na	260	200	154	na	13.16	3880	na	Enriquez-Hidalgo *et al*. (2014)[j]
	na	260	0	154	na	13.05	3728	na	

LU, Livestock unit; DM, dry matter.

[a] Bryant *et al*. (1982) – Calving in late winter and cows were milked at pasture. Rotational grazing. Lactation length was largely determined by pasture supply.

[b] na, Data not available.

[c] No significant differences in concentrates fed per cow (4 kg/cow/day) or in milk production per cow (22.3 kg fat corrected milk/day).

[d] Calving in late winter; grazing season from 9 April to 20 October. Rotational grazing. No fertilizer N was applied to the WC-based swards used for grazing; fertilizer N was applied to a non-WC silage area on the low fertilizer N input system. WC content refers to the WC content of the WC-based swards in late summer only.

[e] Grass–arable systems with continuous grazing.

[f] Ledgard *et al*. (1998, 1999, 2001) – Calving in late winter and cows were milked for 250–290 days at pasture. Rotational grazing. Minimal amounts of concentrate supplementation were fed to cows.

[g] Schils *et al*. (2000a, b) – Calving from October to April; grazing season from first week of April to last week of October.

[h] Leach *et al* (2000) – Results from final year of a 3-year experiment. Autumn calving; cows dry during much of the grazing season that extended from late spring to mid-October. Nine days later turnout in spring on the WC-based swards.

[i] Compact calving during 12-week period in spring with a mean calving date in mid-February, cows turned out to pasture as they calved from late January onwards and remained at pasture until late November depending on ground conditions. Rotational grazing. Milk was produced until mid-December each year.

[j] Mean calving date 19 February. Results presented from 17 April until 31 October 2011. Rotational grazing.

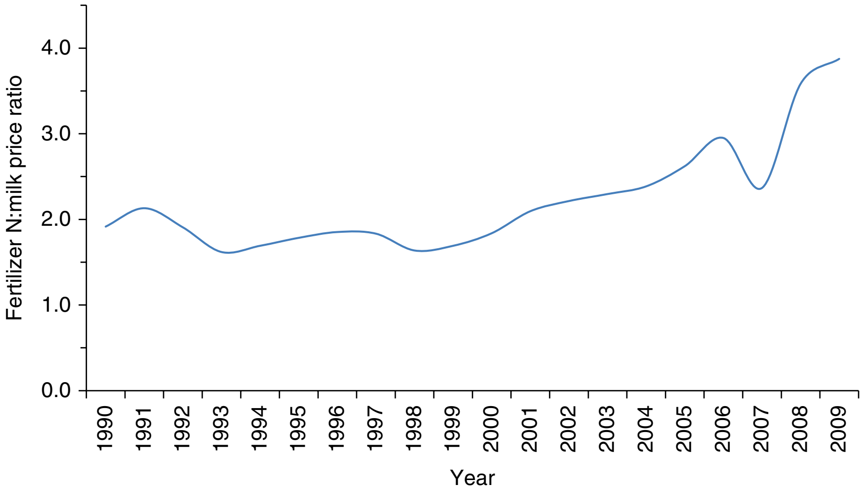

Fig. 9.1. Changes in the fertilizer N:milk price ratio in Western Europe (EU-15) between 1990 and 2011. The data are derived from Eurostat 'purchase prices of the means of agricultural production' and 'selling price of agricultural goods'. (From Eurostat, 2013.)

Nitrates Directive, the Water Framework Directive, the National Emission Ceilings Directive and the European Commission (EC) Climate and Energy Package (European Council, 1991; European Parliament and Council, 2000, 2001). In general, WC-based systems are associated with lower stocking densities, higher N use efficiency, lower surplus N per ha, lower losses of nitrate to water and emissions of ammonia and nitrous oxide (a potent greenhouse gas (GHG)) to the atmosphere than N-fertilized grass-based systems. These differences can be largely attributed to lower N fluxes associated with the generally lower productivity of WC.

In studies of dairy production systems conducted during the 1980s and 1990s, the net margin per hectare of WC-based systems was between 65% and 95% that of intensively fertilized grassland. More recent analyses have found that the difference in net margin per hectare between WC and grass-only systems was not clear cut (Humphreys *et al.*, 2012). It was concluded that if the 1990–2010 trend in fertilizer N and milk prices continued, the WC-based system would become an increasingly more profitable alternative to intensive N fertilizer use for pasture-based dairy production. There is also evidence of increasing interest in the use of WC on farms, for example 50% of sown pastures in the west of France in 2009 were composed of a mix of grasses and WC compared with less than 10% in 1985 (Peyraud *et al.*, 2009).

