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Optimising intensive grazing: a comprehensive review of rotational grassland management, innovative grazing strategies and infrastructural requirements

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Abstract

Grazing is a crucial component of dairy farms across many regions of the world. This review explores challenges related to grazing infrastructure and opportunities for future improvement. Farmers who aim to increase pasture utilisation face heightened inter-animal competition necessitated by pasture restriction to achieve target post-grazing sward heights. Increasing the frequency of fresh pasture allocation beyond once per day has been observed to reduce milk production in primiparous animals, due to intensified competition for limited feed resources. Implementing grazing paddocks tailored for 24- to 36-hour allocations helps to mitigate inter-animal competition while concurrently preventing the grazing of fresh regrowth. Crucial to this approach is establishing farm roadway infrastructure that allows access to all sections of the grazing platform. However, the development of these roadway networks has often occurred without a comprehensive assessment of their impact on the efficiency of the dairy herd's movement between grazing paddocks and the milking parlour. The efficiency of the dairy herd's movement is most significantly influenced by the location of the milking parlour within the grazing platform. Extreme walking distances or challenging terrain on farm roadways may have an impact on milk production per cow. Factors such as farm roadway surface quality and width significantly influence cow throughput on farm roadways. Recent studies have highlighted inadequate roadway widths on many farms relative to their herd size, while surface condition may also be limiting cow throughput on these farms. Enhancing roadway width and surface condition of farm roadways may improve labour efficiency on commercial farms.

Introduction

Grazed herbage provides a highly nutritious, low-cost protein and energy supply for ruminants in temperate regions (Dillon *et al.*, 2005), while converting a human inedible feed source (pasture) into a human edible form, particularly protein based sources in the form of meat and milk (Hennessy *et al.*, 2020). Pasture-based systems have been reported to pose lower risks for animal health issues such as subclinical and clinical mastitis, metritis and mortality compared to confinement-based systems (Mee and Boyle, 2020). Cows at pasture still face some environmental risks including heat stress and wet conditions (Daros *et al.*, 2022). In contrast, cows housed indoors often face reduced space allowance per animal, leading to social stress related to access to resources such as feed (Burow *et al.*, 2013). However, in general across Europe, the proportion of grazed pasture within dairy production systems is declining as production systems intensify (van den Pol *et al.*, 2005; Van den Pol-van Dasselaar *et al.*, 2018).

With the abolition of milk quotas in 2015, dairy farms across the EU were given the opportunity to grow their dairy herds (Groeneveld *et al.*, 2016; Klopčič *et al.*, 2019). However, many EU member states saw dairy herd sizes decline due to lower milk prices (Läpple *et al.*, 2022). Two European countries that have intensified their production systems with alternative strategies are Ireland and the Netherlands. The Netherlands focused on increasing milk production through purchased inputs (Van den Pol *et al.*, 2015), while Ireland focused on increasing milk production through a grazing pasture-based system (Läpple and Sirr, 2019), both expansion strategies required capital investment to accommodate increased animal numbers. The gross investment in dairy farms in the Netherlands is four times higher than that of Irish dairy farms. This is mainly due to the implementation of intensive pasture-based systems in Ireland, which require lower capital investment to expand, where cows spend up to nine months of the year grazing pasture (Läpple *et al.*, 2012). Nonetheless, in pasture-based systems, capital expenditure is still required, particularly for investing in grazing infrastructure (fencing, farm roadways and a water supply) (Clarke, 2016) to optimise the utilisation of the grazing area (Roche *et al.*, 2017a; Goliński *et al.*, 2022; Maher *et al.*, 2023a).

Increasing annual pasture utilised (t DM/ha) is critical in pasture-based systems, as in temperate regions grazing pasture is the most cost-effective feed source (Finneran *et al.*, 2012; Peyraud and Delagarde, 2013; Hennessy *et al.*, 2020). Grazing infrastructure has evolved over time without an in-depth review of developments in this area. Previous studies have assessed animal performance from varying herbage allowances (HA) (McEvoy *et al.*, 2009; Curran *et al.*, 2010; Pollock *et al.*, 2020). However, these studies did not account for impacts of grazing severity on regrowth potential of the sward (Donaghy and Fulkerson, 1998) or the reality that pasture allocation on commercial farms are dictated largely by the size of the paddocks on those farms which can be limited by farm configuration (Maher *et al.*, 2023a). While roadway networks have developed to better connect all paddocks on the grazing platform to the milking parlour (Maher *et al.*, 2023a), there is yet to be a review of the development of these roadway networks for the efficient movement of animals, or a review of the factors which impact the time taken to move the dairy herd on farm roadways.

Farm roadways on commercial farms require constant maintenance to reduce any potential incidents of lameness within the dairy herd (Chesterton *et al.*, 1989). However, there has only been a limited review of factors that affect roadway surface condition on commercial farms. This is critical for developing guidelines for future roadway networks that are suitable for animal movement.

This review aims to investigate grazing management strategies in pastoral dairy systems, the role of grazing infrastructure on commercial dairy farms and to identify areas for future research. The main objective of this review is to provide 1) An assessment of grassland management techniques that ensure adequate grazing conditions to optimise animal pasture intake without hindering sward quality or plant regrowth potential for commercial dairy farms and 2) a review of the impact that both walking distance and farm roadway quality have on the movement of the dairy herd on farm roadways.

Grassland management

Rotational grazing systems

In intensive rotationally managed pasture-based systems, return on investment of grazing infrastructure can only be established with increased stocking rate (SR) (McMeekan and Walshe, 1963; Macdonald *et al*, 2011; McCarthy *et al.*, 2013). The SR dictates the area of grassland available per cow, over a period of time (Allen *et al.*, 2011). Challenges still remain with adopting rotational grazing across parts of the world. Including capital expenditure on grazing infrastructure, labour requirements and water source constraints (Hyland *et al.*, 2018a; Wang *et al.*, 2020; Jordon *et al.*, 2023).

Requirement for grazing infrastructure on pastoral farms

Optimal grazing infrastructure is required to efficiently carry a higher SR on commercial grassland farms to increase output per Ha. Grazing infrastructure is a term that encompasses all materials required for pasture-based farming, categorised into two main sections: pasture allocation frequency (PAF) (through optimally sized paddocks to meet herd demands (Pollock *et al.*, 2020) and adequate roadway networks (Maher *et al.*, 2023a; Maher *et al.*, 2023b). Herbage allowance is a term to describe the kg of dry matter (DM) of pasture allocated to an animal over a given time period (McEvoy *et al.*, 2009). In pasture-based dairy farms, where rotational grazing is practiced, HA for a herd is defined by the size of the grazing paddocks on the farm (Pollock *et al.*, 2020; Maher *et al.*, 2023a). The herd is retained within these paddocks using electrified fence wire, which sends out an aversive stimuli where animals come into contact with the wire (Markus *et al.*, 2014). Pasture allocation frequency defines how often the animals are allocated fresh pasture (Pollock *et al.*, 2020). This is generally split into three periods of time on Irish farms, where one allocation is defined as a 12-hour allocation, the time between successive milkings. While two allocations represents a 24-hour period and three allocations represents a 36-hour period spent in an individual paddock (Fallon *et al.*, 2023), where the HA per cow is equal to a peak daily dry matter intake (DMI) of 17.7 kg DM/cow (Walsh *et al.*, 2024). Increasing the grazing time of a paddock over 36 hours can impact the regrowth potential of the grazed plant (Fulkerson and Slack, 1995). Pollock *et al.* (2020) reported where grazing allocations were reduced to 12-hour allocations per paddock, milk production reduced when compared to 24- or 36-hour allocations per paddock where low post grazing sward heights (PoGSH) of 4 cm were achieved (Table 1).

Roadway networks on dairy farms are a key tool for moving animals to grazing paddocks to access fresh pasture, roadway networks enable access to the milking shed (Figure 1) (Roche *et al.*, 2017b; Fenton *et al.*, 2021; Maher *et al.*, 2023a). Sufficient roadway networks are essential to achieving a greater number of grazing days per year, through increasing accessibility to pasture in during inclement conditions (Undersander *et al.*, 2002; Clarke, 2016). Achieving grazing for even for two short periods (3–4.5 hours) per day resulted in no difference in milk production relative to a herd at pasture full time during unfavourable climatic conditions for grazing (Kennedy *et al.*, 2009). This short-term strategy during wet conditions reduces poaching damage while maintaining pasture in the diet of the animal. Hanrahan *et al.* (2019) reported that farms on heavy soils can achieve high net profit per kg of milk solids sold, through the adoption of grassland management practices (Hanrahan *et al.*, 2017) and the implementation of adequate drainage and optimal grazing infrastructure with multiple access points to grazing paddocks to allow access to all areas of the farm are considered essential for grazing in heavy soils. Fenger *et al.* (2022) reported that increasing time at pasture in suboptimal grazing conditions increased soil surface deformation; however, it did not affect annual pasture production (DM/ha); however, there was an increase in milk solids production per cow (due to increased protein concentration of the milk). It has been reported, where excessive treading damage occurs, it can negatively impact on DM yield per ha by up to 30% (Menneer *et al.*, 2005; Tuñon *et al.*, 2014), increase bulk density of the soil and diminish proportions of large (air-filled) soil pores (Phelan *et al.*, 2013a; Herbin *et al.*, 2011).

Despite these potential challenges with grazing in suboptimal grazing conditions, it is still recommended where possible, to allow dairy cows access to pasture. Due to the potential increase in net profit of €1.85 per cow/day for every additional day at pasture achieved (Hanrahan *et al.*, 2018). A study by Hyland *et al.* (2018b) reported that grazing management practices as a major issue to the implementation of the spring rotation planer on dairy farms, with farmers not creating sub-divisions of paddocks for early spring grazing.

