Will current rotational grazing management recommendations suit future intensive pastoral systems?

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Abstract

This review aimed to determine whether current grazing management practices will suit future intensive rotationally grazed pastoral systems. A review of literature on grazing management recommendations found that there was good agreement on the 'principles' required for optimal grazing management. While these management practices have stood the test of time, it is concluded that shifts in external pressures (e.g., climate, plant selection and breeding, system intensification) compared to the period when farm-level grazing recommendations were first developed, may necessitate a rethink of current grazing recommendations. Examples include greater pasture masses (e.g., around 4000 kg dry matter (DM)/ha vs. the recommended range of 2600 to 3200 kg DM/ha) where short-rotation (annual, biennial) and tetraploid ryegrasses are sown, provided a consistent post-grazing residual can be maintained (possibly between 40- and 70- mm height). Milder winters and the use of ryegrass cultivars with higher growth rates in late winter/early spring may necessitate either lower target pasture covers at calving or shorter rotation lengths during winter. Longer grazing rotations (well beyond the 3-leaf stage, i.e., equivalent to deferred grazing) can be recommended for select paddocks from mid-spring into summer, to increase seasonal resilience across the farm. Longer residuals (even up to 70 mm - i.e., almost double the recommended height) might improve plant survival during periods of high stress (e.g., heatwaves, droughts). Lastly, diverse species pastures may require specific management to suit dominant species other than perennial ryegrass.

Keywords: diverse pastures, grazing principles, grazing rotation, leaf regrowth stage, post-grazing residual

Background

The economic competitiveness of pastoral industries is underpinned by the ability to use livestock to graze pastures *in situ* for as long as possible during the year. Multiple studies in the dairy industry have identified that the consumption of pasture is the most important factor impacting on profit (Dillon et al. 2005; Ramsbottom et al. 2015; Beca 2020). Grazing management of various pasture species, focusing either at the level of the plant, the grazing ruminant, or the whole farm, has been the subject of decades of research. Notwithstanding that in many cases, 'grazing management' research has been separated into a focus predominantly on plants, or on animals (Fulkerson & Donaghy 2001), there is general agreement on the principles required for 'optimal' grazing of a temperate pasture, whether these principles are based on sward height (Hodgson 1990), variable day rotations (Mayne et al. 2000), herbage mass targets (Sheath & Clark 1996), or leaf regrowth stage (Fulkerson & Donaghy 2001). The knowledge and science contained in multiple research studies have been summarised in farmer-friendly publications, and recommendations are broadly applicable to temperate pastoral regions (e.g., Dairy Australia 2011; Lee et al. 2011; McCarthy et al. 2015; Macdonald & Roche 2016).

At the farm level, these principles have been summarised into comprehensive grazing decision guidelines (e.g., Macdonald & Penno 1998; Macdonald et al. 2010), which at the pasture level are based on achieving 'average pasture cover' (average herbage mass) targets at key times of the year. For example, in dairy farm systems, pasture cover targets exist for planned start of calving and again at balance date (when pasture growth equals herd demand), with additional operational support tools such as the 'spring rotation planner' to help farmers achieve these targets (Macdonald & Roche 2016). The basis for so many of the recommended grazing management practices used today have been derived largely from farm systems research undertaken in the 1960s through to the 1990s (Roche et al. 2017a).

ISSN 0118-8581 (Print) ISSN 2463-4751 (Online) https://doi.org/10.33584/rps.17.2021.3464

This farm systems research used decision-making processes to manage pasture with the dual objectives of meeting the animals' requirements while maintaining pasture nutritive value throughout the season (Macdonald & Penno 1998). However, at the farmer level, the application of localised grazing management 'guidelines' can sometimes vary from these grazing management 'principles' (Macdonald et al. 2010). Examples of this can include implementing a grazing rotation that is longer than the 'optimum' range for leaf senescence, in order to transfer autumn-grown pasture into winter (Chapman et al. 2014), or removing stock from the farm during winter and thus 'undergrazing' pasture in order to manage wet soils; both are examples of targeting an optimum outcome for the farm system.

The dependence of pastoral farm systems on the prevailing climate exposes farmers to increasing risk as climate change results in more variability in seasonal conditions, with an increasing number of droughts, floods and/or heatwaves, migration of insect pests and plant diseases into wider areas, and longer feeding seasons of insect pests (Farrow et al. 1993; Ward & Masters 2007; Ministry for the Environment 2018). Consequently, the poor recovery of pastures to increased severity and frequency of adverse environmental conditions impacts pasture persistence and performance. The failure of ryegrass-based pastures 3 or 4 years post-sowing continues to be a significant concern for many farmers, particularly in the upper North Island. This, combined with the introduction of new pasture types and cultivar selections, and changes to system intensification, has resulted in a loss in confidence in perennial ryegrass and associated industry recommendations for grazing management. Thus, the purpose of this review of literature is to answer the question "Will current rotational grazing management recommendations suit pastoral systems over the coming several decades?" The review will explore these practices at both the fundamental (i.e., pasture management at a plant level) and the systems level (i.e., at a farm scale). Given the importance and abundance of perennial ryegrass (*Lolium perenne* L.) in temperate pastoral agriculture (Kemp et al. 2000), much of the review will focus on this grass.

The foundations of grazing management

There are four broad objectives of grazing management: optimising pasture production, nutritive value, and persistence, along with utilisation by the grazing animal (Roche et al. 2017b). They are linked, in that similar grazing management decision rules can optimise all four objectives (Fulkerson & Donaghy 2001). The two most important characteristics of rotational grazing management are grazing interval (when to graze a paddock or area; colloquially known as rotation or round length) and grazing intensity (how hard to graze a paddock or area; colloquially known as post-grazing residual, Roche et al. 2017b). At the plant level, these objectives acknowledge the energy status of the plant following a defoliation event (Fulkerson & Donaghy 2001; Chapman 2016). A starting point for designing an efficient grazing management system is an understanding of the pasture regrowth curve (Chapman 2016). Brougham (1955) first noted that following defoliation to 50 mm residual height, grass regrowth followed a sigmoidal (S-shaped) pattern, starting slowly with a 'lag phase' and then increasing exponentially, reaching a constant maximum rate and then eventually declining as a 'ceiling yield' is reached, at which leaf death equals leaf growth. This sigmoid curve was a central tenet in Andre Voisin's textbook 'Grass Productivity', to promote the importance of a suitable 'rest period' between sequential rotational grazings (Voisin 1959), and is also a key principle underpinning current recommendations for grazing management in both rotational and continuous stocking systems (Fulkerson & Donaghy 2001; Lee et al. 2011; Chapman et al. 2014; McCarthy et al. 2014; Chapman 2016; Roche et al. 2017b).

