

Attributes of resilient pasture for achieving environmental outcomes at farm scale

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Abstract

Pasture resilience commonly refers to a pasture's ability to withstand or rebound from pressures to maintain production and quality of sown species. We suggest that a broader definition of pasture resilience is needed that also includes environmental responses, thus ensuring that productivity and environmental outcomes are considered together. Key attributes of resilient pastures to minimise soil erosion and nutrient, greenhouse gas and soil carbon losses are summarised based on current understanding of environmental losses from pastoral systems. These attributes include maintaining consistent pasture cover, high energy and/or low nitrogen species and species diversity that provides complementary root morphology and/or growth seasonality; all are likely to have positive benefits for production and productivity. There is a potential tension, however, between productivity and methane emissions, as methane production increases with increased feed intake. Increasing pasture quality is therefore also an important consideration for pasture resilience as it can maintain animal productivity at lower levels of feed intake. From a farm systems perspective, the choice of pasture species should reflect the desired attributes for both productivity and environmental outcomes, and ensure that the sown species persist in the sward. Finally, we note that none of the environmental attributes/benefits are likely to deliver major farm-scale improvements on their own; progress will likely be incremental improvements upon implementing a range of attributes.

Keywords: methane, nitrous oxide, nutrient losses, sediment, soil carbon

Introduction

In recent years, the term 'resilience' has often been used to describe how systems and/or system components respond to an increasingly complex array of economic, societal and environmental pressures (Meuwissen et al. 2019). Within pastoral farming systems, pasture resilience is a key component and is often defined as one that withstands changes over time (e.g., due to

climate change) and/or rebounds from a disturbance event (such as drought, animal treading damage or pest incursion). The question we address in this paper is: 'if we have resilient pastures, how does this improve our ability to manage environmental losses?'. This implies that optimizing production quality and productivity are primary goals, while environmental impacts are secondary, when considering pasture resilience. Indeed, Horan & Roche (2019) describe biophysically and financially resilient pasture-based systems as those that enable animals to directly harvest a larger proportion of pasture grown, thus minimising the need for infrastructure and machinery, and reducing exposure to fluctuating feed prices. They also postulate that pasture management should optimise both dry matter (DM) production and utilisation. Attributes such as pasture persistence and improved nutrient use efficiency can deliver these productivity benefits, while also co-benefitting environmental outcomes (Betteridge et al. 2011; Mackay et al. 2011). However, as the need to reduce nutrient and soil losses to water, reduce greenhouse gas (GHG) emissions, and maintain soil carbon (C) is increasingly important for pastoral systems, here we adopt a broader definition of 'resilient pasture' that views environmental outcomes as an integral part of pasture resilience, rather than as secondary co-benefits. We firstly summarise the current state of knowledge on the key factors that drive environmental losses from pastoral systems. We then provide an overview of pasture attributes that are required to avoid or minimise these factors and discuss their role in enhancing resilience for achieving environmental as well as productivity outcomes within the context of a whole-farm system.

Environmental Impacts

Nutrient loss and cycling

An increasingly important aspect of pasture performance is the ability of the sward to capture nutrients that would otherwise be susceptible to loss via processes such as leaching, surface runoff, volatilization or denitrification. