

OPTIMIZING PRODUCTIVITY FROM PASTURE BASED SYSTEMS – A CASE STUDY FOR HIGH FORAGE FEEDING LEVELS

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INTRODUCTION

The global population is expected to increase from 7.2 to 9.6 billion by 2050 (UN, 2013). This 33% rise, coupled with increased demand for dairy products worldwide due to increasing global standards of living, means that the demand for agricultural products will increase by about 70% in the same period (FAO, 2009). However, this increased demand comes concurrent with the realization that consumers want agricultural products that are produced in a sustainable and environmentally benign manner (Godfray et al., 2010). To help meet this 70% increase in demand it is expected that milk production will increase from 644 million tons (in 2006) to 1,077 million tons (by 2050; Alexandratos and Bruinsma, 2012). Livestock products provide 17% of global kilocalorie consumption and 33% of global protein consumption and are therefore important agricultural commodities for global food security (Rosegrant et al., 2009). The return on human edible protein inputs, for dairy cattle, is larger than 1, with a typical range of 1.4 to infinite; infinite being those diets containing no human edible protein i.e. grazing (Dijkstra et al., 2013; Karlsson et al., 2018). This indicates that dairy cattle add to the total human food supply in a manner that does not compete with food resources for humans.

Irrespective of this powerful contribution to food security, popular press continuously associates milk production with inefficient use of natural resources. Livestock production uses 75% of grassland land (Foley et al., 2011) of which one third of the land area is arable and two thirds are grasslands and rangelands (Steinfeld et al., 2006), consumes 35% of grain products (Alexandratos and Bruinsma 2012) and emits 14.5% of global greenhouse emissions (Gerber et al., 2013). As the population of the planet and demand for human-edible plant resources is increasing rapidly, livestock production in the future might not have access to this arable land and inventory of grain products. Therefore, the ability of ruminants to turn human inedible fibrous feed resources and by-products from the human food chain, into edible human food of high biological value, may become more significant. In a recent analysis, forage, particularly pasture, was the largest component of the Irish cow diet, typically accounting for 82% of the diet on a dry matter basis (O'Brien et al., 2017). Grazed pasture was the dominant source of forage from March to October and usually contributed 95% to 97% of the diet as fed in the summer period. Of course, there were periods of the year when average contribution of concentrate was substantial such as the early spring months of January and February (30% to 35% of dry matter). This high utilization of non-edible human resources can be achieved in synchrony with maintaining a profitable farm business structure. Due to climatic factors, such dependence on grazing is not possible in many parts of the world however, there is significant opportunity to increase forage inclusion levels in many

ruminant diets. This trend is already being seen in the industry as in a feed industry professionals survey (Chase, 2017), 91.5% of responders stated that in the last 10-15 years, the level of forages fed in the dairy herds they work with has increased. By describing certain management practices, and new insights recently gained in efficient pasture-based systems, strategies to achieve higher forage (human inedible) diets will be proposed.

PLANT MATURITY

The timing of harvesting, which in pasture-based systems is achieved directly by the ruminant, is of vital importance to both plant and animal performance. Perennial ryegrass (PRG) is the predominant species of grass grown in Ireland. As PRG is a '3-leaf' plant, only 3 green leaves exist at any one time with the initiation of a new leaf coinciding with senescence of the oldest fourth leaf (Donaghy, 1998; Figure 1). If the plant matures past the '3-leaf' stage, pasture wastage will therefore occur with overall pasture quality also diminishing. Therefore, the time required for the plant to reach this stage sets the maximum grazing interval (i.e. rotation length). This onset of senescence drives implementation of management practices that aim to maintain the pasture in an immature stage. Fulkerson and Donaghy (2001) also show that, the metabolizable energy (ME) level declines gradually from the 1-leaf stage to the 4-leaf stage, 2.62 Mcals/kg dry matter (DM) to 2.15 Mcals/kg DM, respectively. This would suggest to harvest as early as possible however, studies have shown that subsequent regrowth is suppressed if plants are defoliated before the 2-leaf stage of regrowth. In intensive pasture based systems, high pasture utilization is favored and a post grazing sward height of 4 cm is often targeted. This forces the plant to rely on and deplete stored water-soluble carbohydrate (WSC) reserves to grow new shoots. When 75% of the first new leaf has regrown the plant then has adequate photosynthetic capacity for growth and maintenance and WSC content begins to replenish. If the grazing rotation is too short, and animals enter the paddock prior to the 2-leaf stage, there will not have been sufficient time for the concentration of WSC to replenish. This will affect overall productivity of the swards, as regrowth will be suppressed, while also having the potential to reduce sward persistence in the longer term. Thus, replenishment of WSC reserves and the gradual decline in ME sets the optimum harvesting interval at the 2–3 leaf stage. From the criteria set out above, the grazing interval can be expressed in a similar morphological stage of growth or pasture mass (discussed later), irrespective of season or location and has been shown to maximize growth and persistence of ryegrass and optimize the levels of most nutrients in pasture required by dairy cattle including protein, WSC, calcium, potassium and magnesium (Fulkerson and Donaghy, 2001).