Current recommendations for grazing management: the plant level

In a rotational grazing system, the optimal grazing rotation at the plant level is based on the dominant grass species attaining a set number of live leaves per tiller, after which the emergence of each additional new leaf is balanced by the death of the oldest leaf (Fulkerson & Donaghy 2001). This 'leaf stage' is defined by the lifespan of leaves and varies between species (Roche et al. 2017b).

Leaf regrowth stage has been proposed as a practical tool to set grazing interval in order to optimise the persistence, production and nutritive value of a range of pasture species, including perennial ryegrass, biennial ryegrass (*Lolium multiflorum* L.), tall fescue (*Festuca arundinacea* Schreb., syn., *Schedonorus arundinaceus* and *Lolium arundinaceum*), prairie grass (*Bromus willdenowii* Kunth.), kikuyu (*Pennisetum clandestinum* Hochst. ex. Chiov.), and cocksfoot (*Dactylis glomerata* L.) (Fulkerson et al. 1993; Fulkerson & Slack 1994, 1995; Donaghy et al. 1997, 2008; Fulkerson et al. 1998, 2000; Fulkerson & Donaghy 2001; Rawnsley et al. 2002, 2014; Turner et al. 2006a, b; Hendriks et al. 2016; Kaufononga et al. 2017; Pembleton et al. 2017). At the lower (more frequent) scale of defoliation, the grazing interval should allow enough time for plants to regain their energy reserves to 'cope' with another grazing (i.e., the 2-leaf stage in ryegrass pastures; Donaghy & Fulkerson 1998), while at the upper (less frequent) scale of defoliation, the grazing interval should avoid significant herbage senescence and declining herbage nutritive value (i.e., the 3-leaf stage in ryegrass pastures; Fulkerson & Donaghy 2001). Leaf stage relates to the aforementioned sigmoid curve (Brougham 1955), with the 2- to 3-leaf stage generally coinciding with the period of maximum average growth rate (Parsons & Chapman 2000; Chapman 2016), indicating the optimum balance between the amount of new leaf produced and the amount of old leaf dying (Chapman et al. 2014).

Leaf emergence is affected predominantly by temperature, and to a lesser extent by soil moisture availability (Mitchell 1953; Fulkerson & Donaghy 2001; Rawnsley et al. 2010), and so leaf stage remains relatively consistent in plants within and between paddocks of farms in close proximity for any given period of time. However, pasture growth and therefore accumulation of herbage mass is affected by many other factors in addition to temperature and moisture, including tiller density, botanical composition, light, soil fertility and previous grazing management (Brougham 1957; Langer 1979). Thus, at canopy closure, the point beyond which no further improvement in interception of photosynthetically-active radiation occurs (Akmal & Janssens 2004), there is an increase in fibrous stem material and a decline in net pasture growth rate, tillering and pasture nutritive value (Rawnsley et al. 2007, 2014; Pembleton et al. 2017). Canopy closure is not always linked directly to a specific leaf stage, and paddocks that are at or close to canopy closure should be grazed regardless of leaf stage (Rawnsley et al. 2014; Roche et al. 2017b). This is because, as canopy closure progresses, shading of the pasture base increases, which is a major factor in tiller death (Ong & Marshall 1979). Shading of the pasture base also results in aerial tillering (Hughes & Jackson 1974; Korte et al. 1987), in which daughter tillers arise from elevated apical meristems and are unable to effectively develop roots (McKenzie 1998), which negatively impacts on tiller replacement and eventually pasture persistence (Hughes & Jackson 1974). At the level of the paddock or farm, this optimum grazing interval translates to the aim of maintaining pasture in a high-quality, vegetative state and minimising senescence and stem production (Parsons & Chapman 2000), to achieve efficient conversion of pasture into animal product (Mayne et al. 2000).

The optimal post-grazing residual at the plant level is based on leaving 40-50 mm of plant behind, as this is where temperate grasses store the majority of their energy reserves (Fulkerson & Donaghy 2001). More severe grazing removes progressively more leaf area and also reduces the major energy storage areas of the plant (tiller base) resulting in reduced regrowth and may impact negatively on persistence (Fulkerson & Donaghy 2001; Lee et al. 2008a). There is little effect on subsequent pasture yield of post-grazing residuals varying from 40 mm to 80 mm height, however more lax grazing reduced herbage nutritive value (Lee et al. 2008a). Although increased yields of pasture have been achieved with longer post-grazing residuals (e.g., 1895, 1602 and 1382 kg dry matter (DM)/ha for pasture field plots harvested to 100, 80 and 60 mm residual stubble height, respectively), they are only in the short term (i.e., the first of seven subsequent 3-leaf regrowth cycles following implementation of defoliation treatments), and cumulative yields were significantly lower at the end of the seven harvests (11.3, 13.3 and 13.7 t DM/ha, for 100, 80 and 60 mm residual stubble height, respectively, Lee et al. 2008a). Additionally, any further transient pasture growth that may occur under more lax defoliation does not compensate for the associated herbage loss through leaf senescence along with reduced rates of tillering (Fulkerson & Slack 1995; Lee et al. 2007, 2008a). Hunt & Brougham (1967) found that where repeated lax defoliation (cutting to 100 to 140 mm height over 7 weeks) of perennial ryegrass left enough herbage to intercept around 95% of incident light, the amount of green leaf and the number of tillers initiated declined progressively, while the proportion of dead material increased, which those authors concluded indicated the need for periodic close defoliation to renew the photosynthetic capacity of the grass sward and to prevent shading of tiller bases.

Post-grazing residual impacts on the sigmoid regrowth curve, with more severe grazing resulting in a longer lag phase and a longer time to reach ceiling yield, and more lax grazing resulting in a shorter or no lag phase, and a shorter time to reach ceiling yield (Parsons et al. 1988; Chapman 2016). Thus, although most pastures can recover from very low post-grazing residuals (e.g., 20 mm) if enough time is allowed (i.e., a long subsequent rotation), higher post-grazing residuals (e.g., >70 mm) require shorter associated rotations to maintain high quality pasture, and these shorter rotations (through preventing replenishment of plant energy reserves) can compromise yield and persistence (Chapman 2016; Roche et al. 2017b).

The optimal post-grazing residual of 40-50 mm results in a high-quality pasture and allows the implementation of a rotation in the optimal range (2- to 3-leaf stage). Importantly also from the point of view of the grazing animal, post-grazing residuals are a practical indicator of how well animals are being fed. Baudracco et al. (2010) showed that a quadratic relationship exists between pre-grazing herbage DM/ha and daily DM intake/cow; as pre-grazing herbage DM increased, the post-grazing residual increased at a greater rate than that of the herbage DM intake. In an analysis of the review by Baudracco et al. (2010), Wilkinson et al. (2020) determined that the lines for daily herbage intake/cow and post-grazing residual DM intersected at a post-grazing residual of around 1500 kg DM/ha. Post-grazing residuals can therefore be used as a proxy for pasture offered - as they increase, the increase in DM intake relative to what is offered declines. In a dairy pasture, post-grazing heights greater than around 50 mm indicate that pasture is being wasted and the DM intake of cows is not greatly increased, whereas at post-grazing heights less than around 35 mm, the DM intake of cows significantly declines (Roche et al. 2017b).

Current recommendations for grazing management: the farm level

Macdonald & Penno (1998) reviewed grazing management research and summarised a series of decision rules to manage seasonal calving pastoral dairy farms, focusing on achieving two important targets to ensure a profitable and sustainable farm system: cow body condition and average herbage mass at start of calving. Average herbage mass provides a measure of the amount of feed energy available within the farm (assuming average metabolisable energy values of pasture), and this is more important during the calving period, as underfeeding around this time impacts on herd performance for the remainder of the season (Macdonald & Penno 1998).

However, these target pasture covers at calving have been variously reported as 2000 (Bryant 1990), 2200 (Macdonald & Penno 1998), between 1800 and 2200 (Sheath & Clark 1996), between 2200 and 2400 (Macdonald et al. 2010), and 2500 (Claffey et al. 2019) kg DM/ha. These differences in targets probably reflect differences in stocking rates, calving rate, pasture growth rates and amount of nitrogen (N) fertiliser and supplementary feed used and may also reflect an impact of climate change, which is altering seasonal pasture growth. Current advice is to use a feed budget to more accurately predict average pasture cover required at calving on an individual farm basis (DairyNZ 2020).

To achieve these target pasture covers on farm, the recommended pre-grazing mass for lactating cows ranges from 2600 to 3200 kg DM/ha, and the recommended post-grazing residual ranges from 1500 to 1600 kg DM/ha (McCarthy et al. 2014). Most of the dairy grazing studies used rising plate meters (Earle & McGowan 1979) to record pasture mass. Using the New Zealand standard rising plate meter equation of "kg DM/ha = average compressed pasture height × 140 + 500" (DairyNZ 2008), this equates to pre-grazing heights of 75-100 mm compressed height (which, depending on pasture density and stem content, probably equates to 85-110 mm sward surface height) and post-grazing heights of 35-40 mm compressed height (probably equating to 40-45 mm sward surface height). These target pre-grazing heights fit within the recommended 80-100 mm sward surface heights for high-yielding cows determined in a review of literature by Mayne et al. (2000); at shorter heights, daily herbage intake was reduced, and animal production declined (Mayne et al. 2000). Furthermore, the target post-grazing heights allow temperate grasses to retain their energy reserves (Fulkerson & Donaghy 2001).

A decision support resource used by many dairy farmers is the spring rotation planner, which was developed in New Zealand for use in temperate pastoral regions regardless of stocking rate, amount of supplementary feed allocated, or cow breed (Macdonald & Roche 2016). The rotation planner allows farmers to manage their allocation of pasture and rotation length either during the autumn and winter period before spring calving, or from calving to balance date (Macdonald & Roche 2016).

Grazing outside of these management recommendations

Grazing rotation

Multiple studies using leaf stage as a criterion for defoliation have concluded that repeated (≥2) defoliations less than the 2-leaf stage (ranging from the 1-leaf to 1.5-leaf stage) reduce plant energy reserve levels, tillering, root mass, DM yield of pasture and nutritive value of herbage, and increase tiller and plant death, and invasion of less-desirable plant species into the pasture (Fulkerson & Slack 1994, 1995; Donaghy et al. 1997; Donaghy & Fulkerson 1998, 2002; Fulkerson et al. 1998; Turner et al. 2006a, b; Rawnsley et al. 2014; Pembleton et al. 2017). The only instances where a fast rotation (<2-leaf stage) could be beneficial are: 1) during reproductive growth; 2) when rust fungus has infected significant areas of pasture early in regrowth; 3) when ryegrass growth has almost ceased and invading summer grasses need to be controlled (Donaghy et al. 1997); or 4) when canopy closure is occurring early in regrowth (Roche et al. 2017b).

In diploid perennial ryegrass, the onset of canopy closure usually occurs at a pasture mass of around 3000 to 3500 kg DM/ha (Rawnsley et al. 2014), while in tetraploid perennial ryegrass and annual (*L. temulentum* L. or *L. rigidum* Gaudin) and biennial genotypes, the onset of canopy closure is seen at pasture masses as high as 3700 to 4000 kg DM/ha, due to their more open growth habit (fewer, larger tillers, larger leaves). Thus, the recommended pre-grazing target range for pasture mass (2600 to 3200 kg DM/ha; McCarthy et al. 2014) coincides with the onset of canopy closure in diploid perennial ryegrass pastures. The use of tetraploid ryegrass, or shorter rotation ryegrass, allows the opportunity to graze higher pasture masses than this (but still prior to, or at, canopy closure in those ryegrass types), while still achieving high utilisation (i.e., consistent and even post-grazing residuals) and animal production (Edwards & Bryant 2016). In a grazing study comparing milk production from cows grazing diploid and tetraploid perennial ryegrasses to either between 2900 and 3200 kg DM/ha, or between 3800 and 5000 kg DM/ha, Bryant & Edwards (2012) confirmed that milk production decreased by 0.14 kg milksolids/cow/day when the diploid cultivar was grazed at the greater mass range, but was unaffected when the tetraploid cultivar was grazed at the greater mass range.

Multiple studies have confirmed that in more stressful environments (e.g., subtropical/tropical), longer rotations (e.g., the 3- or 3.5-leaf stage) maximise plant energy reserves and associated tillering and root production, and therefore plant persistency and survival, and enhance the ability of temperate species to reduce the ingress of summer grasses (Fulkerson et al. 1993; Fulkerson & Slack 1994, 1995; Donaghy et al. 1997; Donaghy & Fulkerson 2002). Interestingly, Donaghy et al. (1997) found that there was little impact of rotation length (3-leaf vs. 1-leaf stage) on plant survival during a subtropical winter in northern New South Wales, Australia (where the climate is mild in comparison to winter conditions in most pastoral temperate regions), however there was a major impact on how ryegrass/white clover (*Trifolium repens* L.) pastures survived the subsequent harsher summer, with more perennial ryegrass plants surviving summer (74 vs. 54 plants/m^2) and less tropical grass [primarily kikuyu, paspalum (*Paspalum dilatatum* Poiret) and summer grass (*Digitaria sanguinalis* (L.) Scop.)] plant incursion (46 vs. 60 plants/m^2) under the 3-leaf winter rotation. In other words, it was how the plants were 'pre-treated' prior to the major stress period (subtropical summer), which had the most influence on their survival.

Delayed or deferred grazing

Under periods of increasing climatic stress (e.g., more frequent and severe droughts as a result of climate change), tiller mortality is likely to increase, with detrimental subsequent effects on tiller density and pasture productivity. Strategies are required that can enhance pasture resilience by enabling tiller populations to withstand, and recover from, these periods of stress.

One such strategy is the concept of 'late control' (Matthew et al. 2000), which involves removing a paddock from grazing from mid-spring until early summer, allowing anthesis to occur. Most of the carbohydrate reserves are prioritised for seed-head development and the production of new tillers is suppressed (i.e., apical dominance; Jewiss 1972), however, a small but biologically-significant amount of carbohydrate accumulates at the base of the plant for the growth of young tillers (Matthew 2002). When the developing seed-head is decapitated following 6-12 weeks of regrowth, apical dominance is removed, and the tiller buds can produce new tillers, fuelled by these carbohydrate stores (Hampton et al. 1987; Matthew et al. 1991). Although plot studies have demonstrated a great deal of promise for late control (Hernandez Garay et al. 1997a, b), the attainment of whole-farm benefits in herbage production have been inconsistent (Bishop Hurley et al. 1997; Da Silva et al. 2004). Also, from a practical sense, when a manager is aiming to match livestock demand to pasture supply, it can be difficult to time the grazing so that it corresponds with anthesis. Further, if these new tillers are subjected to drought and other stresses over summer, they may not survive. Nevertheless, more work investigating the balance between above- and below-ground soil-pasture fluxes during spring and summer would be warranted.

An alternative strategy to late control is 'deferred grazing', where the removal from grazing is longer, from mid-spring until mid-summer, after seed has fallen (Tozer et al. 2020a). This avoids the difficulty of timing the grazing specifically during anthesis and enables pasture to accumulate in the paddock, that can subsequently be grazed at the end of summer when feed may be scarce, especially after a summer drought. Although this pasture could also be conserved as silage or hay, these are both more expensive options and also may not be able to be implemented on hilly paddocks for example, and thus, deferred grazing utilises principles of ecophysiology in order to increase persistence and resilience of pastures. Deferred grazing allows plants to flower and set seed, and as was the case with late control, carbohydrate accumulated in the tiller base can be used for the development of new tillers in autumn, once reproductive development has completed and climatic conditions are conducive for tiller growth and survival. While this practice has a short-term negative impact on pasture nutritive value and utilisation during the period in which grazing is deferred (Tozer et al. 2020b), there may be substantial benefits for tiller populations, pasture production and profitability at a farm scale (Dowling et al. 1996; Waller & Sale 2001; Tozer et al. 2021a, b). Firstly, tiller densities in the deferred pastures may increase through reseeding (L'Huillier & Aislabie 1987) and/or increased tillering from existing plants (Waller & Sale 2001). Reseeding is more important under conditions of drought stress, while the increased tillering from existing plants is more important in a benign environment (Tozer et al. 2020b). Secondly, associated with this increased tillering is an increase in herbage production, which can last for up to 12 months after the deferred period in beef and sheep hill country pastures (Tozer et al. 2020b). The deferred pasture can also provide grazing at the end of a summer drought, which increases the resilience of farms to climatic shocks. Thirdly, deferred grazing can be used to control pasture nutritive value at a farm scale and better match feed supply to livestock demand. When paddocks are removed from the rotation, livestock have a smaller effective grazing area and are better able to utilise the spring pasture, where growth often exceeds livestock demand (Suckling 1959). It can also increase nutritive value by increasing the legume content (e.g., Nie et al. 1996), although this depends on the timing of closing and re-opening pastures to grazing and on the other species present in the sward. This enables livestock to better maintain pastures in a high-quality vegetative state, such that pastures are grazed at the 2- to 3-leaf stage. In this way, deferred grazing integrates traditional pasture principles, which focus on maintaining high-quality leafy material, and additionally harnesses the plant's reproductive cycle, resulting in benefits for resilience at both the pasture and farm scale.

Thus, while there are few reasons to rotationally graze pastures faster than recommended with respect to pasture persistence, there is evidence that the grazing 'rules' can be bent by grazing pastures at higher masses than recommended, especially in the case of annual, biennial and tetraploid ryegrass cultivars, and for longer intervals than recommended (i.e., deferred grazing), trading off loss of nutritive value at the level of some paddocks with increased seasonal resilience at the level of the farm.

Post-grazing residual

Previous studies (e.g., Mayne et al. 1987) reported that lower post-grazing residuals resulted in reduced milk production (13.7, 16.0 and 17.0 kg milksolids/cow/day, from pasture grazed to 50-, 60- and 80-mm residual sward heights, respectively). A feature of some previous studies (e.g., Le Du et al. 1979; Mayne et al. 1987; Wales et al. 1998) was that when pre-treatment pastures were homogenous, decreasing pasture allowance by providing smaller grazing areas resulted in reduced post-grazing residual. In an experiment where pasture allowance was separated from post-grazing residual (i.e., pasture allowance was similar and post-grazing residual was varied), Lee et al. (2008b) explored post-grazing residuals to compressed heights (pasture measured with a rising plate meter) of around 40, 50 and 60 mm, and found only a minor effect of post-grazing residual on milk production (23.4, 23.1 and 20.8 kg milksolids/cow/day, respectively), despite consistent low post-grazing residuals (to approximately 20 mm) reducing annual DM yield (Lee et al. 2008a).

In terms of longer post-grazing residuals, a number of studies have reported that more lax grazing in spring (the period of surplus pasture) resulted in a decrease in growth rates of steers (Dawson et al. 1981) and lower milk production, ranging from 1 L/cow/day (Hoogendoorn et al. 1985), to 2.2 L/cow/day (Michell & Fulkerson 1987) and between 1 and 3 kg/cow/day (Stakelum & Dillon 1990) of cows in the subsequent summer. The 'lax grazing' ranged from 70 mm (Dawson et al. 1981), to between 81- and 130-mm post-grazing residuals (Stakelum & Dillon 1990), to pre-grazing masses of 4680 kg DM/ha (Hoogendoorn et al. 1985), and post-grazing residuals of 2600 kg DM/ha (Michell & Fulkerson 1987). The reduced animal production with more lax spring grazing was because pasture that regrows from longer post-grazing residuals (≥70 mm) contains more stem and dead material, and has lower digestibility (Hoogendoorn et al. 1985; Michell & Fulkerson 1987; Stakelum & Dillon 1990; Pembleton et al. 2017), leading to a reduction in pasture utilisation (Dalley et al. 1999; Wales et al. 1999), compared with the previously-defined more optimal residuals.

Grasses exhibit phenotypic plasticity (changes to growth habit) when subjected repeatedly to either high or low post-grazing residuals. Close grazing (i.e., <30 mm height) naturally favours species such as white clover, browntop (*Agrostis capillaris* L.) and many broadleaved species [e.g., thistles, dandelion (*Taraxacum* spp.), broadleaf plantain (*Plantago major* L.), etc.] while the opposite is true of more lax grazing (i.e., >80 mm height), which favours species with more upright growth habit, including most pasture grasses along with forbs such as plantain (*Plantago lanceolata* L.) and chicory (*Cichorium intybus* L.). Ryegrass is resilient across a range of post-grazing residuals, exhibiting a more prostrate habit under close grazing and a more upright habit under lax grazing. However, continual adaptation by grasses to varying post-grazing residuals limits their growth potential (Lee et al. 2008a), by reducing the radiation-use efficiency of the canopy, through increasing shading of newer photosynthetically-efficient leaves by older leaves or by increasing the amount of light intercepted by the tiller base rather than the leaf (Pembleton et al. 2017).

In the longer term (over a 5-month period), repeated lax defoliation (to 160 mm height) reduced photosynthesis, through a loss in leaf area index due to pseudostem development (which doubled from 84.9 to 170.7 g/m^2 as cutting height increased from 20 to 160 mm), and through reduced photosynthesis per unit leaf area, possibly as a result of a higher proportion of older leaves, or a metabolic compensation with more severe defoliation pressure (Hernández Garay et al. 2000). Conversely, repeated close defoliation (20 to 25 mm) reduces DM yield (Leafe & Parsons 1983; Hernández Garay et al. 2000; Lee et al. 2008a), root growth (Evans 1971, 1973; Hernández Garay et al. 2000; Lee et al. 2008a) and tiller density (Hernández

Garay et al. 2000; Lee et al. 2008a), and increases the period of reliance on plant energy reserves (Davidson & Milthorpe 1965; Fulkerson & Donaghy 2001), putting plants at greater risk of death during adverse climatic conditions and also necessitating a longer subsequent rotation for plants to recover (Chapman 2016; Roche et al. 2017b). To illustrate this last point, Chapman (2016) reported data from pasture defoliated to 1500 kg DM/ha (representing 'target' post-grazing residual) and 1150 kg DM/ha (representing 'overgrazing'). Pasture defoliated to 1500 kg DM/ha reached maximum average growth rate after 30 days of regrowth (= 2-leaf regrowth stage), and ceiling yield (~3500 kg DM/ha) after 45 days of regrowth (= 3-leaf regrowth stage), whereas pasture defoliated to 1150 kg DM/ha had still not reached either maximum average growth rate or ceiling yield after 45 days (Chapman 2016).

The results of Lee et al. (2008b) indicate that consistent post-grazing residuals are the key to maintaining animal production, and it is possible that within a range of post-grazing residuals (possibly between 40- and 70-mm compressed height), as long as the post-grazing residual is consistent, there will be little negative impact on either DM yield of pasture, or milk production. However, based on the aforementioned negative results of leaving residuals longer than 70 mm height, it would be wise to recommend that post-grazing residuals not exceed this.