The purpose of this review is to examine the potential for using WC in pasture-based systems in Western Europe in the context of rising fertilizer N costs and recently implemented environmental regulations curtailing fertilizer N use and stocking densities on farms. The review will identify the potential of WC to contribute to the future sustainability of ruminant production systems, the challenges that currently impede the use of WC in those systems and newly emerging solutions to those challenges.

BNF and Herbage Production

The quantity of reactive N fixed in temperate pastures with WC varies from 10 kg/ha to 300 kg/ha (Andrews *et al.*, 2007; Ledgard *et al.*, 2009), depending mainly on management factors that affect sward WC content. In general, potential herbage production from WC-based systems can be as high as from grassland grown with high rates of fertilizer N input. However, high rates of fertilizer N input generally have a negative impact on BNF as a result of the gradual decline of sward WC content and WC fixation activity. For example, in a 5-year study in Germany, fertilizer N input reduced sward WC content under a wide range of grazing/cutting management systems (Trott *et al.*, 2004). A 2-year study in Ireland carried out as part of the Legume Futures project found a reduction in WC fixation activity to be the most important factor reducing BNF in grassland receiving fertilizer N. Annual fertilizer N inputs of 86 kg/ha, 140 kg/ha and 280 kg/ha reduced BNF by 19%, 17% and 41%, respectively, relative to WC pastures receiving no fertilizer N (Burchill *et al.*, 2014). Meta-analysis of the effect of N fertilizer on WC content and BNF across a range of experiments revealed an exponential reduction in annual pasture WC content in response to annual fertilizer N inputs (Phelan, 2013). From 0 kg/ha to 200 kg/ha, the response is generally linear with a 1.5% reduction in WC content for every 10 kg additional fertilizer N input (Fig. 9.2). The main economic motivation for the inclusion of WC in swards is BNF, so maintaining the WC component of the sward for this purpose is an important aspect of sward management. For this reason, WC swards often receive no or relatively low inputs of fertilizer N, applied only in spring when the contribution of BNF to sward supply is low.

In temperate regions, the WC content of swards usually undergoes a typical cycle in the growing season that complements the growth of PRG. WC content tends to be relatively low in spring. It tends to increase steadily during late spring and summer to reach the highest levels during late summer and autumn, and decline again during the winter although this annual trend is influenced by management (Figs 9.3 and 9.4).

The seasonal fluctuations in WC content and BNF described above mean that some fertilizer N input may be necessary to increase herbage production in early spring, before BNF contributes substantially to sward growth. In the Netherlands, Schils *et al.* (2000a, b) found that WC-based grassland receiving fertilizer N input of 17 kg/ha in spring produced 95% of the herbage of a grass-only swards receiving annual fertilizer N input of 208 kg/ha. Likewise in Ireland, Humphreys *et al.* (2009) showed that WC-based pastures receiving between 80 kg/ha and 90 kg/ha of fertilizer N in spring had herbage production that was 92% of grass-only pastures receiving 226 kg/ha of N and 80% of grass-only pastures receiving 353 kg/ha.

As well as variation in BNF within years, there can also be considerable variation in BNF from year to year. For example, Burchill *et al.* (2014) found a two- to threefold difference in BNF between consecutive years. Therefore, while WC can make a valuable contribution to the availability of plant-available N in the soil, both the within- and between-year variation in the supply of N from this source creates challenges at farm level for the management of BNF and N nutrition of grassland. Management of BNF is mediated most directly through the management