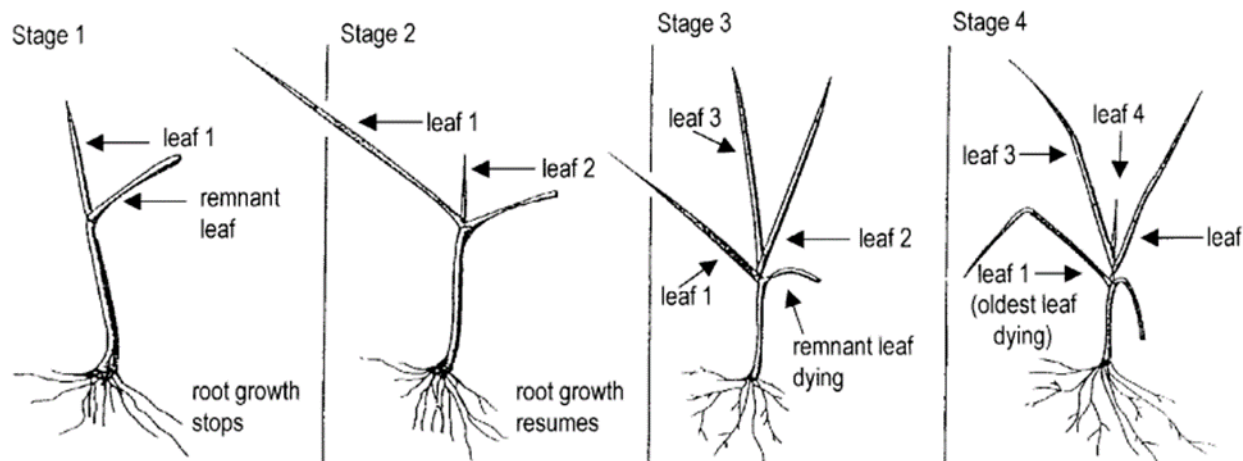


Figure 1. Regrowth of a ryegrass tiller following defoliation (Donaghy, 1998)

A similar approach for setting criteria for alfalfa/grass stands could be considered. The optimization of both yield and quality is of high importance when selecting a harvesting time. However, yield and quality is contradictory as the two variables are not in synchrony, maximal yield peaks around day 35 of regrowth whereas quality begins to decline from day 15 onwards (Undersander, 2017). Work in Italy has shown that indigestible NDF levels increase as alfalfa stands were harvested with a 21-d cutting schedule, at a pre-bloom stage; with a 28-d schedule, at about first-bloom stage; and at a 35-d cutting schedule, full bloom (15.5, 17.2, and 18.3 iNDF % DM, respectively; Palmonari et al., 2014). Further, it was shown that cows fed early-cut orchardgrass-based total mixed ration (TMR) had greater DMI, milk production, and milk protein than those fed late-cut orchardgrass-based TMR (Cherney et al., 2002). The fiber digestibility of early-cut orchardgrass was much greater than late-cut orchardgrass, contributing to the improved dry matter intake (DMI) of cows on the early-cut orchardgrass TMR. Therefore, if high forage rations are to be implemented optimization of harvesting time needs to account for forage maturity, yield, and NDFom content and digestibility.