Changes facing pastoral systems in recent decades

Impacts of climate change

Climate change projections for New Zealand indicate that temperatures will rise, rainfall and windfall patterns will change (Table 1) and atmospheric carbon dioxide (CO_2) concentrations will increase (Ministry for the Environment 2018). While the predictions vary in other similar high-rainfall pastoral regions of southern Australia and Ireland, the impacts are likely to be similar and will affect pasture production, pasture nutritive value and botanical composition. Sheep and beef farming systems and low-input dairy farming systems are likely to be most affected (Ministry for the Environment 2001), as home-grown pasture is their main feed source.

Pasture production (annual and seasonal)

There are conflicting arguments regarding the potential effect of climate change on total annual pasture DM yield. Many reports suggest that annual DM yield could increase by up to 10-20% as a result of warmer temperatures (particularly during winter), and increased CO_2 concentrations leading to more efficient rates of photosynthesis (Ministry for the Environment 2001). This is most likely to be the case in regions like Southland, New Zealand, where by 2040 winter temperatures are predicted to increase by approximately

Table 1 Climate change projections for New Zealand (Ministry for the Environment 2018).

Climate variable	Description of change	Change in 2090	Spatial and seasonal variation
Mean temperature	Overall increasing.	+3.0°C	Warming greatest at higher elevations. Warming greatest in summer and autumn, and least in winter and spring.
Minimum and maximum temperatures	Overall increasing.	Increase up to 2°C.	Greatest changes in higher elevations, particularly for maximum temperature.
Number of hot days (>25°C)	Increase, particularly in already warm regions.	Average 300% increase.	Number of days increase greatest in hottest regions.
Average rainfall	Regional and seasonal variation.		Winter decreases: Hawke's Bay and Canterbury. Winter increase: Southland. Spring decreases: Northland and Bay of Plenty.
Drought	Increase in severity and frequency.	Increase up to 250 mm per year in potential evapotranspiration deficit.	Increases most marked in already dry areas.
Wind	Varies seasonally. Incidence of extreme wind speeds increasing.		More northeast airflow in summer. Strengthened westerlies in winter. Greater increases in wind speed in southern half of North Island and throughout South Island.

1°C and annual rainfall is expected to rise by 2-4% (Ministry for the Environment 2018). However, in a global meta-analysis, Hovenden et al. (2019) found that the impact of elevated CO_2 on pasture production rose as mean spring rainfall increased but fell as mean rainfall in other seasons increased. They concluded that any potential increase in pasture yield due to elevated CO_2 would be dependent on the site's seasonality of rainfall, and as such the predicted increase in pasture yield could be substantially less than anticipated.

Alternatively, flowering date may be advanced by up to 10 days as a result of higher temperatures (Bloor et al. 2010) and elevated CO_2 concentrations (Maw et al. 2014). This could result in reduced peak spring pasture growth rates, thereby reducing the potential amount of excess pasture available for harvesting as hay or silage and reducing annual pasture production. This will make it more difficult for farmers to manage typical seasonal feed shortages (summer and winter) and may require adjustments in stocking rates and calving dates, or greater use of more costly supplementary feed sources.

Other reports suggest that in eastern parts of New Zealand (Hawke's Bay, Bay of Plenty, Christchurch) more variable rainfall patterns, a greater number of hot days and increased intensity of summer droughts may decrease pasture growth rates during summer and autumn and therefore reduce annual pasture production (Kenny et al. 2001; Lieffering et al. 2016). Moore & Ghahramani (2013) demonstrated that changes in the seasonality of pasture growth as opposed to total pasture production required greater changes in farm management strategies and stock policies. This suggests that climate change is likely to have greater impacts on farming systems in the warmer, eastern parts of New Zealand.

Recent farm-system studies have highlighted the impact of changing climate on pasture growth and the subsequent possible changes to grazing management, at both an operational and strategic level. At the strategic level, a greater number of growing days during winter and less frequent bouts of rain in summer in regions such as coastal Taranaki and Waikato have motivated some farmers to move calving dates forward (e.g., from July to June) to capture more days in milk before the summer-dry takes effect, or alternatively change from spring to autumn calving in an attempt to better match pasture supply with herd demand (Jarman 2020). Additionally, a 3-year farm systems trial established in Waikato to validate the DairyNZ Forage Value Index (FVI) at farm scale, has highlighted where traditional operational pasture management practices may not have achieved optimal performance at the pasture or farm level. In the past 2 years, pasture growth rates have been greater than expected during winter, and following the current recommendations for winter rotation lengths resulted in greater than target pasture mass at calving. This in turn caused difficulties in maintaining pasture quality and appropriate rotation lengths, while achieving target pasture residuals and animal performance in spring. This outcome was exacerbated in the "high" cultivar farmlets (where cultivars are selected from the FVI 4- and 5-star rating bands for the upper North Island; see section: Impacts of ryegrass selection and breeding) as these cultivars have greater growth rates during winter (Chapman et al. 2017). If climate change continues in the same pattern (i.e., milder winters), it may be necessary to shorten the winter rotation length targets, and potentially the pasture mass targets at calving. Farm system modelling programs such as Farmax (Bryant et al. 2010) should be used to identify the strategic (e.g., calving date, stocking rate) and operational decisions (e.g., rotation length and pasture mass) that may need to be changed based on climate variations and cultivar performance.

Pasture species

Higher temperatures favour C_4 species at the expense of C_3 species. Consequently, there has been an observed increase in the proportion of kikuyu and paspalum in pastures in the Northland and Waikato regions of New Zealand (Field & Forde 1990; Ministry for the Environment 2001) and modelling suggests that these species will continue to invade further south and increase in prevalence (Clark et al. 2001). These subtropical C_4 pasture species are of lower nutritive value than temperate C_3 species (Barbehenn et al. 2004), however they do provide animal feed during periods of low soil moisture. Adjustments in grazing management practices, including rotation length and/or post-grazing residual height, will be required to both minimise the spread of these species and to maximise the animal performance from pastures which become dominated by these C_4 species.