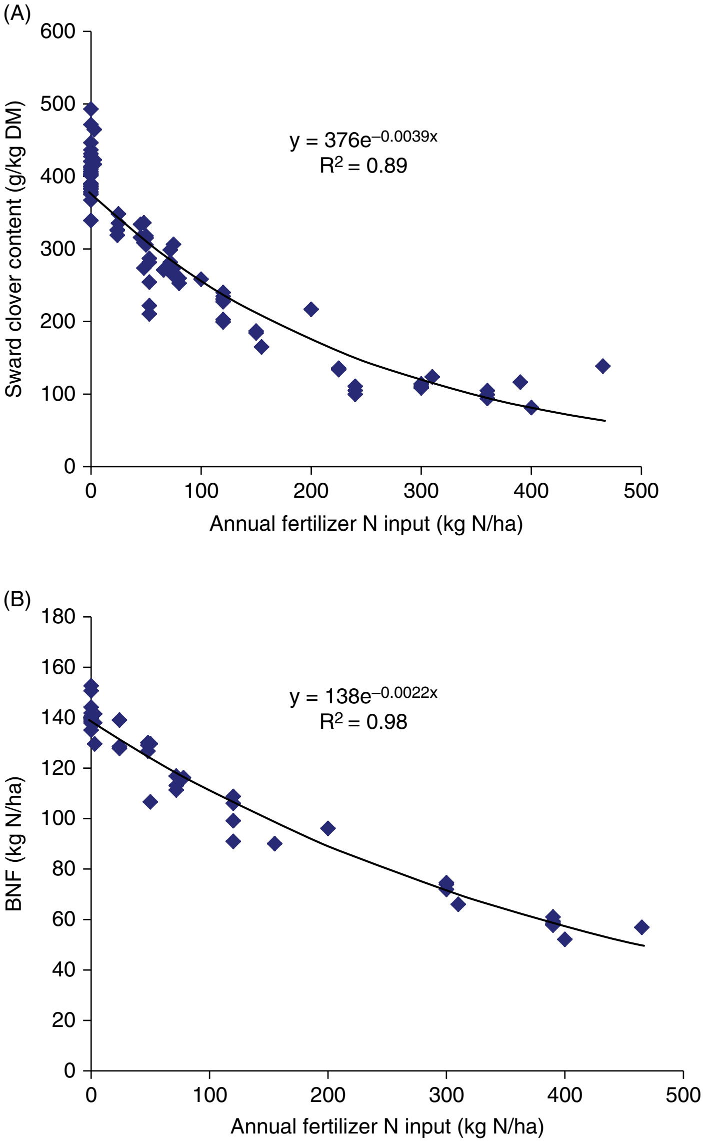

Fig. 9.2. Meta-analysis of the effects of annual fertilizer N input on (A) annual sward white clover (WC) content and (B) annual biological nitrogen fixation (BNF) in grass–WC swards ($P < 0.001$ in both cases). DM, Dry matter. (From Phelan, 2013.)

of WC in the sward. As BNF increases soil N over time, the grass component becomes more competitive and maintaining WC content of the sward can become difficult. This is generally not a major problem in temporary grass–arable rotations because soil N tends to be low after a sequence of arable crops and when soil N increases and WC content declines, it can simply be cultivated for arable production again. In permanent grassland, declining WC contents are more difficult to

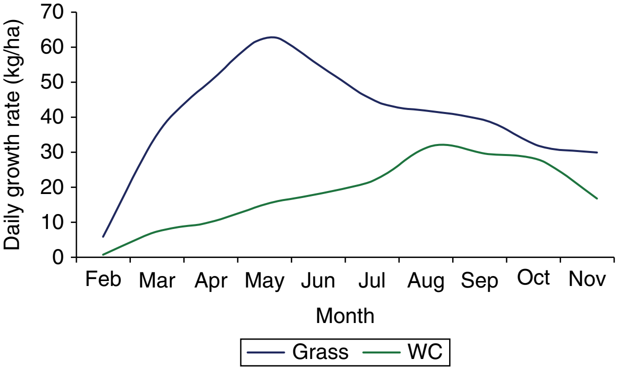

Fig. 9.3. Grass and white clover (WC) growth rates throughout the growing season in Ireland.

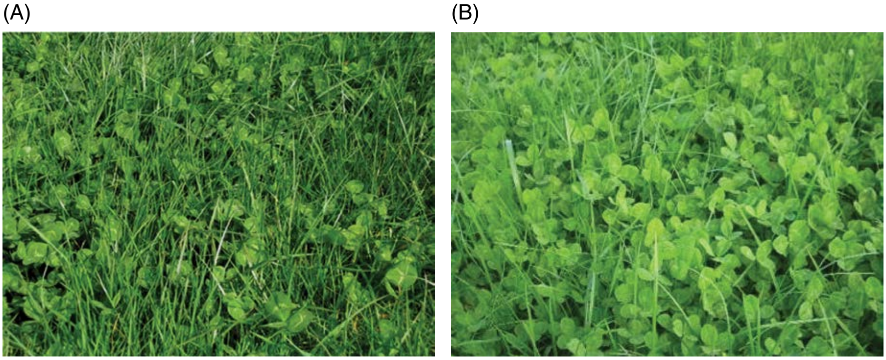

Fig. 9.4. Clover during April (A) and estimated to be 35–45% of dry matter in August (B).

manage and it is the lack of consistency of WC BNF from year to year that largely accounts for the general unpopularity of WC for permanent pastures in Western Europe.