Recent work carried out by Teagasc on dairy farms classified as part of the 'Teagasc Heavy Soils Programme' has highlighted strategies to improve accessibility in suboptimal conditions (Teagasc, 2021). Spur roadways were identified as a key tool to

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Table 1. Review of intensive rotational grassland management practices

Study	Location	Sample size	Duration	Findings
McMeekan and Walshe, 1963	New Zealand	160 cows	4 years	Reported the full benefits of rotational grazing as opposed to continuous grazing cannot be identified unless stocking rate is increased
McCarthy *et al.*, 2011	Ireland	Review of 109 experiments	N/A	Increasing stocking rate by one cow/ha resulted in reduced milk production per cow by 7.4% to 8.7% but increased milk production on a per Ha basis by 19.6% to 20.1%
Walsh *et al.*, 2024	Ireland	80 cows	12 weeks	Average DMI of cows in early lactation (27% primiparous cows) increased from 13.2 kg DM/cow/day on week two of lactation up to 17.7 kg DM/cow/day on week 12 of lactation
Curran *et al.*, 2010	Ireland	64 cows	30 weeks	Implementing a pre-graze cover of 1600 kg DM/ha (> 4 cm) of perennial rye grass, resulted in increased milk production when compared to a pre-graze cover of 2400 kg DM/ha (> 4 cm), this may be due to the high neutral detergent fibre present with high pre-grazing herbage mass, which influences sward digestibility
Ganche *et al.*, 2013	Ireland	90 cows	40 weeks	It was reported that grazing swards to less than 4.2 cm resulted in a reduced annual herbage yield of 1.4 t DM/ha, while milk production reduced by 2.6 kg/cow/day when PoGSH was reduced to 2.7cm
Pollock *et al.*, 2020	Northern Ireland	87 cows	20 weeks	Energy corrected milk solids production of primiparous animals was negatively affected by more frequent pasture allocations, when low post grazing heights are maintained

Figure 1. A layout of a pasture based dairy farm. An integrated farm roadway network and the farmyard location within the grazing platform. Red box: farmyard location. Figure sourced from Maher *et al.* (2023a).

access areas of pasture from farm roadways while reducing treading damage to the paddock. This involves the creation of narrow roadways (1–2 m wide) to allow the herd to access the furthest points of grazing paddocks without causing damage to areas already grazed. It has also been recommended that the furthest point from a roadway to the back of a paddock is no more than 250 m on dry land and 50–100 m on heavier soil types (Teagasc, 2021). Adding additional entry/exit points to paddocks reduces treading damage of a single entry/exit point which deteriorates the quality of the surface. This has been associated with increased lameness on pasture-based farms (Browne *et al.*, 2022a).

Maher *et al.* (2023a) reported that the milking parlour location within the grazing platform was the most critical factor affecting the distance walked between pasture and the milking parlour, agreeing with previous work by Tucker *et al.* (2005). Figure 1 displays the typical layout of a modern pasture-based rotationally grazed dairy farm (Maher *et al.*, 2023a). These systems do not require high capital expenditure when compared to confinement systems of similar herd sizes (Roche *et al.*, 2017b).

Impact of grazing strategies on animal and farm performance

Herbage allowance

Herbage allowance is controlled by the positioning of electric fences (Roche *et al.*, 2017a), which are in fixed positions on commercial farms (Maher *et al.*, 2023a) or by virtual fences (McSweeney *et al.*, 2020; Colusso *et al.*, 2021; Goliński *et al.*, 2022). Increasing HA through larger paddock sizes or increased pre-grazing herbage mass will result in an increase in DMI. However, at very high pre-grazing herbage mass (PGHM) (5,000 kg DM/ha), DMI may decrease due to a greater proportion of pseudostem per kg of DM available compared to lower PGHM (2,200 kg DM/ha) (Muñoz *et al.*, 2016). Increasing HA by 1 kg of DM/cow/day increased milk production by 1.01 kg/cow/day (Curran *et al.*, 2010; Kennedy *et al.*, 2011; Claffey *et al.*, 2020). These studies also observed a reduction in pasture utilisation with increased HA ($P < 0.001$). The reduction in pasture utilisation highlighted in these studies may significantly affect profitability on pasture-based dairy farms (Hanrahan *et al.*, 2018; Palma-Molina *et al.*, 2023).

A study by Walsh *et al.* (2024) reported a total DMI of 17.7 kg/cow/day, where HA was adjusted to maintain a PoGSH of 4 cm. Mayne *et al.* (1987) reported that low grazing pressure significantly reduced the organic matter digestibility of swards from mid-June onwards, while Lee *et al.* (2008) determined a low PoGSH of 4 cm ensured grass organic dry matter digestibility was higher than in swards that did not achieve a low post-grazing sward height (Macdonald *et al.*, 2018). It is imperative in all pasture-based systems that HA for the purpose of increasing milk production per cow must be balanced with pasture utilisation to maintain profitability.

Pre-grazing herbage mass

Adjusting the PGHM of the pasture offered is one such strategy that may be deployed to adjust HA per livestock unit (LU) in a rotational grazing system with fixed paddock sizes (McEvoy *et al.*, 2009; Fernández *et al.*, 2011; Doyle *et al.*, 2023). Herbage mass significantly affects pasture digestibility as herbage mass, sward structure and density and pasture organic matter digestibility are all interrelated (Stakelum and Dillon, 2004). Pre-grazing herbage mass has been described as a major determinant of pasture DMI

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(Combellas and Hodgson, 1979). Both Curran *et al.* (2010) and Tuñon *et al.* (2011) reported cows grazing swards with a low PGHM had greater milk production compared to those grazing swards with a high PGHM, due to an increased leaf material proportion with lower PGHM (Wims *et al.*, 2014).

Wims *et al.* (2014) reported increased body condition score of cows grazing a PGHM of 1400 kg DM/ha (9.6 cm), compared to either 1150 kg DM/ha (8 cm) or 2000 kg DM/ha (12 cm). It is therefore recommended to keep the PGHM equal to 1400 kg DM/ha (9.6 cm) across the grazing season in rotational grazing systems (Wims *et al.*, 2014). While Doyle *et al.* (2023) reported an increase in live weight gain from pasture at a lower PGHM (1500 kg DM/ha (9.9 cm)), compared to a higher PGHM (2500 kg DM/ha (13.9 cm)) in rotationally grazed suckler beef systems.

Post grazing sward height

Previous studies have shown increasing grazing severity through higher SR leads to high nutritive value of the sward (Michell *et al.*, 1987; Hoogendoorn *et al.*, 1992; Lee *et al.*, 2007) and increased annual DM production (Macdonald *et al.*, 2008; Phelan *et al.*, 2013b). However, Ganche *et al.* (2013) and Donaghy and Fulkerson (1998) observed a reduction in annual DM production as PoGSH decreased below 4.2 cm, due to reduced stem water-soluble carbohydrate content and extended regrowth periods (Table 1).

A reduction in milk production and DMI with increased grazing severity has also been widely reported (Le Du *et al.*, 1979; Mayne *et al.*, 1987; Ganche *et al.*, 2013; Menegazzi *et al.*, 2021). The optimal PoGSH for intensively managed pasture-based dairy systems to balance animal DMI and sward utilisation is reported to be 4–5 cm (Ganche *et al.*, 2013; Wilkinson *et al.*, 2020; Donaghy *et al.*, 2021). It is imperative that this PoGSH is achieved within a short period of time following the first allocation of new pasture to the herd. This ensures the new tiller growths are not consumed where only a single leaf present, which can limit plant growth and increases the time taken to replenish water soluble concentrates (Donaghy and Fulkerson, 1998). Therefore, creating optimally sized paddocks for a dairy herd should allow for allocations that both provide optimal PGHM (1400 kg DM/ha, (9.6 cm)) (Wims *et al*,. 2014)), with a HA per LU of 17.7 kg DM/LU (Walsh *et al.*, 2024) and ensure target PoGSH (4 cm) is achieved to provide nutritious herbage at subsequent grazings.

Regrowth interval

Regrowth interval (or rotation length) refers to the number of days between successive grazings of the same paddock (Allen *et al.*, 2011). Fulkerson and Slack (1995) highlighted that defoliating perennial ryegrass plants at the one-leaf stage, as opposed to three fully expanded leaves, can negatively impact the replenishment of water-soluble carbohydrates in the stubble of the plant (14 vs 364 mg water-soluble carbohydrates) and the tillering capability of the plant. Fulkerson and Donaghy (2001) reported that water-soluble carbohydrates replenishment only occurs in the plant when the third leaf appears on the plant, after this point the first leaf beings to senescence and herbage nutritive value declines. The ryegrass plant follows a sigmodal growth curve Brougham (1955), with the three leaf stage closely aligned with the maximum growth potential of the plant (Chapman *et al.*, 2012). Failure to allow the plant to build up energy reserves through frequent defoliation at the one leaf stage increases plant mortality. In one study, 70% of plants died when perennial ryegrass was defoliated at a height of 2 cm, 3 days and 6 days after initial defoliation (Fulkerson, 1994).

The creation of individual paddocks on commercial farms allows for plants within that paddock to rebuild water-soluble carbohydrate reserves before the next grazing. The division of a farm into optimally sized paddocks for grazings (Maher *et al.*, 2023a) allows the farmer to control the rotation length to prevent redefoliation of perennial ryegrass plant, as re-defoliation 72 hours after initial defoliation can impact regrowth potential of the plant by 55% (Fulkerson, 1994). While controlling rotation length allows the plant to achieve the optimal PGHM with the use of supplementary feed where pasture growth is below the demand of the herd (Claffey *et al.*, 2019).

Effect of frequency of feed delivery

The impact of feed delivery frequency has been a subject of study in both confinement and pasture-based systems. Farmers aim to enhance DMI and milk production in the dairy herd, emphasizing the importance of efficient feed utilisation. In confinement systems, this is dictated by the frequency with which the operator introduces fresh feed at the feed barrier. In contrast, pasture-based systems rely on factors such as the movement of a strip wire (restricting pasture access) or the herd's transition to a new paddock to regulate feed availability.

On commercial pasture-based dairy farms, the size of paddocks is significant as it determines the number of grazings that can be accomplished in each paddock between milkings, as reported by Maher *et al.* (2023a). This practice is used to create short-term variations in pasture availability and inter animal competition for resources, potentially impacting grazing behaviour and herbage DMI (Pollock *et al.*, 2020).

Benchaar and Hassanat (2020) reported no effect on DMI or milk production with increasing feeding rate above once per day in confinement systems. While another study documented animals in confinement systems became restless and had a decreased lying time with increased feeds per day (Mäntysaari *et al.*, 2006). When feeding frequency was reduced to alternative days, Phillips and Rind (2002) reported that milk production increased and there was less aggression shown between animals, indicating a more relaxed environment.

Pasture-based studies have also assessed increasing allocation above once per day to improve output per cow. Allocations on commercial pasture-based farms are routinely allocated every 12, 24 or 36 hours (Pollock *et al.*, 2020; Maher *et al.*, 2023a). Both Dalley *et al.* (2001) and Granzin (2003) observed no improvement in milk production on pasture-based systems when feeding allocation was increased above once per day. Verdon *et al.* (2018) reported a reduction in fat and protein corrected milk (−0.9 kg cow^{-1} day^{-1}) where fresh allocations per day increased. Importantly neither study by Dalley *et al.* (2001) nor Verdon *et al.* (2018) included primiparous animals. Pollock *et al.* (2020) saw a reduction in milk solids production in primiparous animals of between 5% and 8% when PAF was increased from every 36 hours to every 12 hours. An interaction between PAF and milk energy output was observed in primiparous animals, as reported by Pollock *et al.* (2020). This phenomenon could be attributed to the broader distribution of daily grazing activity associated with 36-hour allocations in contrast to those on 12-hour allocations. This variance is thought to arise from decreased competition for available feeds, especially considering the subordinate classification of primiparous animals within the herd (Pollock *et al.*, 2022).

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It is reported that on farms with large herd sizes (≤ 250 cows), 46% of paddocks available for grazing are only suitable for 12-hour allocations (Maher *et al*., 2023a). The implementation of 12-hour allocations may restrict pasture DMI, with increased grazing bite frequency where HA is restricted due to inaccurate allocations (Werner *et al*., 2019), placing greater competition on primiparous animals for feed resource in short supply. In contrast to 36-hour allocations, where animals may only have to compete for herbage during the last grazing per paddock (Pollock *et al*., 2022). These studies may help to alleviate issues on commercial farms with regard suboptimal PAF (Maher *et al*., 2023a) and improve performance of primiparous animals.

Social dominance among the grazing herd

Social dominance within the herd is positively correlated with age ($r = 0.35$–0.93, $P < 0.05$), body weight ($r = 0.47$–0.87, $P < 0.01$) (Schein and Fohrman, 1955; Phillips and Rind (2002) and milk production (Hussein *et al*., 2016), leaving primiparous animals classified as sub ordinate animals. Studies have assessed the benefit of separating primiparous animals from the rest of the herd (Krohn and Konggaard, 1979; Phelps and Drew, 1992), with Hussein (2019) reporting lower body weight gain and DMI reducing by 0.99 kg DM/day due to competition from more dominant cows. There is limited practical value in these studies for pasture-based systems in countries with smaller herd sizes such as Ireland (C.S.O., 2020; ICBF, 2021) relative to countries such as Australia (Dairy Australia, 2023) or New Zealand (DairyNZ, 2023).

Multiparous animals can consume 34–50% greater feed compared to primiparous animals following fresh allocations of feed (Hart *et al*., 2014; Walsh *et al*., 2024). In pasture-based systems, this may result in dominant animals seizing the most favourable grazing sites at the expense of primiparous animals within the pasture (Pollock *et al*., 2022), particularly where HA is restricted to ensure optimal PoGSH. Stressful social interactions between dominant and submissive animals can generate conditions that impact milk production (Sottysiak and Nogalski, 2010) and DMI (Werner *et al*., 2019) in submissive animals.

Grazing time was significantly longer for primiparous animals relative to multiparous animals with 12-hour allocations, while for the 36-hour allocation there was a distinct difference with a shorter grazing for primiparous animals relative to multiparous animals (Pollock *et al*. 2022). The observed reduction in grazing time during 36-hour allocations may be attributed to diminished competition, facilitated by larger pasture quantities in the initial two allocations. This availability of ample pasture in the early allocations allows primiparous animals' access to high-quality swards, with reduced competition for a resource in restricted supply.

Roadway infrastructure

Roadway infrastructure on commercial dairy farms

To access pasture and utilise it effectively, high-quality roadway infrastructure is required to allow animals to move efficiently from each paddock to the milking parlour and vice versa (Clarke, 2016; Roche *et al*., 2017a). However, this may not always be the case, as often roadway networks are developed over time as new paddocks are included on the grazing platform. This can result in inefficient layouts on commercial farms, where new paddocks are added to the periphery of the grazing platform, causing cows to walk further than the projected distance for a given herd size (Maher *et al*., 2023a).

Walking distance on pasture-based dairy farms

As farmers aim to achieve a long grazing season, increase pasture in the animals' diet and improve profitability (Hanrahan *et al*., 2018), there will likely be increased distance walked on farm roadways to and from pasture for milking (Hund *et al*., 2019). Although it is widely accepted that dairy cows may have to walk several kilometres to and from pasture daily (Beggs *et al*., 2015; Maher *et al*., 2023a), there are very few metrics to quantify the distance dairy herds walk per year on commercial farms. Hall *et al*. (2023) reported steps taken per hour reduced when cows were milked either once per day or three times in two days compared to traditional two milkings per day. Interestingly, farm size (hectares farmed) is reported to account for 3–4 to 49% of the variation in walking distance, while farm shape, topography and location of milking parlour are key metrics that effect the distance walked (Tucker *et al*., 2005; Maher *et al*., 2023a). Furthermore, Maher *et al*. (2023a) highlighted the maximum distance to a paddock to be a significant influencing factor on the total distance walked for the dairy herd on farm roadways ($R^2 = 0.64$), while the mean distance provided the greatest insight to the distance walked yearly (Table 2).

However, herd size still influenced the distance walked on roadways, with herds ≥ 250 cows walking 718 km per year on farm roadways, which was almost twice that of herds of less than 100 cows. Greater distance walked on roadways has previously been suggested as a risk factor for lameness in dairy cows (Hund *et al*., 2019).

One factor often overlooked while reviewing the distance walked by the dairy herd on farms is the efficiency of the roadway infrastructure for the movement of the dairy herd. Where farms have expanded their herd sizes post milk quota abolition (Kelly *et al*., 2020), the efficiency of the roadway infrastructure for animal movement has significantly improved on some farms while remaining static on others. Maher *et al*. (2023a) described how the location of additional grazing land accessed beside the grazing platform greatly affects the efficiency of the dairy herd movement on farm roadways. This is reported as the distance from a paddock to the milking parlour relative to the size of the grazing platform, this metric allows farms of various herd sizes to be compared again one another. In figure 2, Farm C reduced the relative mean distance from grazing paddocks to the milking parlour by 40 %, while Farm D only reduced the relative mean distance from grazing paddocks to the milking parlour by 0.34 %. It is advisable that future research utilises this metric for benchmarking farm roadway efficiency.

Effect of walking distance on milk production

Available literature has showed conflicting data regarding the effect of walking distance on milk production (Thomson and Barnes, 1993; D'Hour *et al*., 1994; Pratumsuwan, 1994; Coulon *et al*., 1998; Neave *et al*., 2021) (Table 2).

Results from these studies have identified that only distances above 6.4 km/day caused reductions in milk production of 1.2–1.9 kg/cow/day, increasing to 2.5 kg/cow/day where walking increased to 9.6 km/cow/day, while the concentration of milk fat and milk protein both increased with greater distance walked. Interestingly, the difference in milk production was predicted to be 5.7 kg/cow/day due to lower energy supply and increased energy requirements. It is hypothesised that cows call on body reserves to limit this

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Table 2. Review of walking distance by dairy herds to pasture and impact on milk production

Study	Location	Sample size	Duration	Findings
Beggs *et al.*, 2015	Australia	863 farms	N/A	Larger herds had an increased distance to the furthest paddock, averaging 2.3 km of a maximum distance to a paddock on herds greater than 700 cows
Maher *et al.*, 2023a	Ireland	93 farms	10 months	The mean distance to the furthest paddock on Irish dairy farms was 475 m. This study reported how the milking parlour location is more important than the herd size when assessing the distance walked, with milking parlour location accounting for 82% of the variation compared to herd size accounting for 45% of the variation
Tucker *et al.*, 2005	New Zealand	132 farmers	N/A	The average walking distance to a paddock from the milking parlour was 1.9 km for a mean herd size of 910 and SD of ± 466. Herd size only accounted for 3–4% of the variation in the walking distance on farm
Neave *et al.*, 2021	Australia	87 cows	16 days	On days where cows spent an increased time away from pasture there was a reduction in milk production of 1.3 kg/cow/day. There was no effect of the distance walked on milk production
Pratumsuwan 1994	New Zealand	26 cows	4 weeks	Where cows walked 7.5 km/day compared to those in the control group walking 1.5 km/day to pasture, there was no effect on milk production, SCC or body weight where pasture was not limited
D'Hour *et al.*, 1994	France	12 cows	3 years	Milk production was negatively affected by walking distances of 6.4 km or greater. All cows regained pre walking yields within three days following extreme walking

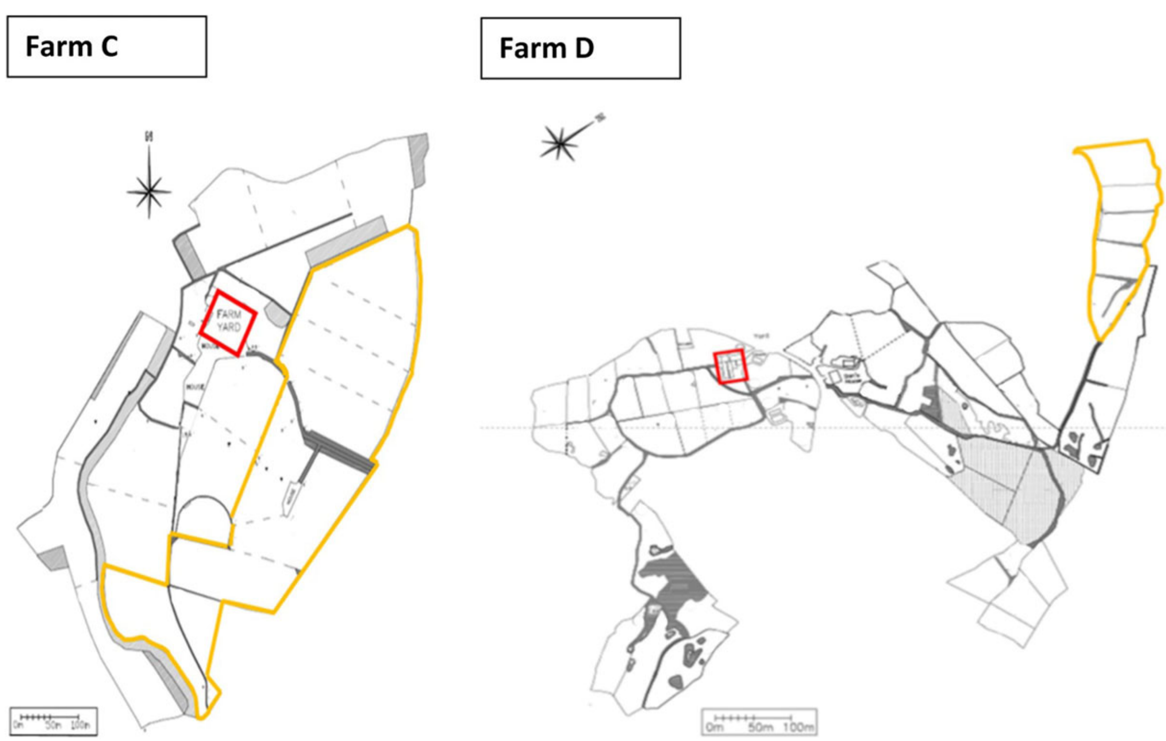

Figure 2. Farm maps displaying the farmyard location and new paddocks accessed within the grazing platform for Farm C and D. Red box: farmyard location within the grazing platform. Yellow box: new paddocks added to grazing platform (Open source). Figure sourced from Maher et al. (2023a).

difference in milk production, as reported with higher nonesterified fatty acids following walking. There was also a significant increase in milk somatic cell count (115,000 cell/ml), for cows that experienced walking for 9.6 km/day compared to those that remained in the barn (Coulon *et al.*, 1998). Some commercial herds may experience a reduction in milk yield due to excessive walking, with herds walking greater than the 6.4 km/day threshold outlined in this review (Beggs *et al.*, 2015; Maher *et al.*, 2023a).

In contrast, some researchers highlighted that milk production was not reduced with increased walking distance. Pratumsuwan (1994) saw no significant effect on milk production or the production of any constituents, where cows were grazed on the same pasture but a subgroup of the herd walked 7.5 km/day compared to 1.5 km/day for the control group. Although the distance walked was greater than the threshold of 6.4 km, there was no slope effect in the study by Pratumsuwan (1994), which was reported to be one of the main factors influencing energy expenditure while walking (Ribeiro *et al.*, 1977).

Larger herd sizes may spend more time away from pasture due to longer milking times and longer walking times to the milking parlour from pasture (Beggs *et al.*, 2018). This longer time away from pasture has been associated with a reduction in lying time and

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milk production (– 0.3–1.3 kg/cow/day off pasture, $P < 0.05$) (Jung *et al* 2002; Neave *et al*., 2021; Beggs *et al*., 2015). Lying time is an indicator of animal welfare with reduced lying time being a sign of inadequate time allocation for normal animal behaviour (Tucker *et al*., 2005). Relocating the milking parlour to a more central location on large farms may alleviate some of these potential issues (Maher *et al*., 2023a) or improvement of roadway surfaces to increase cow throughput (Maher *et al*., 2023b). Nonetheless, there are currently no data that may identify potential labour savings if these upgrades were carried out or indeed the potential cost of upgrading such roadway networks.

Energy cost of walking

Literature has reported the energy cost of walking cows above maintenance is 2.0 J NE_1/kg body weight/m for horizontal movement and 26.0 – 28.0 J NE_1/kg body weight/m for vertical movement (Ribeiro *et al*., 1977). Metabolic cost increases linearly with speed of walking ($R^2 = 0.52$) (Yousef, 1985; Lawrence and Stibbards, 1990; Di Marco and Aello, 1998). It has been reported every 1 km walked per day between pasture and the milking parlour requires an additional 1,882 J NE_1/kg body weight/day, this is an additional 5% of maintenance requirements (NRC, 2001), equating to 2.15 MJ of NE_1 for a 600 kg dairy cow walking the mean distance per day (1,902 m) from the herds studied by Maher *et al.* (2023a). Neave *et al.* (2021) suggested that the increased DMI and decreased rumination time on days where cows walk further were a result of increased energy requirement. However, this additional energy demand is predicted to be only 0.14 kg DM per km walked (Rattray *et al*., 2007).

A topic that remains difficult to quantify the energy requirements of grazing dairy cows walking on hills due to variances in slope. It has been highlighted however that cows walking of vertical distance of 200 m required a 50% increase in maintenance requirements (NRC, 2001). While Brosh *et al.* (2010) reported vertical walking to be eight times more energy intensive than horizontal walking in beef cows.

Options to reduce the energy demand associated with walking include reducing milking frequency from twice a day milking to once a day milking or three milkings in two days, which would reduce the distance walked per day (Hall *et al*., 2023). Future research in this area should further investigate the effect varying slopes on roadways have on the energy expenditure of dairy cows walking between pasture and the milking parlour.

Effect of walking distance to pasture and herbage intake

Studies have described where walking distance increased to over 6 km/day there was no impact on herbage intake where pasture was not restricted (Pratumsuswan, 1994; Thomson and Barnes, 1993; Matthewman, 1989). However, Coulon and Pradel (1997) did experience a reduction in DMI (–1.1 kg DM/cow/day) where animals had to walk extreme distances of 12.8 km/day. This may be due to the significant increase in body temperature imposed by strenuous exercise and the animals' efforts to decrease their heat load by reducing feed intake (Yousef, 1985). In a study be Neave *et al.* (2021), days where cows walked greater distances (up to 4 km) to pasture, grazing time increased by 14 minutes per cow/day. This may be due to the increased energy demands from animals walking (Ribeiro *et al*., 1977, Kaufmann *et al*., 2011). While Neave *et al.* (2021) also remarked that increase in grazing time is more than adequate to meet the additional energy demands (0.14 kg DM/km) for walking (Rattray *et al*., 2007).

Road surface quality

The primary objective of a roadway network is to enable efficient movement of the herd from pasture to the milking parlour and back to pasture after milking (Roche *et al*., 2017a), dairy herds on pasture-based farms make up to 600 trips per year on farm roadways (Clarke, 2016). Farm roadways closer to the farmyard tend to be better developed, while those on the extremities are less developed (Maher *et al*., 2023b). As farms have expanded their herd sizes since milk quota abolition (45% increase between 2012 and 2022 (Dillon *et al*., 2023)), a patch work of roadways has been developed on many farms to access additional land areas creating a series of different surfaces animals must travel across (Fenton *et al*., 2021). Stock movement can be hindered by a number of factors including uneven/damaged surfaces, potholes, build-up of grass at margins, loose stones and excessive dirt on roadways (Clarke, 2016). The evaluation of suitable surfaces for animal movement has been explored in the literature (Berry *et al*., 2008; Ranjbar *et al*., 2016; Hund *et al*., 2019), assessing lameness on farms. While some studies assessed speed of movement on different surfaces (Maher *et al*., 2023b; Rushen and de Passillé, 2006; Chapinal *et al*., 2011; Buijs *et al*., 2019), where smoother surfaces had improved locomotion of cows. Many of these studies only assessed one cow or two cows walking at a time in a single file, there has only been one study to assess the impact of floor surface type on cow throughput at a herd scale (Maher *et al*., 2023b).

Impact on speed of movement of dairy animals

As herd size increases, the distance walked to pasture tends to increase (Beggs *et al*., 2015; Maher *et al*., 2023a). There is evidence that the diverse roadway surfaces on which cows walk to and from pasture can affect the pace at which they move (Maher *et al*., 2023b). Telezhenko and Bergsten (2005) reported a disparity in walking speeds of cows on different floor surfaces. Cows exhibited significantly higher speeds on solid concrete floors (1.08 m/s) in comparison to solid rubber floors (1.01 m/s; $P < 0.05$). Conversely studies by Flower *et al.* (2007), Chapinal *et al.* (2011) and Rushen and de Passillé (2006) have reported that cows walked faster on softer surfaces as opposed to concrete, with walking speed increasing by 4–6%. This trend was consistently observed in a study by Buijs *et al.* (2019), where artificial grass was placed over a stone roadway with a dust covering resulted in enhanced walking speeds.

Increasing the abrasiveness of the floor type has shown to increase stride length but in doing so, reduced the speed of walking, it is thought this increase in stride length is due to the animals' attempt to limit their interaction with the uncomfortable floor type (Phillips and Morris, 2001). Furthermore, Maher *et al.* (2023b) observed, in a herd of cows, that smoother surfaces contributed to increased cow throughput on farm roadways. This suggests that the type of flooring or surface material can significantly impact the walking behaviour and speed of cows, with implications for the overall efficiency and management of farm operations.

However, the benefits of upgrading surfaces to increase walking speed and reduce the total labour input to move the dairy herd have yet to be quantified. The study by Maher *et al.* (2023b) did report the potential increase in cow throughput with improvements in roadway floor surface; however, it did not investigate labour savings for the movement of the herd to the milking parlour or indeed the costs required to carry out such upgrades. Previous technical literature has reported the cost of creating new roadways

Table 3. Review of the impact roadway surfaces have on animal movement and lameness within the herd

Study	Location	Sample size	Duration	Findings
Buijs *et al.*, 2019	United Kingdom	200 cows	6 days	The utilization of artificial grass as a roadway resulted in a 4% increase in the walking speed of the animals. Notably, animals identified as lame exhibited a preference for walking on the artificial grass surface over a roadway treated with stone dust
Maher *et al.*, 2023b	Ireland	60 cows	2 months	Wider roadway widths and improved surface condition have greater cow throughput, while public road crossing reduced cow throughput by 32%
Flower and Weary, 2009	Canada	Review paper	N/A	Walking speed of dairy cows increased by 4–6% when walking on softer floors as opposed to concrete floors
Browne *et al.*, 2022a	Ireland	100 farms	2 farm visits	This study reported roadway condition was not associated with increased lameness on farm but the presence of stones at field entry points was a risk factor. However, only the section of roadway in use on the day of the visit was assessed
Chesterton *et al.*, 1989	New Zealand	62 dairy farms	27 months	The condition of worst section of roadway was associated with increased lameness on the farm. While the herdsperson pushing cows was also associated with increased lameness
Tranter and Morris, 1991	New Zealand	3 dairy farms	12 months	Wet conditions on farm roadways can result in softening of the hoof horn and consequently increase claw wear, while wet conditions also reduce the quality of the farm roadway exposing large stones on the roadway which may further increase lameness on farm

on farms but did not delve into the costs associated with upgrading infrastructure (Teagasc, 2021).

There has been very limited research assessing the impact roadway widths have on dairy herd movement, with the exception of a study by Maher *et al.* (2023b), which has reported a strong correlation ($R^2 = 0.95$) between roadway width and dairy herd movement (Maher *et al.*, 2023b). Therefore, increasing roadway width may reduce the overall time taken to move the dairy herd to the milking parlour. However, the impact of wider roadways is hindered by poor quality roadway surfaces. It has been highlighted across Irish dairy farms that roadway widths are suboptimal for herd sizes present (Browne *et al.*, 2022b; Maher *et al.*, 2023b).

Impact on animal lameness

Lameness is one of the most important animal welfare issues (Flower and Weary, 2009; Crossley *et al.*, 2021) and has been shown to affect walking speed (Alsaaod *et al.*, 2017). Lameness is an issue that is more associated with cows within confinement systems as opposed to pasture-based systems due to the softer surface material in the form of pasture (Olmos *et al.*, 2009; Alsaaod *et al.*, 2017). While a lower animal stocking density at pasture and a reduced exposoure to manure-contaminated enviroments are also associated with lower proportion of lameness amongst animals at pasture (Roche *et al.*, 2023). Despite this, the annual incidence of lameness on pasture-based systems was 19% (Ranjbar *et al.*, 2020) and ranges from 5 to 45% (Harris *et al.*, 1988; Tranter and Morris, 1991; Browne *et al.*, 2022b), which is similar to that described in confinement systems (von Keyserlingk *et al.*, 2012; Adams *et al.*, 2017).

Some of the key causes of lameness on pasture-based farms are poor roadway surfaces, long walking distances to the milking parlour and poor herding skills (Arkins, 1981; Chesterton *et al.*, 1989; Chesterton, 2015; Ranjbar *et al.*, 2016; Hund *et al.*, 2019). Chesterton (2011) reported the walking distance to and from pasture for milking directly affected the lameness of the herd due to excessive wear on the sole of the hoof. It was proposed that reducing milking to once per day as opposed to traditionally twice per day reduced lameness due to lower walking distance and reducing time spent on concrete. Similar findings were reported by Edwards *et al.* (2022), whereby reducing milking frequency to three milking's in two days reduced lameness in the herd. Interestingly, Chesterton (2011) suggested the use of a day and night paddock where cows were walking large distances to pasture allowing a shorter walk to a paddock at night. However, this practice may be of limited use if farmers choose their paddocks based on the amount of herbage available within each paddock (Pasturebase Ireland; Hanrahan *et al.*, 2017), while this practice may also affect the milk production of first lactation animals (Pollock *et al.*, 2020).

Increasing loose stone content of roadways is known to increase the incidence of lameness on pasture-based farms (Chesterton *et al.*, 1989; Bran *et al.*, 2018). Chesterton *et al.* (1989) also reported that the patience of the farmer herding the cows and poorer sections of farm roadways were associated with an increased risk of lameness on the farm. The presence of small stones on the roadway particularly where the roadway is a concrete surface was also a major cause of traumatic lameness on commercial farms (Chesterton, 2011). Wet conditions on roadways can also lead to increased lameness on farms in France (Faye and Lescourret, 1989) and New Zealand (Tranter and Morris, 1991) (Table 3). Wet conditions can also soften the hoof horn and consequently increase claw wear, while also increasing erosion of the roadway exposing stones and sharp, rocky material, creating an abrasive surface (Tranter and Morris, 1991; Browne *et al.*, 2022a). However, there have been other studies that have not associated lameness in dairy cows with roadway condition. O'Connor *et al.* (2020) and Browne *et al.* (2022a) reported roadway condition was not associated as a risk factor for lameness (Table 3), this may be due to the fact only 50 m of each roadway closest to the milking parlour was assessed, with the exception of the roadway in use on the day of the visit. However, the study by Browne *et al.* (2022a) did report loose stones in paddock entrances as a risk factor.

Roadways with increased traffic and repeated faecal depositions from the herd create a muddy appearance which were recorded as having a high contamination of *Streptococcus uberis* (mastitis causing pathogen) (Lopez-Benavides *et al.*, 2007) and may lead to increased SCC on commercial farms (O'Brien *et al.*, 2009). White *et al.* (2001) observed that the quantity of defecations was shown to be connected with the amount of time animals remained static in a certain location, with the largest densities seen around water troughs and farm roadways. Reducing congestion points on roadways through avoidance of bottlenecks was noted to be associated with improved roadway conditions for animal movement (Maher *et al.*, 2023b, Fenton *et al.*, 2021). Another potential strategy to remove

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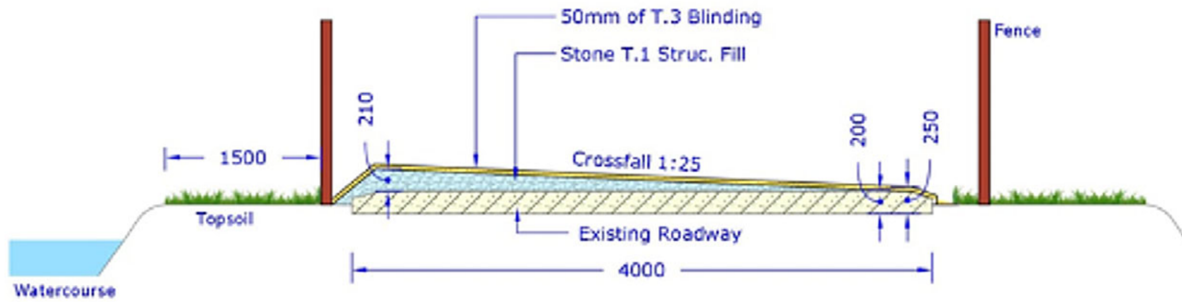

Figure 3. Farm roadway redesigned to direct roadway runoff away from stream onto pasture with a resurfaced camber (all units are in mm). Figure sourced from (DAFM, 2021).

faecal depositions or reduce muddy conditions on farm roadways is to improve water runoff, which will also allow faecal depositions on roadways to be washed onto adjoining paddocks. Maher *et al.* (2023b) observed on commercial farms an improved roadway surface condition where water runoff into adjoining pasture could freely occur, indicating faecal material may have been washed off the road surface.

Soiled water on farm roadways

Rice *et al.* (2022) described farm roadways as a risk factor for nutrient loss, while Ledgard *et al.* (1999) demonstrated in New Zealand approximately 15% of nitrogen is deposited on farm roadways and the milking parlour. Farm roadways are also reported to have elevated concentration of phosphorous content present when compared to fresh stone roadway aggregates and surrounding fields (Fenton *et al.*, 2022). While roadways that are in frequent use (100 m from the farmyard) experience higher frequency of excreta depositions than those on the periphery on the farm (Monaghan and Smith, 2012). This increased occurrence necessitates heightened attention to prevent runoff from these areas entering water courses. Efforts to manage and mitigate potential environmental impacts should be particularly focused on these more frequented roadways to ensure responsible agricultural practices and water quality preservation.

It is the case that roadway runoff is already being redirected and discharged from the majority of farm roadways for maintenance purposes to provide a smooth walking surfaces for cows, worryingly 12% of farm roadways reported to have discharge entering water courses (Maher *et al.*, 2023b), as a result, the starting point is not neutral from a pollution perspective (Monaghan and Smith, 2012; Fenton *et al.*, 2021). A detailed review of the potential strategies to prevent roadway runoff from entering water courses has been highlighted by Fenton *et al.* (2021). Recommendations included the use of grade breaks (creation of a reverse gradient) to direct water to adjoining pasture or the implementation of a resurfaced camber to direct water away from a water course (Figure 3).

Nevertheless, not every roadway can be remedied through camber adjustment, especially considering variations in soil type or topography of the landscape. In instances where the farm roadway is positioned below that of the surrounding area, it may be necessary to elevate the profile of the roadway in relation to the adjoining pasture (Bloser and Sheetz, 2012).

Other strategies to reduce roadway runoff are the reduction of time spent on farm roadways (Fenton *et al.*, 2021). This can be improved by using optimal roadway surfaces and roadway widths, which can improve cow throughput (Telezhenko and Bergsten, 2005; Buijs *et al.*, 2019; Maher *et al.*, 2023b).

Conclusion

The development of rotational grazing has significantly impacted product output per hectare in pasture-based systems. However, effective management of pastures within these rotational grazing systems also plays a crucial role in influencing production per hectare. Studies highlighted in this review emphasise the pivotal role of HA in enhancing milk production per cow. Managing pasture swards to achieve optimal PGHM is equally vital, with swards ranging between 1200 and 1500 kg DM/ha (> 4 cm) exhibiting a higher leaf proportion compared to those with higher PGHM.

In rotational grazing systems, an additional critical metric alongside PGHM is the PoGSH. Failure to attain optimal PoGSH not only diminishes pasture utilisation but also compromises pasture quality for subsequent grazings, subsequently impacting farm profitability. Determining the correct paddock size for 24- to 36-hour allocations per paddock and achieving optimal PGHM are key considerations to ensure adequate intake for all animals, particularly primiparous animals.

The literature reviewed also delves into the factors influencing walking distance on dairy farms. While previous studies primarily measured the distance to the furthest paddock, recent research has investigated the impact of milking parlour location and the incorporation of new lands into the grazing platform on the efficiency of animal movement between pasture and the milking parlour. A centrally located milking parlour within the grazing platform has been associated with increased farm roadway network efficiency. The studies further assessed the influence of different roadway surfaces and widths on dairy herd movement, revealing that smoother surfaces and wider roadways enhance cow throughput. However, there remains a notable gap in research regarding the impact of roadway camber and slopes on cow throughput on farm roadways. This research needs to be approached from a herd-scale perspective, as herds are typically moved as cohesive groups to the milking parlour. Additionally, studies should focus on the total time required for the dairy herd to transverse from pasture to the milking parlour via farm roadways, coupled with an exploration of potential capital expenditures for necessary upgrades.

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References

Adams AE, Lombard JE, Fossler CP, Román-Muñiz IN and Kopral AC (2017) Associations between housing and management practices and the prevalence of lameness, hock lesions, and thin cows on US dairy operations. *Journal of Dairy Science* **100**, 2119–2136.

Allen VG, Batello C, Berretta EJ, Hodgson J, Kothmann M, Li X, Mcivor J, Milne J, Morris C, Peeters A, Sanderson M, Forage T and Committee GT (2011) An international terminology for grazing lands and grazing animals. *Grass and Forage Science* **66**, 2–28.

Alsaaod M, Huber S, Beer G, Kohler P, Schüpbach-Regula G and Steiner A (2017) Locomotion characteristics of dairy cows walking on pasture and the effect of artificial flooring systems on locomotion comfort. *Journal of Dairy Science* **100**, 8330–8337.

Arkins S (1981) Lameness in dairy-cows. 1. *Irish Veterinary Journal* **35**, 135–140.

Beggs D, Jongman E, Hemsworth P and Fisher A (2018) Implications of prolonged milking time on time budgets and lying behavior of cows in large pasture-based dairy herds. *Journal of Dairy Science* **101**, 10391–10397.

Beggs DS, Fisher AD, Jongman EC and Hemsworth PH (2015) A survey of Australian dairy farmers to investigate animal welfare risks associated with increasing scale of production. *Journal of Dairy Science* **98**, 5330–5338.

Benchaar C and Hassanat F (2020) Frequency of diet delivery to dairy cows: Effect on nutrient digestion, rumen fermentation, methane production, nitrogen utilization, and milk production. *Journal of Dairy Science* **103**, 7094–7109.

Berry E, Stoddart M and Broughan J (2008) Locomotion scoring of cattle using a lameness-speed index on different types of track. *The Veterinary Record* **163**, 601.

Bloser S and Sheetz B (2012) *Sediment Production from Unpaved Oil Well Access Road in the Allegheny National Forest*. University Park (PA): Center for dirt and gravel road studies, The Pennsylvania State University. Report prepared for United States Department of Energy, National Energy Technology Laboratory through URS Corporation and USDA Northern Research Station.

Bran JA, Daros RR, Von Keyserlingk MAG, Leblanc SJ and Hötzel MJ (2018) Cow- and herd-level factors associated with lameness in small-scale grazing dairy herds in Brazil. *Preventive Veterinary Medicine* **151**, 79–86.

Brosh A, Henkin Z, Ungar ED, Dolev A, Shabtay A, Orlov A, Yehuda Y and Aharoni Y (2010) Energy cost of activities and locomotion of grazing cows: a repeated study in larger plots1. *Journal of Animal Science* **88**, 315–323.

Brougham RW (1955) A study in rate of pasture growth. *Australian Journal of Agricultural Research* **6**, 804–812.

Browne N, Hudson CD, Crossley RE, Sugrue K, Kennedy E, Huxley JN and Conneely M (2022a) Cow- and herd-level risk factors for lameness in partly housed pasture-based dairy cows. *Journal of Dairy Science* **105**, 1418–1431.

Browne N, Hudson CD, Crossley RE, Sugrue K, Kennedy E, Huxley JN and Conneely M (2022b) Lameness prevalence and management practices on Irish pasture-based dairy farms. *Irish Veterinary Journal* **75**, 14.

Buijs S, Scoley G and McConnell D (2019) Artificial grass as an alternative laneway surface for dairy cows walking to pasture. *Animals* **9**, 891.

Burow E, Rousing T, Thomsen PT, Otten ND and Sørensen JT (2013) Effect of grazing on the cow welfare of dairy herds evaluated by a multidimensional welfare index. *Animal* **7**, 834–842.

C.S.O. (2020) Central Statistics Office Demographic Profile of Farm Holders. Available at https://www.cso.ie/en/releasesandpublications/ep/p-coa/censusofagriculture2020-preliminaryresults/demographicprofileoffarmholders (accessed 04th December 2023).

Chapinal N, De Passillé AM, Pastell M, Hänninen L, Munksgaard L and Rushen J (2011) Measurement of acceleration while walking as an automated method for gait assessment in dairy cattle. *Journal of Dairy Science* **94**, 2895–2901.

Chapman DF, Tharmaraj J, Agnusdei M and Hill J (2012) Regrowth dynamics and grazing decision rules: further analysis for dairy production systems based on perennial ryegrass (*Lolium perenne* L.) pastures. *Grass and Forage Science* **67**, 77–95.

Chesterton RN (2011) Cow tracks and cow flow and how they apply to lameness. Cattle Lameness Conference, 13–19.

Chesterton RN (2015) The lame game-Chile vs New Zealand–can we both be winners. 18th International Symposium and 10th Conference on Lameness in Ruminants, Valdivia, Chile, 26–29.

Chesterton RN, Pfeiffer DU, Morris RS and Tanner CM (1989) Environmental and behavioural factors affecting the prevalence of foot lameness in New Zealand dairy herds — a case-control study. *New Zealand Veterinary Journal* **37**, 135–142.

Claffey A, Delaby L, Boland TM and Egan M (2020) Implications of adapting autumn grazing management on spring herbage production––the effect on late lactation milk production and the subsequent response in early lactation animal performance. *Livestock Science* **231**, 103870.

Claffey A, Delaby L, Galvin N, Boland T and Egan M (2019) The effect of spring grass availability and grazing rotation length on the production and quality of herbage and milk in early spring. *The Journal of Agricultural Science* **157**, 434–448.

Clarke P (2016) Chapter 21: Grazing Infrastructure, Dairy Farm Manual, Section 8, Cattle Health. Teagasc. Available at https://www.teagasc.ie/media/website/animals/dairy/GrazingInfrastructure.pdf (accessed 04th December 2023).

Colusso PI, Clark CE, Green AC and Lomax S (2021) The effect of a restricted feed ration on dairy cow response to containment from feed using a virtual fence. *Frontiers in Animal Science* **2**, 710648.

Combellas J and Hodgson J (1979) Herbage intake and milk production by grazing dairy cows 1. The effects of variation in herbage mass and daily herbage allowance in a short-term trial. *Grass and Forage Science* **3**, 209–214.

Coulon J and Pradel P (1997) Effect of walking on roughage intake and milk yield and composition of Montbeliarde and Tarentaise dairy cows. *Annales de Zootechnie* **46**, 139–146.

Coulon JB, Pradel P, Cochard T and Poutrel B (1998) Effect of extreme walking conditions for dairy cows on milk yield, chemical composition, and somatic cell count. *Journal of Dairy Science* **81**, 994–1003.

Crossley RE, Bokkers EA, Browne N, Sugrue K, Kennedy E, De Boer IJ and Conneely M (2021) Assessing dairy cow welfare during the grazing and housing periods on spring-calving, pasture-based dairy farms. *Journal of Animal Science* **99**, skab093.

Curran J, Delaby L, Kennedy E, Murphy J, Boland T and O'Donovan M (2010) Sward characteristics, grass dry matter intake and milk production performance are affected by pre-grazing herbage mass and pasture allowance. *Livestock Science* **127**, 144–154.

D'Hour P, Hauwuy A, Coulon J and Garel J (1994) Walking and dairy cattle performance. *Annales de Zootechnie* **43**, 369–378.

DAFM (2021) Department of Agriculture Food and the Marine. 2019. Minimum specifications for farm roadways, S199. Available at https://www.gov.ie/en/collection/65f5b-tams-farm-building-and-structures-specifications (accessed 04th December 2023).

Dairy NZ (2023) New Zealand Dairy Statistics 2021–22. Available at https://www.dairynz.co.nz/media/uzeekwgr/nz-dairy-statistics-2021-22-web.pdf (accessed 04th December 2023).

Dairy Australia (2023) Australian Dairy Industry in Focus. Available at https://www.dairyaustralia.com.au/industry-statistics/industry-reports/australian-dairy-industry-in-focus (accessed 04th December 2023).

Dalley D, Roche J, Moate P and Grainger C (2001) More frequent allocation of herbage does not improve the milk production of dairy cows in early lactation. *Australian Journal of Experimental Agriculture* **41**, 593–599.

Daros RR, Weary DM and Von Keyserlingk MAG (2022) Invited review: Risk factors for transition period disease in intensive grazing and housed dairy cattle. *Journal of Dairy Science* **105**, 4734–4748.

Di Marco ON and Aello MS (1998) Energy cost of cattle walking on the level and on a gradient. *Journal of Range Management* **51**, 9–13.
Dillon E, Donnellan T, Moran B and Lennon J (2023) Teagasc National Farm Survey 2022, Agriculture Economics and Farm surveys Department, Teagasc, Athenry, Co. Galway. Available at https://www.teagasc.ie/media/website/publications/2023/NFSfinalreport2022.pdf (accessed 04th December 2023).
Dillon P, Roche J, Shalloo L and Horan B (2005) Optimising financial return from grazing in temperate pastures." In *Utilisation of Grazed Grass in Temperate Animal Systems*. Wageningen: Wageningen Academic.
Donaghy D, Bryant R, Cranston L, Egan M, Griffiths W, Kay J, Pembleton K and Tozer K (2021) Will current rotational grazing management recommendations suit future intensive pastoral systems?. *NZGA: Research and Practice Series* **17**, 225–242.
Donaghy D and Fulkerson WJ (1998) Priority for allocation of water-soluble carbohydrate reserves during regrowth of Lolium perenne. *Grass and Forage Science* **53**, 211–218.
Doyle PR, McGee M, Moloney AP, Kelly AK and O'Riordan EG (2023) Effect of pre-grazing herbage mass and post-grazing sward height on herbage production and intake and performance of suckler-bred steers within a weanling-to-beef production system. *The Journal of Agricultural Science* **161**, 297–312.
Edwards JP, McMillan N, Bryant RH and Kuhn-Sherlock B (2022) Reducing milking frequency from twice each day to three times each two days affected protein but not fat yield in a pasture-based dairy system. *Journal of Dairy Science* **105**, 4206–4217.
Fallon T, Tuohy P and Maher PJ (2023) Planning for good grazing infrastructure. Irish Dairying, Securing a Sustainable Future, Teagasc Moorepark 23. Available at https://www.teagasc.ie/media/website/publications/2023/Moorepark23–Book.pdf (accessed 15th November 2023).
Faye B and Lescourret F (1989) Environmental factors associated with lameness in dairy cattle. *Preventive Veterinary Medicine* **7**, 267–287.
Fenger F, Casey AI, Holden NM and Humphreys J (2022) Access time to pasture under wet soil conditions: Effects on productivity and profitability of pasture–based dairying. *Journal of Dairy Science* **105**, 4189–4205.
Fenton O, Rice P, Murnane J, Tuohy P and Daly K (2022) Dairy farm roadway surface materials as a P-source within the nutrient transfer continuum framework. *Frontiers in Environmental Science* **10**, 878166.
Fenton O, Tuohy P, Daly K, Moloney T, Rice P and Murnane JG (2021) A review of on-farm roadway runoff characterisation and potential management options for Ireland. *Water, Air, & Soil Pollution* **232**, 1–22.
Fernández AIR, O'Donovan M, Curran J and Rodríguez AG (2011) Effect of pre-grazing herbage mass and daily HA on perennial ryegrass swards structure, pasture dry matter intake and milk performance of Holstein-Friesian dairy cows. *Spanish Journal of Agricultural Research* **9**, 86–99.
Finneran E, Crosson P, O'Kiely P, Shalloo L, Forristal D and Wallace M (2012) Stochastic simulation of the cost of home–produced feeds for ruminant livestock systems. *The Journal of Agricultural Science* **150**, 123–139.
Flower FC, De Passillé AM, Weary DM, Sanderson DJ and Rushen J (2007) Softer, higher-friction flooring improves gait of cows with and without sole ulcers. *Journal of Dairy Science* **90**, 1235–1242.
Flower FC and Weary D (2009) Gait assessment in dairy cattle. *Animal* **3**, 87–95.
Fulkerson WJ and Donaghy DJ (2001) Plant-Soluble carbohydrate reserves and senescence - key criteria for developing an effective grazing management system for ryegrass-based pastures: a review. *Australian Journal of Experimental Agriculture* **41**, 261–275.
Fulkerson WJ (1994) Effect of redefoliation on the regrowth and water soluble carbohydrate content of Lolium perenne. *Australian Journal of Agricultural Research* **45**, 1809–1815.
Fulkerson WJ and Slack K (1995) Leaf number as a criterion for determining defoliation time for Lolium perenne: 2. Effect of defoliation frequency and height. *Grass and Forage Science* **50**, 16–20.
Ganche E, Delaby L, O'Donovan M, Boland TM, Galvin N and Kennedy E (2013) Post-grazing sward height imposed during the first 10 weeks of lactation: Influence on early and total lactation dairy cow production, and spring and annual sward characteristics. *Livestock Science* **157**, 299–311.
Goliński P, Sobolewska P, Stefańska B and Golińska B (2022) Virtual fencing technology for cattle management in the pasture feeding system—a review. *Agriculture* **13**, 91.
Granzin B (2003) The effect of frequency of pasture allocation on the milk production, pasture intake and behaviour of grazing cows in a subtropical environment. *Tropical Grasslands* **37**, 84–93.
Groeneveld A, Peerlings J, Bakker M and Heijman W (2016) The effect of milk quota abolishment on farm intensity: shifts and stability. *NJAS - Wageningen Journal of Life Sciences* **77**, 25–37.
Hall LS, Bryant RH, Kuhn-Sherlock B and Edwards JP (2023) Comparison of dairy cow step activity under different milking schedules. *Animal Production Science* **64**, AN22354.
Hanrahan L, Geoghegan A, O'Donovan M, Griffith V, Ruelle E, Wallace M and Shalloo L (2017) PastureBase Ireland: a grassland decision support system and national database. *Computers and Electronics in Agriculture* **136**, 193–201.
Hanrahan L, McHugh N, Hennessy T, Moran B, Kearney R, Wallace M and Shalloo L (2018) Factors associated with profitability in pasture-based systems of milk production. *Journal of Dairy Science* **101**, 5474–5485.
Hanrahan L, Tuohy P, Mchugh N, O'Loughlin J, Moran B, Dillon P, Breen J, Wallace M and Shalloo L (2019) A description and evaluation of the physical and financial characteristics of dairy farms operating on soil types classified as poorly drained and associated with high rainfall. *Grass and Forage Science* **74**, 548–558.
Harris D, Hibburt C, Anderson G, Younis P, Fitspatrick D, Dunn A, Parsons I and Mcbeath N (1988) The incidence, cost and factors associated with foot lameness in dairy cattle in south-western Victoria. *Australian Veterinary Journal* **65**, 171–176.
Hart KD, McBride BW, Duffield TF and Devries TJ (2014) Effect of frequency of feed delivery on the behavior and productivity of lactating dairy cows. *Journal of Dairy Science* **97**, 1713–1724.
Hennessy D, Delaby L, Van Den Pol-Van Dasselaar A and Shalloo L (2020) Increasing grazing in dairy cow milk production systems in Europe. *Sustainability* **12**, 2443.
Herbin T, Hennessy D, Richards KG, Piwowarczyk A, Murphy JJ and Holden NM (2011) The effects of dairy cow weight on selected soil physical properties indicative of compaction. *Soil Use and Management* **27**, 36–44.
Hoogendoorn C, Holmes C and Chu A (1992) Some effects of herbage composition, as influenced by previous grazing management, on milk production by cows grazing on ryegrass/white clover pastures. 2. Milk production in late spring/summer: effects of grazing intensity during the preceding spring period. *Grass and Forage Science* **47**, 316–325.
Hund A, Logroño JC, Ollhoff RD and Kofler J (2019) Aspects of lameness in pasture based dairy systems. *The Veterinary Journal* **244**, 83–90.
Hussein AN (2019) *Effects of Social Dominance on Milk Production and Grazing Behaviour of Lactating Dairy Cows: A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy at Lincoln University*. Lincoln: Lincoln University.
Hussein AN, Al-Marashdeh O, Bryant RH and Edwards G (2016) Relationship between social dominance and milk production of dairy cows grazing pasture. *New Zealand Society of Animal Production* **76**, 69–72.
Hyland JJ, Heanue K, McKillop J and Micha E (2018a) Factors underlying farmers' intentions to adopt best practices: the case of paddock based grazing systems. *Agricultural Systems* **162**, 97–106.
Hyland JJ, Heanue K, McKillop J and Micha E (2018b) Factors influencing dairy farmers' adoption of best management grazing practices. *Land Use Policy* **78**, 562–571.
ICBF (2021) Irish Cattle Breeding Association Dairy Cow Population by County 2017–2021 – ICBF. Available at https://www.icbf.com/dairy-cow-population-by-county-2017-2021/ (accessed 04th December 2023).
Jordon MW, Winter DM and Petrokofsky G (2023) Advantages, disadvantages, and reasons for non-adoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms. *Agroecology and Sustainable Food Systems* **47**, 330–354.
Jung J, Yngvesson J and Jensen P (2002) Effects of reduced time on pasture caused by prolonged walking on behaviour and production of Mpwapwa Zebu cattle. *Grass and Forage Science* **57**, 105–112.

Kaufmann L, Münger A, Rérat M, Junghans P, Görs S, Metges C and Dohme-Meier F (2011) Energy expenditure of grazing cows and cows fed grass indoors as determined by the 13C bicarbonate dilution technique using an automatic blood sampling system. *Journal of Dairy Science* **94**, 1989–2000.

Kelly P, Shalloo L, Wallace M and Dillon P (2020) The Irish dairy industry – Recent history and strategy, current state and future challenges. *International Journal of Dairy Technology* **73**, 309–323.

Kennedy E, Curran J, Mayes B, McEvoy M, Murphy J and O'Donovan M (2011) Restricting dairy cow access time to pasture in early lactation: the effects on milk production, grazing behaviour and dry matter intake. *Animal* **5**, 1805–1813.

Kennedy E, McEvoy M, Murphy JP and O'Donovan M (2009) Effect of restricted access time to pasture on dairy cow milk production, grazing behavior, and dry matter intake. *Journal of Dairy Science* **92**, 168–176.

Klopčič M, Kuipers A, Malak-Rawlikowska A, Stalgiene A, Ule A and Erjavec K (2019) Dairy farmers' strategies in four European countries before and after abolition of the milk quota. *Land Use Policy* **88**, 104169.

Krohn C and Konggaard S (1979) Effects of isolating first-lactation cows from older cows. *Livestock Production Science* **6**, 137–146.

Läpple D, Carter CA and Buckley C (2022) EU milk quota abolition, dairy expansion, and greenhouse gas emissions. *Agricultural Economics* **53**, 125–142.

Läpple D, Hennessy T and O'Donovan M (2012) Extended grazing: a detailed analysis of Irish dairy farms. *Journal of Dairy Science* **95**, 188–195.

Läpple D and Sirr G (2019) Dairy intensification and quota abolition: a comparative study of production in Ireland and the Netherlands. *EuroChoices* **18**, 26–32.

Lawrence PR and Stibbards RJ (1990) The energy costs of walking, carrying and pulling loads on flat surfaces by Brahman cattle and swamp buffalo. *Animal Science* **50**, 29–39.

Le Du YLP, Combellas J, Hodgson J and Baker RD (1979) Herbage intake and milk production by grazing dairy cows 2. The effects of level of winter feeding and daily herbage allowance. *Grass and Forage Science* **34**, 249–260.

Ledgard SF, Penno JW and Sprosen MS (1999) Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *The Journal of Agricultural Science* **132**, 215–225.

Lee J, Donaghy D and Roche J (2007) The effect of grazing severity and fertiliser application during winter on herbage regrowth and quality of perennial ryegrass (Lolium perenne L.). *Australian Journal of Experimental Agriculture* **47**, 825–832.

Lee JM, Donaghy DJ and Roche JR (2008) Short communication: effect of postgrazing residual pasture height on milk production. *Journal of Dairy Science* **91**, 4307–4311.

Lopez-Benavides MG, Williamson JH, Pullinger GD, Lacy-Hulbert SJ, Cursons RT and Leigh AJ (2007) Field observations on the variation of streptococcus uberis populations in a pasture-based dairy farm. *Journal of Dairy Science* **90**, 5558–5566.

Macdonald K, Glassey C, Kay J and Wims C (2018) Effect of post-grazing residual pasture height in spring on pasture quality in summer and autumn. Sustainable meat and milk production from grasslands. *Grassland Science of Europe* **23**, 277–279.

Macdonald K, Penno J, Lancaster J and Roche J (2008) Effect of stocking rate on pasture production, milk production, and reproduction of dairy cows in pasture-based systems. *Journal of Dairy Science* **91**, 2151–2163.

Macdonald KA, Beca D, Penno JW, Lancaster JAS and Roche JR (2011) Short communication: effect of stocking rate on the economics of pasture-based dairy farms. *Journal of Dairy Science* **94**, 2581–2586.

Maher PJ, Egan M, Murphy M and Tuohy P (2023a) Assessment of the current performance of grazing infrastructure across Irish dairy farms. *Journal of Dairy Science* **106**, 4759–4772.

Maher PJ, Murphy MD, Egan M and Tuohy P (2023b) An evaluation of parameters that affect dairy herd movement on Irish pasture-based farms. *The Journal of Agricultural Science* **161**, 589–598.

Mäntysaari P, Khalili H and Sariola J (2006) Effect of feeding frequency of a total mixed ration on the performance of high-yielding dairy cows. *Journal of Dairy Science* **89**, 4312–4320.

Markus SB, Bailey DW and Jensen D (2014) Comparison of electric fence and a simulated fenceless control system on cattle movements. *Livestock Science* **170**, 203–209.

Matthewman RW (1989) *The Effects of Exercise on the Lactational Performance of Cattle.* Edinburgh: University of Edinburgh.

Mayne C, Newberry R, Woodcock S and Wilkins R (1987) Effect of grazing severity on grass utilization and milk production of rotationally grazed dairy cows. *Grass and Forage Science* **42**, 59–72.

McCarthy B, Delaby L, Pierce K, Journot F and Horan B (2011) Meta-analysis of the impact of stocking rate on the productivity of pasture-based milk production systems. *Animal* **5**, 784–794.

McCarthy B, Pierce K, Delaby L, Brennan A, Fleming C and Horan B (2013) The effect of stocking rate and calving date on grass production, utilization and nutritive value of the sward during the grazing season. *Grass and Forage Science* **68**, 364–377.

McEvoy M, O'Donovan M, Kennedy E, Murphy J, Delaby L and Boland T (2009) Effect of pregrazing herbage mass and pasture allowance on the lactation performance of Holstein-Friesian dairy cows. *Journal of Dairy Science* **92**, 414–422.

McMeekan CP and Walshe MJ (1963) The inter-relationships of grazing method and stocking rate in the efficiency of pasture utilization by dairy cattle. *The Journal of Agricultural Science* **61**, 147–166.

McSweeney D, O'Brien B, Coughlan NE, Férard A, Ivanov S, Halton P and Umstatter C (2020) Virtual fencing without visual cues: design, difficulties of implementation, and associated dairy cow behaviour. *Computers and Electronics in Agriculture* **176**, 105613.

Mee JF and Boyle AL (2020) Assessing whether dairy cow welfare is "better" in pasture-based than in confinement-based management systems. *New Zealand Veterinary Journal* **68**, 168–177.

Menegazzi G, Giles PY, Oborsky M, Fast O, Mattiauda DA, Genro TCM and Chilibroste P (2021) Effect of post-grazing sward height on ingestive behavior, dry matter intake, and milk production of holstein dairy cows. *Frontiers in Animal Science* **2**, 742685.

Menneer JC, Ledgard SF, Mclay ACD and Silvester WB (2005) The effects of treading by dairy cows during wet soil conditions on white clover productivity, growth and morphology in a white clover–perennial ryegrass pasture. *Grass and Forage Science* **60**, 46–58.

Michell P, Fulkerson W and Michell PJ (1987) Effect of grazing intensity in spring on pasture growth, composition and digestibility, and on milk production by dairy cows. *Australian Journal of Experimental Agriculture* **27**, 35–40.