HOW TO CONTROL PLANT MATURITY

To continuously achieve this optimum harvesting interval, both physical labor and mental commitment is required. In the context of pasture-based grazing systems, the PRG plant can have a large range in daily growth rates (0 - > 200 kg DM/hectare/day) depending on a number of factors such as climatic, soil temperature, nutrient administration etc. This makes the grazing management process very dynamic and complex. In recent years the development of reliable, easy to use web based decision support tools has facilitated improved feed budgeting and grazing management on grassland farms (e.g. PastureBase Ireland; PBI; Hanrahan et al., 2017). The farmer enters weekly pasture cover estimations, attained using a favored measuring technique, from which PBI produces a series of daily and periodic outputs (Figure 2). Some of these outputs include:

- Spring rotation planner - used from turnout until grass growth equals herd demand
- Pasture wedge - used to control grass supply during mid-season taking into account herd demand, rotation length and post-grazing residual. Allows early identification of pasture surpluses and deficits
- Autumn feed budgets - used to maximize the amount of grazed grass utilized while at the same time ensuring that the grazing season is extended into late-November/early-December

Outputs such as above can support the farmer in the day-to-day decisions required such as pasture allocation, concentrate supplementation and winter forage preservation. These types of tools allow farmers to enhance their grazing management skills through grazing pasture at the right stage ultimately increasing DMI and quality and the achievement of higher performances from pasture-based systems (O'Donovan and Dillon, 1999). An additional benefit, as each individual farms database develops, evaluation of DM yields at the paddock level can occur which can help determine high or low performing paddocks and associate different causes such as cultivar, soil fertility, etc.

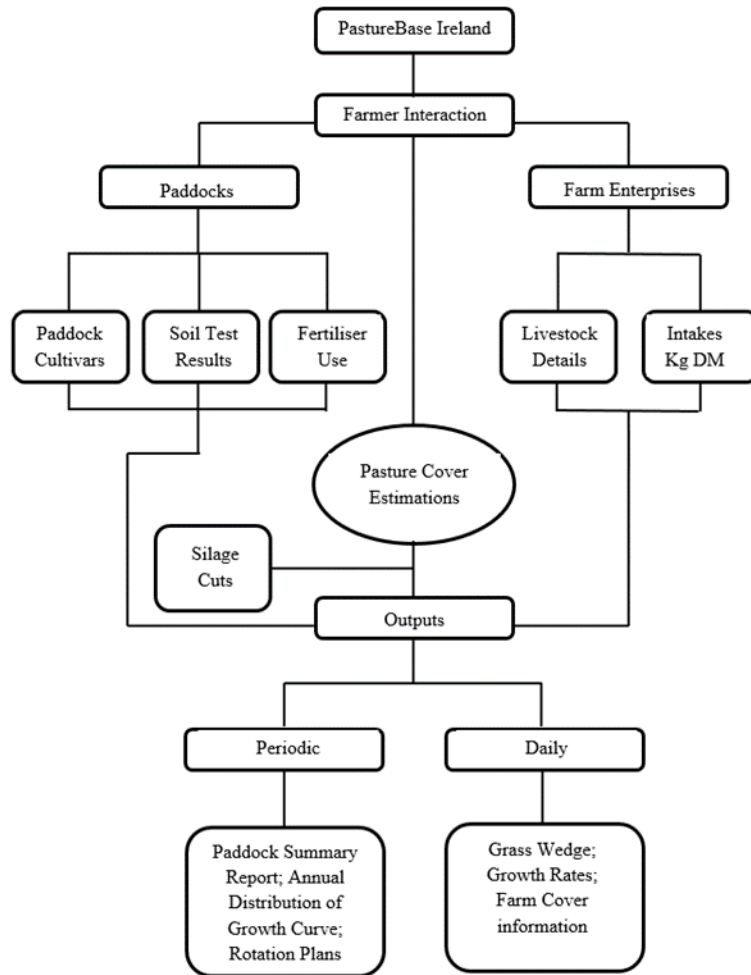


Figure 2. Flow diagram of grazing management web based decision support tool, PastureBase Ireland (Hanrahan et al., 2017)

Similar strategies have been proposed and can be implemented to maintain high quality forage mixtures in TMR systems. “Dynamic harvesting” is a field organizational method that aims to capture each field when forage quality is high with requirement for the process to be dynamic not static (Lawrence, 2018). This strategy helps mitigate some of the weather related issues with harvesting time. The ‘dynamic harvesting’ method aims to reduce the number of predetermined fields for non-lactating or heifer feed (poorer quality) and therefore help achieve the required high quality forage needed for high-producing animals. Another example of this involves ‘sequential’ versus ‘staggered’ cutting system for alfalfa stands. A study in California demonstrated that the number of high quality cuttings was increased using a ‘staggered’ cutting order. Other areas of opportunity exist such as forage storage strategies to help allocate high quality forage for high producing animals.

ANIMAL PERFORMANCE AND FORAGE DIGESTIBILITY

Once targets are set and implemented successfully, highly digestible forage can be consistently grown and harvested. Pasture mass is a quantitative measure, utilized to indicate plant maturity. It is a measure of the quantity of pasture DM, above 4 cm, in a given area and typical expressed as kg DM/ha. O’Donovan (2000) developed targets for average pasture mass based on the factors described above (see plant maturity) with the 3-leaf stage or optimal entry time typically reached at a pasture mass of 1,500 kg DM/ha. Many experiments utilizing lactating dairy cattle at Teagasc Moorepark, Ireland, have shown that this pasture mass (or lower) improves animal performance (McEvoy et al., 2010; Wims et al., 2010). Further a number of in-vivo digestibility studies using sheep have shown that there is a decline in DMI, DM digestibility (DMD), organic matter digestibility (OMD) and NDF digestibility (NDFD) as pasture mass increases past the 3-leaf stage (Garry et al., 2014; Beecher et al., 2018). In the Beecher et al., (2018) experiment, on the high quality PRG swards, the authors noted the importance of fiber digestibility, as the measured NDFD had a significant positive relationship with DMI of the sheep. Pasture mass is not the only factor influencing sward digestibility. Many agronomic conditions (e.g. light, heat, water stress, soil type), plant genetics and season can impact digestibility and must be accounted for. The effect of season on feed chemistry and aNDFom fractionation is shown in Table 1. Pasture mass and CP were not significantly different across season however, the aNDFom concentration in autumn swards was elevated. The rate at which the potentially digestible (pdNDF) pool degraded was faster for spring compared to autumn pasture (9.53 versus $7.76 \pm 0.6\%$ hour⁻¹, respectively). Furthermore, the extent to which aNDFom was digested was greater for spring compared to autumn (9.75 versus $15.50 \pm 0.44\%$ uNDF, respectively). Predictions of the ME per kg of DM of the swards showed that spring pasture had a higher energy density ($P < 0.01$) and also supplied a higher amount of grams of Metabolizable Protein (MP; $P < 0.01$) to the animal.

Table 1. Effect of season on pre-grazing yield and nutritive value of pasture swards

Variable ¹	Spring	Autumn	S.E.	P-value
Pasture mass (kg DM ha ⁻¹)	1,691	1,494	137	0.228
Crude protein (g kg ⁻¹ DM)	214	190	10	0.106
aNDFom ¹ (g kg ⁻¹ DM)	325	355	8	0.006
Rate of degradation (% hour ⁻¹)	9.53	7.76	0.60	0.021
uNDF ² (% aNDFom)	9.75	15.50	0.44	<.001
ME ³ (Mcal kg ⁻¹ DM)	2.68	2.52	0.04	0.003
MP ⁴ (g kg ⁻¹ DM)	121	112	2.2	0.004

¹aNDFom = Neutral Detergent Fibre; ²uNDF = undigested NDF; ³ME = Metabolisable energy; ⁴MP = Metabolisable protein

This analysis shows that aNDFom as a fraction can behave differently, even within plant species. The fraction can differ in degradation rates and the extent to which it degrades. Season can affect these characteristics, independent of pasture mass. Increased degradation of aNDFom can affect energy supply to the animal through increased volatile fatty acid production and increased flow of microbial protein, while also affecting DMI. Therefore, the measurement of pasture mass alone, is not dynamic enough to capture the variation and it is essential that determination of these aNDFom fractions are included in all basic pasture feed analyses. When swards such as those described above are fed, impressive performance can be achieved. Previous research indicates that with high yielding dairy cows in early lactation on pasture only, grass DMI of 17 kg can be achieved supporting milk production of 30 kg/d, under good grazing conditions (Kennedy et al., 2003, McEvoy, 2008). Additionally, multiyear lactation long grazing experiments have demonstrated exemplary performance per cow (410 kg milk solids; MS; kg fat + protein) and per hectare (1,165 kg MS), when lactating cows were maintained on a > 95% pasture diet throughout lactation (Dineen, 2017). When a mixed sward of PRG and white clover was available, performance per cow and per hectare increased further (460 kg MS/cow and 1265 kg/ha). These animals will typically weigh 500 to 530 kg and can consistently consume 18 kg DM/d from pasture (3.4% to 3.6% BW) with a number of the animals within these populations producing their body weight in milk solids on a > 95 % forage diet. To achieve such performance from high forage diets, forage digestibility is key. Therefore, the above data supports that we should maximize harvesting highly digestible feeds to help support high performance.

In the 'high forage feeding' survey (Chase, 2017) mentioned previously, 85% of responders cited 'forage quality not being good enough' as the main reason that they would be hesitant to feed higher levels of forages in lactating cow ration. Similar data exists for the effect of NDF digestibility on animal performance in TMR systems. Both Dado and Allen (1996) and Oba and Allen (2000) have identified increased NDF digestibility as being positively associated with DMI and milk production. Considerations are required for both timely harvest and selection of forage varieties when implementing high forage diet rations.

RUMEN TURNOVER

Over the past 2 years, we have conducted some studies in Ireland on cattle consuming high quality PRG pastures. The average PRG pasture used in the experiments varied in aNDFom and was generally grazed between 30% and 35% aNDFom with sugar levels between 10% and 15%. In grasses, the veins with their associated sclerenchyma strands, especially in an enlarged midrib when present, provide the leaf with tensile strength. These strands can link to the vascular tissue and form strong 'I' girder engineering structures. This acts to strengthen epidermis attachment, and slow the splitting of leaves when consumed. To allow for more microbial digestion and passage out of the rumen, rumination and particle size reduction are considered essential functions to increase surface area of these feed particles. However, in the immature temperate grasses, this 'I' structure is not completely formed. Instead, epidermis cells are attached by mesophyll cells, which are readily digested or break allowing the epidermis to be shed. Also, temperate grasses have straight-sided epidermal cells which allows easy splitting along the middle lamella. This allows the leaf to rapidly fragment into long vascular strands. In the immature pastures, rumination and chewing is still important, but the rate of digestion of the fast pool of aNDFom and the size of the pool alter the relationship between particle size reduction and digestion due to the speed of digestion. For example, when we fractionate the aNDFom of the spring pasture into pools, the kd for the fast pool aNDFom was 0.24/h and represents 66% of the aNDFom in this forage. Using the aNDFom passage rate equation in the CNCPS v6.55, an equation developed for the NorFor model (NorFor, 2011), the calculated passage rate for these cattle was 0.017/h. Thus, when calculating the simple integration of this relationship ($kd/(kd+kp)$), $(0.24/(0.24+0.017)) = 0.934$, the result is nearly 94% of the fast pool is digested in the rumen. The rate with which disappearance is occurring, can have a dramatic effect on rumen emptying and consequently intake, due to the space created by microbial degradation of the forage independent of particle size reduction. Since the epidermis cells are attached by mesophyll cells, there is lower resistance against the microbes to digest the aNDFom and this is described mathematically by the size of the fast pool of digestible aNDFom. This will ultimately result in a lower proportion of the digestible aNDFom escaping fermentation. These calculations are in close agreement with the sheep in-vivo total tract NDF digestibility (>80%) reported in Beecher et al., (2018) at similar pasture quality and pasture mass.

COMPLEMENTING HIGHLY DIGESTIBLE FORAGES

Despite these advances in grazing management technologies and cultivar selection, pasture availability can still be limited in the spring, which leaves a requirement to supplement the diet of the lactating cow during this period. This supplementation management practice, can also be utilized tactically in regards to the early spring feed-budgeting scenario, as offering concentrate has the additive effects of maintaining the grazing rotation at the target length until grass growth exceeds herd demand. Nationally the average contribution of concentrate is substantial for the early spring months of January and February (30% to 35% of DMI; O'Brien et al., 2017). Additionally in mid-season and autumn periods of the year pasture availability is dependent on temperature

and precipitation which subjects pasture-based production systems to climatic variations (Roche et al., 2009). In these circumstances, supplements can be utilized to ensure that cows are not underfed when her requirements are not met by pasture availability (Bargo et al., 2003). In a modeling exercise, to establish the financially optimum strategy for Irish dairy farms, it was concluded that on average across a number of stocking rate levels, a concentrate supplementation of 600 kg of DM/cow/yr was the most profitable for most of the different concentrate, silage, and milk price scenarios (Ruelle et al., 2017). However, there was a tipping point in their analysis as continuing to increase concentrate supplementation to 900 kg of DM/cow/yr led to a decrease in the farm profit. In the future the analysis should consider the potential human edible proportion of this supplementation and its availability and not just the profitability.

In practice, the mean response to concentrate supplementation is extremely variable. Some of this variation is attributed to a reduction in pasture intake (i.e., substitution effect) when supplementary feeds are consumed (Leaver, 1985; Stockdale, 2000; Bargo et al., 2003; Sheahan et al., 2011). Studies have also shown animals reduce their time spent grazing when fed a supplement; 12 min/kg supplement (Bargo et al., 2003). Milk response (MR) to concentrate supplementation, which is the increase in milk yield per kilogram of concentrate offered, is reportedly lower in spring compared with summer (Stockdale, 1999) because of the higher energy content of spring grass. Low substitution rates will result in greater MR to the supplement offered, thus making it more economical to offer the supplement to the animals. A reduction in fiber digestion, with the inclusion of starch in the ration when pasture cows are offered supplement, has also been suggested as a cause of the variation in response and potentially a causative link to the substitution effect (Bargo et al., 2003; Doyle et al., 2005; Nousiainen et al., 2009). As suggested earlier, when cattle are fed these highly digestible forages the extent of digestion and the rate with which disappearance occurs allows for faster rumen emptying because of the space created by microbial degradation of the forage. This may have important effects on the cattle stimulation to ruminate and chew. While pasture-based animals achieve a satisfactory intake of aNDFom the amount of supplementation and substitution effect can dramatically alter this. For example, preliminary data from an omasal flow study conducted during mid-lactation (Dineen et al., unpublished), show that the animals on a grass only diet achieved an intake of 16.25 kg DM of which 5.9 kg was aNDFom (1.16% of BW). Through utilization of the rumen evacuation technique, we were able to determine that ruminal aNDFom levels were on average 4.8 kg (0.95% BW). When a starch treatment (3.32 kg DM/cow rolled barley) was offered to the animals, a large substitution effect occurred. Total DM intake was still higher 16.82 kg DM however, grass DMI reduced to 13.5 kg DM. This resulted in a lower overall aNDFom intake (5.5 kg; 1.10% BW). Ruminal aNDFom content was higher at 5.4 kg (1.09 % BW) indicating reduced fiber degradation capability as total aNDFom intake was lower for this treatment. As we know, aNDFom intake is an important variable in terms of allowing the animal to self-buffer, a highly fermentable starch load and a reduction in aNDFom intake might overwhelm this capacity and contribute to a reinforcing loop of reducing rumen pH and consequently a reduction in aNDFom digestion. In a project carried out this past summer, the supplementation of a feed ingredient rich in soluble fiber to grazing dairy cows was assessed. As Ireland experienced its worst drought in 40 years the diets formulated where

different to what was observed. However, when the rain returned and the grass turned back to its lush green self, there was a beneficial effect to supplementing this type of ingredient. A similar example in the TMR system approach is when highly digestible brown midrib corn silage is included in the ration. At equivalent diet inclusion rates as a conventional corn silage variety that has a slower rate of degradation, they will have very different effects on rumination and chewing (Oba and Allen, 2000). If this is exacerbated by poor management practices such as sorting, overcrowded head rails, long time away from pen, the impact on the animal's ability to buffer the system could potentially be detrimental. To overcome these situations, commonly chopped straw has been introduced into the diets. While this may be successful to mitigate the issue, is it the optimal way to complement these highly digestible forages? More research is required into this area. Therefore, considerations are required and rethinking of current recommendations when formulating diets including highly digestible forages.

CONCLUSION

Pasture-based systems and high forage diets have the potential to play a significant role in meeting the increasing global demand for food. The demand for human-edible plant resources is increasing rapidly as the population of the planet also increases. These management practices have the ability to utilize and convert non-human edible forages into high quality human edible protein. However, there is a requirement to enhance the efficiency and productivity of pasture-based and high forage inclusion systems through refinement of certain management and nutritional practices that have been discussed in this paper.

REFERENCES

- Alexandratos, N. and J. Bruinsma. 2012. World Agriculture towards 2030/2050: the 2012 revision (No. 12-03). ESA Working paper, Rome, FAO.
- Bargo, F., L. D. Muller, E. S. Kolver, and J. E. Delahoy. 2003. Invited review: Production and digestion of supplemented dairy cows on pasture. *J. Dairy Sci.* 86:1–42.
- Beecher, M., R. Baumont, M. O'Donovan, T.M. Boland, J. Aufrere, C. Fleming, N. Galvin, and E. Lewis. 2017. Effects of harvesting perennial ryegrass at different levels of herbage mass on voluntary intake and in vivo digestibility in sheep. *Grass Forage Sci.* 73:553–561. <https://doi.org/10.1111/gfs.12319>
- Chase, L.E. 2017. Higher forage feeding survey. Proc. Herd Health and Nutrition Conf. Syracuse, NY.
- Cherney, D.J.R., L.E. Chase, and J.H. Cherney. 2002. Performance of Lactating Holstein Cows as Influenced by Forage Species, Maturity, and Level of Inclusion. *The Prof. Ani. Sci.* Volume 18, Issue 4 , 316 - 323
- Dado, R.G. and M.S. Allen. 1996. Enhanced intake and production of cows offered ensiled alfalfa with higher neutral detergent fiber digestibility. *J Dairy Sci* 79, 418–428.
- Dijkstra, J., J. France, J.L. Ellis, A.B. Strathe, E. Kebreab, and A. Bannik. 2013. Production efficiency of ruminants: feed, nitrogen and methane. In: Kebreab, E. (editor), Sustainable animal agriculture. CAB International, Wallingford, UK.

- Dineen, M. 2017. Impact of *Lolium perenne* L. ploidy and *Trifolium repens* L. inclusion in grazing swards, on milk production of spring calving dairy cattle. Master Thesis. Queens University Belfast, Ireland.
- Donaghy, D. J. 1998. Improving the production and persistence of temperate pasture species in subtropical dairy regions of Australia. PhD Diss. University of Sydney, Australia.
- Doyle, P.T., S.A. Francis, and C. R. Stockdale. 2005. Associative effects between feeds when concentrate supplements are fed to grazing cows: A review on likely impacts on metabolisable energy supply. *Aust. J. Agric. Res.* 56:13.15–13.29.
- FAO (Food and Agricultural Organisation of the United Nations). 2009. Global Agriculture towards 2050. High Level Expert Forum Issues Paper. FAO, Rome.
- Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Blazer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks. 2011. Solutions for a cultivated planet, *Nature* 478: 337-342.
- Fulkerson, W., and D. Donaghy. 2001. Plant-soluble carbohydrate reserves and senescence—Key criteria for developing an effective grazing management system for ryegrass-based pastures: A review. *Aust. J. Exp. Agric.* 41:261–275. <https://doi.org/10.1071/EA00062>.
- Garry, B., M. O'Donovan, T.M. Boland, and E. Lewis. 2014. Effect of Pre-Grazing Herbage Mass on In Vivo Digestibility and Dry Matter Intake of Perennial Ryegrass in Sheep. *Proc. Aust. Soc. Anim. Prod.* Vol. 30:248.
- Gerber, P.J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio. 2013. Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organisation of the United Nations, (FAO), Rome, Italy.
- Godfray, H. C., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. 2010. Food security: the challenge of feeding 9 billion people. *Nature* 327:812-81.
- Hanrahan, L., A. Geoghegan, M. O'Donovan, E. Ruelle, M. Wallace, and L. Shalloo. 2017. PastureBase Ireland: A grassland decision support system and national database. *Comp. and Elec. in Agri.* 136: 193-201.
- Karlsson, J. R. Spörndly, M. Lindberg and K. Holtenius. 2018. Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows. *J. Dairy Sci.* 101:7146-7155.
- Kennedy, J., P. Dillon, L. Delaby, P. Faverdin, G. Stakelum, and M. Rath. 2003. Effect of Genetic Merit and Concentrate Supplementation on Grass Intake and Milk Production with Holstein Friesian Dairy Cows. *J. Dairy Sci.* 86:610-621.
- Lawrence, J. 2018. Dynamic Harvest Schedule. Pp. 4-5 in *The Manager. Pro-Dairy*
- Leaver, J. D. 1985. Milk production from grazed temperate grassland. *J. Dairy Res.* 52:313–344
- McEvoy, M., E. Kennedy, J.P. Murphy, T.M. Boland, L. Delaby, and M. O'Donovan. 2008. The effect of herbage allowance and concentrate supplementation on milk production and dry matter intake of spring-calving dairy cows in early lactation. *J. Dairy Sci.* 91:1258-1269