Nutritive Value and Milk Production

WC herbage has higher nutritive value than PRG herbage and is preferentially grazed by dairy cows. This can increase cows' voluntary dry matter (DM) intake and consequently milk production. This increase can be attributed to a lower cell wall content and different cell wall characteristics of WC compared with grass (i.e. both a lower resistance of the WC herbage to chewing and higher rates of particle breakdown, digestion and passage rate through the rumen, leading to higher intake) (Steg *et al.*, 1994). Higher herbage intakes and higher milk yields of the WC-rich swards can also be attributed to higher crude protein concentration in the herbage DM. However, where fertilizer N use is not limited and where sward crude protein content is therefore high, very high WC contents

(400–500 g/kg DM) are required to get an increase in milk output per cow over that obtained from grass only.

Such high WC contents are rare. None of the systems-scale studies presented in Table 9.1 recorded a significant difference in milk output per cow between the WC-rich and N-fertilized grass-only grassland, because the WC content of herbage DM was typically not high enough to increase milk yield per cow. Even high WC content in grass–arable systems did not contribute to an improvement in milk output per cow (Aaes and Kristensen, 1994; Søegaard *et al*., 2001). It is unlikely that WC sward contents of 400–500 g/kg DM can be sustained in permanent, grazed WC-based grassland at the farm scale except for short periods during the late summer and early autumn. Therefore the use of WC compared with fertilized grass generally has little or no impact on milk output per cow over the course of an entire grazing season or entire lactation.

Management

The main economic motivation for inclusion of WC in grazed grassland is BNF. For a given site, the extent of BNF depends primarily on the WC content of herbage. Therefore an important aspect of managing WC in grassland is maintaining a high WC content throughout the year and from year to year. Grassland management entails multiple objectives such as: (i) maximizing nutritive value; (ii) maximizing herbage production; (iii) budgeting grassland areas to extend the grazing season length; (iv) maintaining a desirable sward structure; (v) protection of the soil; and (vi) maintaining the persistency of desirable botanical components of the sward from year to year. Sophisticated management guidelines have been developed to achieve the optimum balance between these multifaceted objectives, primarily for N-fertilized grass-only swards. Effective implementation at farm level requires training and skill. Indeed, one of the reasons for the decline in grazing on dairy farms in Western Europe is that indoor feeding systems reliant principally on maize silage, grass silage and purchased concentrates are simpler to implement at farm level, particularly where farms are fragmented into separate land parcels. Inclusion of WC in swards and maintaining the balance between species to ensure optimum WC content within years and from year to year substantially increases the complexity of grassland management.

Length of the grazing season

In WC-based pastures, herbage production is slower to commence at the end of winter than in grass-only pastures, particularly on cold, heavy soils. Optimum growth rates of WC are at temperatures between 20°C and 30°C, whereas those of PRG are 15°C–20°C. Therefore WC-based pastures can produce more biomass in summer than grass-only pastures, depending on the level of fertilizer N input.

In the typical Irish system of dairy production, compact calving and early turnout to pasture in spring brings clear economic advantages. WC-based swards receiving no input of fertilizer N have poor spring growth and relatively poor yields of first-cut silage (Frame and Newbould, 1986). Fertilizer N can be applied in spring at rates of 50–70 kg/ha to give improved production in spring without affecting annual production of WC-based swards (Laidlaw, 1980), although it can cause a lower WC content in swards later in the growing season (Frame and Boyd, 1987).

Post-grazing height under rotational grazing

Simulated grazing experiments have found that lowering defoliation height during the main growing season on WC-based grassland generally increases WC content, WC herbage production and total herbage production. While tighter grazing can have a positive impact on herbage yields, lowering the post-grazing height to 4 cm with WC-based swards did not affect annual milk yield under rotational grazing compared with post-grazing heights of 5 cm and 6 cm (Phelan *et al.*, 2013a). Both BNF and herbage production were higher with the tighter grazing treatment in the latter experiment. A post-grazing height of 4 cm is therefore recommended for WC-based grassland under rotational grazing.