Monaghan R and Smith L (2012) Contaminant losses in overland flow from dairy farm laneways in southern New Zealand. *Agriculture, Ecosystems & Environment* **159**, 170–175.

Muñoz C, Letelier AP, Ungerfeld EM, Morales JM, Hube S and Pérez-Prieto AL (2016) Effects of pregrazing herbage mass in late spring on enteric methane emmisions, dry matter intake, and milk production of dairy cows. *Journal of Dairy Science* **99**, 7945–7955.

Neave HW, Edwards JP, Thoday H, Saunders K, Zobel G and Webster JR (2021) Do walking distance and time away from the paddock influence daily behaviour patterns and milk yield of grazing dairy cows?. *Animals* **11**, 2903.

NRC (2001) *Nutrient Requirements of Dairy Cattle.* Washington, D.C.: National Academy Press.

O'Brien B, Berry D, Kelly P, Meaney WJ and O'Callaghan EJ (2009) *A Study of the Somatic Cell Count (SCC) of Irish Milk from Herd Management and Environmental Perspectives.* Oak Park, Carlow: Teagasc.

O'Connor AH, Bokkers EAM, De Boer IJM, Hogeveen H, Sayers R, Byrne N, Ruelle E, Engel B and Shalloo L (2020) Cow and herd-level risk factors associated with mobility scores in pasture-based dairy cows. *Preventive Veterinary Medicine* **181**, 105077.

Olmos G, Boyle L, Hanlon A, Patton J, Murphy JJ and Mee JF (2009) Hoof disorders, locomotion ability and lying times of cubicle-housed compared to pasture-based dairy cows. *Livestock Science* **125**, 199–207.

Palma-Molina P, Hennessy T, Dillon E, Onakuse S, Moran B and Shalloo L (2023) Evaluating the effects of grass management technologies on the physical, environmental, and financial performance of Irish pasture-based dairy farms. *Journal of Dairy Science* **106**, 6249–6262.

Peyraud JL and Delagarde R (2013) Managing variations in dairy cow nutrient supply under grazing. *Animal* **7**, 57–67.

Phelan P, Casey AI and Humphreys J (2013b) The effect of target postgrazing height on sward clover content, herbage yield, and dairy production from grass-white clover pasture. *Journal of Dairy Science* **96**, 1598–1611.

Phelan P, Keogh B, Casey AI, Necpalova M and Humphreys J (2013a) The effects of treading by dairy cows on soil properties and herbage production for three white clover-based grazing systems on a clay loam soil. *Grass and Forage Science* **68**, 548–563.

Phelps A and Drew B (1992) Vastly superior first lactations when heifers fed separately. *Feedstuffs. May* **11**, 11–13.

Phillips CJC and Morris ID (2001) The locomotion of dairy cows on floor surfaces with different frictional properties. *Journal of Dairy Science* **84**, 623–628.

Phillips CJC and Rind IM (2002) The effects of social dominance on the production and behavior of grazing dairy cows offered forage supplements. *Journal of Dairy Science* **85**, 51–59.

Pollock JG, Gordon AW, Huson KM and McConnell AD (2020) The effect of frequency of fresh pasture allocation on pasture utilisation and the performance of high yielding dairy cows. *Animals* **10**, 2176.

Pollock JG, Gordon AW, Huson KM and McConnell AD (2022) The effect of frequency of fresh pasture allocation on the feeding behaviour of high production dairy cows. *Animals* **12**, 243.

Pratumsuwan S (1994) Effect of walking extra distances on the performance of grazing dairy cows in early lactation: a thesis presented in partial fulfilment of the requirements for the degree of Master of Agricultural Science, Massey university, Palmerston North, New Zealand. Master of Agricultural Science (M.Agr. Sc.) Masters, Massey University.

Ranjbar S, Rabiee A, Ingenhoff L and House J (2020) Farmers' perceptions and approaches to detection, treatment and prevention of lameness in pasture-based dairy herds in New South Wales, Australia. *Australian Veterinary Journal* **98**, 264–269.

Ranjbar S, Rabiee AR, Gunn A and House JK (2016) Identifying risk factors associated with lameness in pasture-based dairy herds. *Journal of Dairy Science* **99**, 7495–7505.

Rattray PV, Brooks I and Nicol AM (2007) *Pasture and Supplements for Grazing Animals*. Oamaru: New Zealand Society of Animal Production.

Ribeiro JMDCR, Brockway JM and Webster AJF (1977) A note on the energy cost of walking in cattle. *Animal Science* **25**, 107–110.

Rice P, Daly K, Tuohy P, Murnane JG, Nag R and Fenton O (2022) Evaluating connectivity risk of farm roadway runoff with waters - development and sensitivity analysis of a semi quantitative risk model. *Science of The Total Environment* **851**, 158114.

Roche J, Berry D, Bryant A, Burke C, Butler S, Dillon P, Donaghy D, Horan B, MacDonald K and MacMillan K (2017a) A 100-year review: a century of change in temperate grazing dairy systems. *Journal of Dairy Science* **100**, 10189–10233.

Roche J, Washburn S, Berry D, Donaghy D and Horan B (2017b) Seasonal pasture-based dairy production systems." In *Large Dairy Herd Management*. Champaign, IL: American Dairy Science Association.

Roche SM, Renaud DL, Saraceni J, Kelton DF and DeVries TJ (2023) Invited review: prevalence, risk factors, treatment, and barriers to best practice adoption for lameness and injuries in dairy cattle—a narrative review. *Journal of Dairy Science* **107**, 3347–3366.

Rushen J and De Passillé AM (2006) Effects of roughness and compressibility of flooring on cow locomotion. *Journal of Dairy Science* **89**, 2965–2972.

Schein MW and Fohrman MH (1955) Social dominance relationships in a herd of dairy cattle. *The British Journal of Animal Behaviour* **3**, 45–55.

Sottysiak T and Nogalski Z (2010) The effects of social hierarchy in a dairy cattle herd on milk yield. *Polish Journal of Natural Sciences* **25**, 22–23.

Stakelum G and Dillon P (2004) The effect of herbage mass and allowance on herbage intake, diet composition and ingestive behaviour of dairy cows. *Irish Journal of Agricultural and Food Research* **43**(1), 17–30.

Teagasc (2021) Moorepark Dairy Levy Research Update. Teagasc heavy soils programme – lessons learned. Teagasc Animal and Grassland research and Innovation Centre Moorepark, Fermoy, Co. Cork. Available at https://www.teagasc.ie/media/website/publications/2021/Heavy-Soils-Lessons-Learned_May-2021.pdf (accessed on 20th November 2023).

Telezhenko E and Bergsten C (2005) Influence of floor type on the locomotion of dairy cows. *Applied Animal Behaviour Science* **93**, 183–197.

Thomson NA and Barnes ML (1993) Effect of distance walked on dairy production and milk quality. *Proceedings of the New Zealand Society of Animal Production* **53**, 69–72.

Tranter W and Morris R (1991) A case study of lameness in three dairy herds. *New Zealand Veterinary Journal* **39**, 88–96.

Tucker C, Verkerk GA, Small BH, Tarbottom IS and Webster JR (2005) Animal welfare in large dairyherds: a survey of current practices. *New Zealand Society Of Animal Production* **65**, 127–131.

Tuñon G, Lopez-Villalobos N, Kemp P, Kennedy E, Hennessy D and O'Donovan M (2011) Effect of pre-grazing herbage mass on grazing behaviour, grass dry matter intake and milk production of dairy cows. *Proceedings of the New Zealand Society of Animal Production* **71**, 28–32.

Tuñon G, O'Donovan M, Lopez Villalobos N, Hennessy D, Kemp P and Kennedy E (2014) Spring and autumn animal treading effects on pre-grazing herbage mass and tiller density on two contrasting pasture types in Ireland. *Grass and Forage Science* **69**, 502–513.

Undersander DJ, Albert B, Cosgrove D, Johnson D and Peterson P (2002) *Pastures for Profit: A Guide to Rotational Grazing*. Madison, WI, USA: Cooperative Extensiton Publications, University of Wisconsin-Extension.

Van den Pol A, De Vliegher A, Hennessy D, Isselstein J and Peyraud JL (2015) *The Future of Grazing: Proceedings, Third Meeting of the EGF Working Group" Grazing" (No. 906)*. Wageningen: Wageningen UR Livestock Research.

Van Den Pol A, Vellinga TV, Johansen A and Kennedy E (2005) To graze or not to graze, thats the question. *Proceedings of the 22nd. General Meeting of the European Grassland Federation* **13**, 706–716.

Van Den Pol-Van Dasselaar A, Becker T, Botana AF, Hennessy T and Peratoner G (2018) Social and economic impacts of grass based ruminant production. *Grassland Science in Europe* **23**, 697–708.

Verdon M, Rawnsley R, Raedts P and Freeman M (2018) The behaviour and productivity of mid-lactation dairy cows provided daily pasture allowance over 2 or 7 intensively grazed strips. *Animals* **8**, 115.

Von Keyserlingk MAG, Barrientos A, Ito K, Galo E and Weary DM (2012) Benchmarking cow comfort on North American freestall dairies: Lameness, leg injuries, lying time, facility design, and management for high-producing Holstein dairy cows. *Journal of Dairy Science* **95**, 7399–7408.

Walsh S, Delaby L, Kennedy M, Galvin N, McKay ZC and Egan M (2024) Intake profile, milk production and energy balance of early lactation spring calving Holstein Friesian and Jersey x Holstein Friesian dairy cows in high utilisation pasture-based systems. *Journal of Dairy Science* **10**, 8058–8071.

Wang T, Jin H, Kreuter U, Feng H, Hennessy DA, Teague R and Che Y (2020) Challenges for rotational grazing practice: views from non-adopters across the Great Plains, USA. *Journal of Environmental Management* **256**, 109941.

Werner J, Umstatter C, Kennedy E, Grant J, Leso L, Geoghegan A, Shalloo L, Schick M and O'Brien B (2019) Identification of possible cow grazing behaviour indicators for restricted grass availability in a pasture-based spring calving dairy system. *Livestock Science* **220**, 74–82.

White S, Sheffield R, Washburn S, King L and Green Jr J (2001) Spatial and time distribution of dairy cattle excreta in an intensive pasture system. *Journal of Environmental Quality* **30**, 2180–2187.

Wilkinson JM, Lee MRF, Rivero MJ and Chamberlain AT (2020) Some challenges and opportunities for grazing dairy cows on temperate pastures. *Grass and Forage Science* **75**, 1–17.

Wims C, Delaby L, Boland T and O'Donovan M (2014) Effect of pre-grazing herbage mass on dairy cow performance, grass dry matter production and output from perennial ryegrass (Lolium perenne L.) pastures. *Animal* **8**, 141–151.

Yousef MK (1985) *Stress Physiology in Livestock. Volume I. Basic Principles.*pp.Boca Raton, Florida: CRC press.

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