Elevated CO_2 levels due to climate change will affect forage nutritive value, with studies observing decreased forage N content and increased water-soluble carbohydrate content (Dumont et al. 2015). However, elevated CO_2 levels have also been shown to favour legumes, with the proportion of white clover in grass-based swards being greater at increasing CO_2 levels (Teyssonneyre et al. 2002; Lüscher et al. 2004). However, this generalisation is based on short-term studies (<5 years). In a long-running experiment (11 years) Newton et al. (2014) observed that the increased legume content in the sward in response to elevated CO_2 levels was not sustained, as sheep selectively grazed out the legume, resulting in little difference in pasture composition. Under more intensive grazing conditions, it is therefore unlikely that climate change will result in an increased legume content in grass-based pastoral systems unless plant breeders develop new legume cultivars which are more persistent under selective grazing, or if used in well-managed cattle grazing systems which minimise selective grazing. However, there will likely be an increased use of lucerne (*Medicago sativa* L.) swards.

The distribution and abundance of pastoral weed species will also likely alter with climate change (Potter et al. 2009), however there is a paucity of studies in this area.

Pasture establishment

Successful pasture establishment will likely become increasingly challenging in the future. The more variable rainfall patterns and increasing duration of summer droughts (Ministry for the Environment 2018) may reduce the window of opportunity, where soil moisture levels and ambient temperatures are appropriate to achieve successful autumn sowing. Similarly, wetter winters may make it difficult to establish pastures in early spring before soil moisture levels drop. There will also be increased need for extension agronomists to work with farmers to achieve successful pasture establishment. Moreover, the increasing frequency and intensity of summer droughts is likely to lead to greater plant deaths and will possibly increase the area of pasture needing replacing each year, further exacerbating the dilemma.

Furthermore, as temperatures rise, the geographical spread of pastoral insect pests is likely to expand and their lifecycle is likely to speed up (Farrow et al. 1993; Ward & Masters 2007). These trends in pest distribution and biology may make it more difficult to establish new pastures, further reducing pasture persistence. Going forward, there will likely be an increased focus towards sowing perennial pastures as opposed to short-term pastures and managing them to maximise their persistence. Further, weather forecasting technology for agricultural purposes is continuing to develop and improve (University of Tasmania 2015) and will be helpful for farmers to achieve optimal timing of sowing new pastures, thereby minimising the risks of establishment failure.

Impacts of system intensification

Pastoral systems have intensified significantly since the 1960s to 1990s, when the early systems studies were undertaken that form the basis of modern farm-level grazing recommendations. There are now fewer, larger, more highly-stocked farms, using greater quantities of N fertiliser, irrigation water and supplementary feeds (MacLeod & Moller 2006). This intensification has resulted in a range of issues including increased nutrient loads and pollution in waterways (McDowell et al. 2011), increased production of greenhouse gases (Pinares-Patiño et al. 2009) and negative impacts on soil physical structure (Mackay 2008). For these reasons, it is highly probable that pastoral agriculture will undergo some de-intensification in the coming decades, or at the very least, that past trends of intensification will neither continue nor be maintained. However, it is likely that future systems will remain more intensive than those in the 1960s to 1990s.

In addition to the negative environmental impacts of intensification, there may also be negative impacts on pastures. While high stocking rates (more cows/ha), or at least high stocking intensities at grazing (sufficient animals in the paddock to graze it quickly) are an integral part of successful rotational grazing, these high stock numbers can also exacerbate periods of pasture shortage, especially when animal demands are in excess of pasture growth rates. While ideally, stocking rate should be matched to the amount of forage that the farm can produce, climatic volatility can reduce pasture yield and result in overgrazing of pasture. The immediate effect of higher animal demand relative to pasture supply is lower than optimum post-grazing residuals, and then if the higher demand continues, the slower regrowth caused by the closer grazing will result in a faster than optimal rotation, if no action is taken. This is a classic situation where supplementary feed can be provided to ensure that pasture is grazed optimally, e.g., to ‘protect’ the post-grazing residual from being grazed too closely, or to allow an optimal rotation to be maintained, while animals continue to be well fed (Roche et al. 2017b).

While supplementary feeding can be used to prevent pasture being overgrazed, continual high inclusion of supplementary feeds in pastoral systems can undermine their profitability, as pasture consumption is the single most important factor impacting on profit, as mentioned previously. Therefore, in temperate pastoral dairy systems, it is recommended that supplementary feeds not be provided to cows unless post-grazing residuals are lower than 35 mm compressed height, which indicates that cows are being underfed (Roche et al. 2017b). Further, New Zealand pastoral systems will need to be increasingly flexible, by adjusting feed demand through the sale or movement of livestock, or adjustment in feeding targets or livestock condition targets during times of restricted pasture availability.

Impacts of ryegrass selection and breeding

Perennial ryegrass plant breeders have achieved marginal increases in genetic gain for DM yield, of between 0.35% and 0.7%/year and no evidence of any improvements in forage digestibility (McDonagh et al. 2016). However, with increased demand for high-quality forages, there will be greater requirement for selection based on herbage quality (Tubritt et al. 2020).

The introduction of economic merit indices for cows has assisted beef and dairy farmers to identify the most profitable genetics (Veerkamp et al. 2002) and has benefited the beef and dairy industries for many years. Perennial ryegrass cultivar selection indices are a relatively new development in grassland science and were first developed in Ireland through the Pasture Profit Index (PPI; McEvoy et al. 2011; O'Donovan et al. 2016), then later in New Zealand through the FVI (Chapman et al. 2017), and in Australia through the Australian FVI (Leddin et al. 2018). Within these selection indices, perennial ryegrasses are ranked on an expected economic value based on measurable traits (seasonal yield, nutritive value, silage yield, persistency and region) that have an economic effect on pastoral systems (Tubritt et al. 2020). A new grass utilisation sub-index has been developed and incorporated into the PPI to aid farmers in identifying cultivars with superior grazing efficiency, to increase grass utilisation on farm (Tubritt et al. 2020). The New Zealand FVI does not include a similar trait, because research by Griffiths et al. (2020) found no consistent evidence of any effect of phenotype (morphology or heading date) on milk production in dairy cows, that would add value to the FVI additional to that attributed to metabolisable energy.