Continuous versus rotational grazing

Under continuous grazing (set-stocking), managing sward height is more complex as it is a result of grazing pressure (the balance between herbage production and demand), so it reflects both grazing frequency and grazing severity. However, lower sward heights are associated with higher sward WC contents. Gibb *et al.* (1997) found that under continuous grazing, maintaining a sward height of 7 cm achieved higher intake rates in dairy cows than heights of either 5 cm or 9 cm.

Rotational grazing generally promotes sward WC contents better than continuous grazing. Hay *et al.* (1989) compared WC-based swards grazed with ewes either rotationally or continuously in New Zealand and found that the rotationally grazed swards had higher mean annual WC content (26% compared with 6%) and stolon DM mass (46 g/m^{-2} compared with 14 g/m^{-2}). Davies (2001) reported that switching from continuous to rotational grazing caused an increase in WC content and WC stolon size, and Harris (1987) reported that allowing a continuously grazed sward a rest of 1 month in late summer/autumn could increase WC content five- to tenfold. Therefore, rotational or strip grazing should generally be used on WC-based pastures. If continuous grazing is used, a rest (ungrazed) period can increase WC content.

Cutting versus grazing

WC-based swards tend to be relatively more productive under cutting than under grazing regimes, because cutting tends to deplete soil N reserves, which increases BNF and the competitiveness of WC within the sward (Frame and Newbould, 1986). In contrast, under grazing, a large proportion of N taken up by the sward is directly recycled in excreta of the grazing livestock. Animal treading and selective grazing affects the WC content of grassland. Under grazing, transfer of fixed N from WC to grass can be higher and the competitive ability of WC is lower than under cutting. Hence, strategic harvesting of herbage for conservation as winter feed benefits the competitiveness and persistence of WC in swards.

Rotation length in rotational grazing systems

In the UK and Ireland, the recommended grazing rotation lengths are approximately 21 days in late spring and summer and increase to approximately 35 days in autumn. One of the advantages of WC is the lower rate of decline of nutritive value with increasing maturity compared with PRG. Digestibility and voluntary DM intake of grasses decreased with each week of increased rotation interval by approximately 20 g/kg and 0.2 kg/day, respectively, while the rate of decline of WC herbage was half that of PRG (Peyraud *et al.*, 2009). This can make WC-based pastures easier to manage than grass-only pastures; rotation lengths can be longer without adverse effects on the nutritive value of the sward, particularly during the late summer and autumn when the PRG component of the sward remains largely in the vegetative state (much less likely to produce flower and seed heads).

Rotation lengths are often extended in autumn to increase the mass of herbage available on the farm. By this means, grazing can be extended into the late autumn and early winter. Phelan *et al.* (2014) studied late summer and autumn grazing, examining the impact of rotation lengths between 21 days and 84 days on herbage production, WC persistence and carry-over effects into the following spring and early summer. A 42-day rotation length during the late summer and autumn gave optimum herbage production, nutritive value, WC content and stolon mass, and enabled greater management flexibility in extending the grazing season into the late autumn and early winter.

Autumn and winter management

WC can be the dominant component of pasture during the late summer and autumn. Sward WC content typically declines in winter. Its leaves tend to be positioned lower in the sward than grass leaves. As a result WC is less competitive with grasses for light during the winter and early spring. Hence, sward management in late autumn, winter and early spring is critical for the persistency of WC in grassland. A prolonged period without defoliation during the winter has a pronounced negative effect on WC content of swards (Laidlaw and Stewart, 1987; Laidlaw *et al.*, 1992). In contrast, grazing during the winter increased BNF and herbage DM production during the following growing season by 35% and 10%, respectively (Phelan *et al.*, 2013b).

The WC content of swards and bloat

Grassland with very high WC content is sometimes associated with bloat. Bloat is mainly a problem when there is a sudden introduction of WC into the diet of grazing ruminants, for example where livestock are moved from WC-free to WC-rich swards. The incidence of bloat is negligible where the rumen flora of grazing livestock has become adapted to a WC-rich diet where the WC content of the sward increases steadily over the course of a growing season.