- McEvoy, M., L. Delaby, J. P. Murphy, T. M. Boland, and M. O'Donovan. 2010. Effect of herbage mass and allowance on sward characteristics, milk production, intake and rumen volatile fatty acid concentration. *Grass and Forage Sci.* 65, 335–347.
- NorFor. 2011. The Nordic feed evaluation system. Wageningen Academic Publishers, The Netherlands.
- Nousiainen, J., M. Rinne, and P. Huhtanen. 2009. A meta-analysis of feed digestion in dairy cows. 1. The effects of forage and concentrate factors on total diet digestibility. *J. Dairy Sci.* 92:5019–5030.
- Oba, M. and M.S. Allen. 2000. Effect of brown midrib 3 mutation in corn silage on productivity of dairy cows fed two levels of dietary neutral detergent fiber: 1. Feeding behavior and nutrient utilization. *J. Dairy Sci.* 83: 1333–1341
- O'Brien, D., B. Moran, and L. Shalloo. 2017. A national methodology to quantify the diet of grazing dairy cows. *J. Dairy Sci.* 101:8595–8604. <https://doi.org/10.3168/jds.2017-13604>
- O'Donovan, M., and P. Dillon. 1999. Measurement of Grassland Management Practice on Commercial Dairy Farms. Dairy Production Department, Dairy Production Research Centre, Moorepark, Fermoy, Co. Cork.
- O'Donovan, M., 2000. The Relationship between the Performance of Dairy Cows and Grassland Management Practice on Intensive Dairy Farms in Ireland. PhD Thesis. National University of Ireland, p. 366
- Palmonari, A., M. Fustini, G. Canestrari, E. Grilli, and A. Formigoni. 2014. Influence of maturity on alfalfa hay nutritional fractions and indigestible fiber content. *J. Dairy Sci.* 97:7729–7734 <http://dx.doi.org/10.3168/jds.2014-8123>
- Roche, J. R., L. R. Turner, J. M. Lee, D. C. Edmeades, D. J. Donaghy, K. A. Macdonald, J. W. Penno, and D. P. Berry. 2009. Weather, herbage quality and milk production in pastoral systems. 3. Interrelationships and associations between climatic variables and herbage growth rate, quality and mineral content. *Anim. Prod. Sci.* 49:211–221.
- Rosegrant, M.W., M. Fernandez, and A. Sinha. 2009. Looking into the future for agriculture and AKST. In: McIntyre, B.D., Herren, H.R. Wakhungu, J., Watson, S.T. (eds.). *International Assessment of Agricultural Knowledge, Science and Technology for the Development (IAASTD), Agriculture at a crossroads*, Island Press, Washington, DC, pp. 307-376.
- Ruelle, E., L. Delaby, M. Wallace, and L. Shalloo. 2017. Using models to establish the financially optimum strategy for Irish dairy farms. *J. Dairy Sci.* 101:614–623 <https://doi.org/10.3168/jds.2017-12948>
- Sheahan, A. J., E. S. Kolver, and J. R. Roche. 2011. Genetic strain and diet effects on grazing behavior, pasture intake and milk production. *J. Dairy Sci.* 94:3583–3591.
- Steinfeld, H., T. Wassenaar, and S. Jutzi. 2006. Livestock production systems in developing countries: status, drivers, trends. *Revue Scientifique et technique-office international des epizooties* 25: 505-516.
- Stockdale, C. R. 1999. The nutritive characteristics of herbage consumed by grazing dairy cows affect milk yield responses obtained from supplementation with concentrates. *Aust. J. Exp. Agric.* 39:379–387.
- Stockdale, C. R. 2000. Levels of pasture substitution when concentrates are fed to grazing dairy cows in Northern Victoria. *Aust. J. Exp. Agric.* 40:913–921.

- UN (United Nations), 2013. World population projected to reach 9.6 billion by 2050. United Nations Department of Economic and Social Affairs. <http://www.un.org/en/development/desa/news/population/un-report-world-population-projected-to-reach-9-6-billion-by-2050.html>
- Undersander, D. 2017. Forage Management: Low Lignin Alfalfa Leaf Loss at Harvest. Proc. Herd Health and Nutrition Conf. Syracuse, NY.
- Wims, C.M., M.H. Deighton, E. Lewis, B. O'Loughlin, L. Delaby, T.M. Boland, and M. O'Donovan. 2010. Effect of pre-grazing herbage mass on methane production, dry matter intake and milk production of grazing dairy cows during the mid-season period. J. Dairy Sci. 93:4976-4985.