Differences in the grazing efficiency of perennial ryegrass cultivars influence the level of grass utilisation on farm, due to specialist traits possessed by certain cultivars that make them better adapted to grazing systems (Byrne et al. 2018). Earlier-heading cultivars display earlier and more rapid declines in digestibility, which can make them less suited to efficient mid-season grazing, however, their high spring growth makes them suitable for specialised silage production (Humphreys & O'Kiely 2006). The move by farmers to select ryegrasses that have an increased grazing efficiency, with a superior nutritive value (Tubritt et al. 2020), has resulted in an increase in the proportion of late-heading cultivars. Late-heading cultivars account for 78% of perennial ryegrass cultivars listed on the PPI in Ireland (Department of Agriculture, Food and the Marine 2020), an increase of 57% since 1982 (Grogan & Gilliland 2011). Late-heading cultivars account for 63% of all cultivars listed on the New Zealand FVI (DairyNZ 2020). Late-heading cultivars delay reproductive development until early/mid-summer (Gately 1984) and tend to maintain their green leaf proportion later into the growing season (Gilliland et al. 2002), resulting in a higher and sustained herbage nutritive value with further beneficial effects on herbage intake and milk production (O'Donovan & Delaby 2005).

The PPI and FVI have informed farmers' decisions on selection of ryegrass cultivars, which may increase demand for a smaller number of cultivars. This is evidenced by the dominance of later-heading ryegrass cultivars present on the PPI and FVI. This can impact on the seasonal growth curve of pasture, with highly-ranked cultivars exhibiting greater growth during winter (Chapman et al. 2017) and later-heading cultivars producing higher yields later in the spring/early summer compared with earlier-heading cultivars, although total annual yield is similar (Gilliland et al. 1995). These changes in seasonal growth patterns might be expected to impact on the achievement of target farm pasture covers throughout the season. The impact of the PPI and FVI have not yet been seen in relation to plant breeding, as the release of a new cultivar is the culmination of a 10-20 year process (Conaghan 2019).

Currently, selection indices are only available for ryegrass species (PPI/FVI), however due to the increased use of other species on pasture-based farms, further selection indices may be required to aid the industry in their selection. For example, white clover, due to its wide climatic range, high nutritive value of herbage, and ability to fix atmospheric N and thereby reduce the dependency on chemical N inputs on farm, has made it the most important pasture legume in temperate regions (Frame & Newbould 1986).

Use of diverse pasture species

The adoption of multiple pasture species in a diverse pasture mix has become an increasingly popular way to combat environmental challenges, from the perspective of both climate and nutrient management (Cranston et al. 2020). When sown to create a diverse, multispecies pasture, the seed mix typically contains three or more species and species which can be selected to represent functional groups across a range of forage grasses, herbs and legumes. Complementary effects in resource use have shown pastures with two or more species capable of greater yields and improved weed suppression compared with monocultures (Sanderson et al. 2005; Black et al. 2017). Inclusion of herbs such as plantain into pasture mixtures is expected to reduce nitrate leaching from soils (Carlton et al. 2019). Diverse pastures with multiple species will continue to be important in the future, though the choice of species and their management will likely vary considerably (Pembleton et al. 2015). Applying appropriate decision rules for grazing management of these species mixtures presents a potential challenge for future pastoralists. Because pastures tend to become dominated by one or two species, fertiliser and grazing management practices which sustain the biodiversity of diverse pastures and encourage high productivity may well require bespoke solutions depending on the pasture type and the environment. Ultimately, selection of species for diverse pastures will need to consider the establishment and grazing management requirements of all species within the mix. The challenge of managing diverse pastures in a commercial setting was evidenced recently in a survey of farmers in Canterbury and Waikato who had tried to incorporate plantain with mixed results (Bryant et al. 2019; Dodd et al. 2019). Realistically, the dominant grass species' grazing management will likely take priority over the other species present in the mixture as the consequences to persistence, productivity or nutritive value will likely outweigh any benefit from the species mixture. In New Zealand, Ireland and southern Australia, most dairy farm systems are built around management of perennial ryegrass-dominant pastures, and as this review attests, there is potentially some flexibility in how to manage these pastures. Furthermore, there may be greater flexibility in grazing management of companion legumes (particularly lucerne in spring) than once thought (Teixeira et al. 2007). Persistence of companion species beyond 3 or 4 years may not be necessary to achieve benefits from diverse pasture mixtures if a regular (c.a. 10-12 years) pasture renovation program is maintained (Pembleton 2015). Recent work on re-establishment methods for herb species (e.g., plantain) within grass pastures has also shown promise (Raedts & Langworthy 2020), reducing the need for long-term persistence within a mixture.

Conclusions

Impacts of climate change, along with system intensification and ryegrass cultivars that are different from those used when the early farm system studies were undertaken to develop modern farm-level grazing recommendations, may necessitate a rethink of those grazing recommendations, and these are listed in the following examples.

Higher pasture masses than currently recommended can be targeted at a paddock level where annual, biennial and tetraploid ryegrasses are sown, as long as a consistent post-grazing residual is maintained. In contrast, at a farm level, it is possible that faster rotations, and lower target pasture covers around calving, would avoid anecdotal issues in recent years of a loss in pasture quality and difficulty in maintaining consistent post-grazing residuals and animal performance in spring due to milder winters, particularly with ryegrass cultivars selected for greater winter growth.

Longer grazing rotations than recommended, well beyond the 3-leaf stage, could be used in selected paddocks (i.e., deferred grazing), to trade off loss of nutritive value at the paddock level for increased seasonal resilience at the farm level.

Consistency of post-grazing residuals was highlighted as the key to maintaining animal production, with no benefit to having shorter post-grazing residuals than recommended. However, it is possible that longer residuals, even up to 70 mm (i.e., almost double the recommended height), might benefit root depth, energy reserves and plant survival during periods of high stress (e.g., heatwaves, droughts). However, early identification of stress periods is important, as management of pastures just before stress has more influence on plant survival than (within reason) how pastures are managed during the stress period.

Lastly, the use of more diverse pastures, to combat both climate and nutrient challenges, may require specific management that better suits dominant species other than perennial ryegrass.

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