The WC content of swards, sward renovation and over-seeding

In grass–arable rotations, the relatively high WC content of swards is maintained when leys are laid down for periods of less than 5 years. In permanent grassland, WC is often not as persistent as the accompanying PRG. As an insurance against WC die-out in permanent grassland, Humphreys *et al.* (2008, 2009) demonstrated in a full-scale production system spanning 11 years that WC can be established and maintained by over-seeding into grass silage stubble. The WC content can be maintained by a programme of over-seeding of about one-fifth of the permanent grassland area each year, securing consistent contribution of WC from year to year.

Conclusions – management

An important obstacle to the wider adoption of WC in permanent pastures is inconsistent production within and between years associated with variable WC persistence, herbage production and BNF. Management practices to promote the persistency of WC in permanent pastures include low N fertilization, reseeding or over-sowing at least one-fifth of the grassland area each year and alternate harvesting for silage within and between years. In temporary grass–WC leys, persistency of WC is not as big a problem but can still be improved by breaks of over 2 years between grass–WC leys. Low post-grazing height should be used (4 cm under rotational grazing), particularly during the winter and spring. A long grazing season can be achieved by applying mineral N to swards in the late winter and early spring and increasing rotation lengths to 42 days in the autumn under rotational grazing. Bloat is generally not an important impediment when livestock are conditioned to grazing WC-rich grassland throughout the growing season.

Economics

It was pointed out above that the substantial increases in the cost of fertilizer N increase the economic performance of WC-based systems compared with grass only. Humphreys *et al.* (2012) showed that dairy production based on N-fertilized grassland was consistently more profitable than WC-based production between 1990 and 2005, which is in general agreement with many previous studies in the north-west of Europe. However, with the steady increase in fertilizer N prices relative to milk price, the difference between N-fertilized and WC-based systems was less clear cut between 2006 and 2010. Projecting into the future and assuming similar trends in fertilizer N and milk prices to the previous decade, this study indicated that WC will become an increasingly more profitable alternative to fertilizer N for pasture-based dairy production.

Environmental Impact

The manufacture of synthetic fertilizer N accounts for 2% of global fossil energy use. There is a strong link between energy prices and fertilizer prices. For environmental as well as economic reasons, the challenge for pasture-based farming systems is to become more N efficient and less reliant on synthetic fertilizers. Energy efficiency, calculated as herbage unit of feed for lactation (UFL) produced per 1 MJ of energy consumed is three times higher for WC–grass pastures than for fertilized grass pastures (2.5 UFL/MJ versus 0.8 UFL/MJ; Besnard *et al.*, 2006).

Losses of N to water

Dairy production systems in Europe are to a large extent based on ley–arable rotations (Vertés *et al.*, 2007). As a consequence of the soil N build-up, the ploughing of grass–WC mixtures is followed by a rapid and extended period of N mineralization as a source of nitrate for leaching. This release of nitrate is often substantial in the first year after cultivation, with N fertilizer replacement values often exceeding 100 kg/ha (Eriksen *et al.*, 2008) and relatively little variation in this value due to grassland age or management, even where there are large differences in grassland fertilization (Eriksen, 2001; Hansen *et al.*, 2005). Mineralization of N following grassland cultivation is a two-stage process with a rapid mineralization over the first 160–230 days, followed by a second phase with mineralization rates two to seven times lower than in the first phase (Vertes *et al.*, 2007). Intense rotary cultivation of the grass sward prior to ploughing can cause quicker availability and better synchrony between N mineralization and plant uptake (Eriksen and Jensen, 2001). The release of large quantities of N from the grass–WC residues means that fertilizer N input to subsequent cereals can be reduced or even eliminated in the first following crop. Catch crops are useful during winters in the arable phase of the crop rotation to reduce nitrate leaching, by removing soil mineral N from the soil profile before winter drainage starts (Hansen *et al.*, 2007).

The general consensus is that the size of N losses to water from permanent pasture-based systems (as nitrate, ammonium, organic N) under a particular set of circumstances of soil, climate and system management depends largely on the amount of N circulating within the system. It is also widely accepted that it does not matter whether the initial source of N is synthetic fertilizer N or from BNF (Ledgard *et al.*, 2009).

Ammonia

Ammonia gas emission from agricultural sources and subsequent re-deposition contributes to the eutrophication and acidification of water bodies and to indirect nitrous oxide emissions. A recent N balance study carried out under the Legume Futures project found that ammonia gas was the largest pathway for environmentally damaging N loss from a WC-based system in Ireland (Burchill *et al.*, 2016). The main sources of ammonia losses on grazed pasture-based farms are from urine patches in grazed swards, fertilizer N applications (i.e. urea), livestock winter housing and the storage, agitation and field application of manures. At the farm scale, as with N losses to water, the intensity of urine patches or slurry application to fields typically depends on the farm stocking density; the more N that is circulating within the system, the greater the extent of ammonia losses. Another source of ammonium for volatilization to ammonia is fertilizer N, particularly ammonium-based fertilizers and urea. Although this issue has not been investigated to any great extent, Ledgard *et al.* (2009) expressed the opinion that the pulse of N in soil following the application of fertilizer N results in greater risk of ammonia loss than the steady release from mineralization of N from WC residues in soil. From this perspective, it seems probable that WC-based grassland carries less risk of ammonia losses than grassland receiving synthetic fertilizer N when all other conditions, such as stocking density, are common to both systems.

Greenhouse gases (GHGs)

Nitrous oxide is a potent GHG with a global warming potential 298 times higher than carbon dioxide over a 100-year time horizon (Solomon *et al.*, 2007). In addition, nitrous oxide currently is the single most important stratospheric ozone-depleting substance and is expected to remain the largest throughout the 21st century (Ravishankara *et al.*, 2009). WC has the potential to impact on nitrous oxide emissions from grassland due to its influence on soil N availability. As with N losses to water and ammonia emissions, at comparable levels of production indirect nitrous emissions resulting from N recycled in livestock excreta are similar for both WC-based and grass pasture. Nevertheless Li *et al.* (2011) found a trend for lower direct and indirect emissions from grazed WC than from N-fertilized grassland. Emissions were 16–19% lower from the WC-rich swards although the stocking density of dairy cows was similar. The lower emissions can be explained by the lower input of N fertilizer, by the process of BNF being a negligible source of nitrous oxide, and by the greater efficiency of WC-rich swards in transforming N into biomass. Following a comprehensive review of the topic, Rochette and Janzen (2005) suggested that evidence for direct release of nitrous oxide from BNF was inadequate to justify a nitrous oxide emission factor for BNF similar to that of fertilizer N.

Carbon footprint calculated by life cycle assessment (LCA) was used to compare GHG emissions from pasture-based milk production based on WC-rich or N-fertilized swards (Yan *et al.*, 2013). Emissions of both nitrous oxide and carbon dioxide were lower in WC, whereas emissions of methane (per kilogram of energy corrected milk) were similar in both systems. Replacing fertilizer N by BNF was shown to have the potential to lower the carbon footprint of pasture-based milk production.

Conclusions – environmental impact

From an environmental perspective, the main advantage of WC-based systems stems from the replacement/reduction of fertilizer N by BNF with all the effects associated with the reduced production of fertilizer. There is generally less N circulating within lower stocked WC-based systems resulting in lower N losses to water and lower ammonia and methane emissions to the atmosphere; losses that are often closely related to stocking density. In addition, direct emissions of nitrous oxide are lower from WC-rich grassland compared with N-fertilized grassland at the same level of productivity and substantially lower than intensively fertilized grassland. Using LCA, a number of studies have shown that WC-based systems have between 11% and 26% lower carbon footprint per litre of milk compared with N fertilized systems, the biggest differences being with more intensive systems reliant on high input of fertilizer N.

Conclusions

WC generally does not make a significant contribution to forage production on conventional farms in Western Europe, but there is considerable potential for growth due to rising fertilizer N costs and implementation of environmental regulations curtailing fertilizer N use and stocking densities on farms. With rising energy and fertilizer N costs, it is likely that WC will become an increasingly profitable alternative to intensively fertilized grass for pasture-based livestock systems in the future. The economic competitiveness is due to lower costs of production that compensate for the lower productivity of WC-based systems. Lower productivity, lower stocking densities and less N circulating within the system contribute to lower losses of N to water and ammonia and GHGs to the atmosphere. WC has the additional advantage of lower direct emissions of nitrous oxide (an important GHG) at the same level of productivity and substantially lower direct and indirect emissions compared with intensively fertilized grassland. From the perspective of the overall future sustainability of pasture-based ruminant production, WC-based systems offer economic competitiveness, lower energy dependency and lower environmental impact.

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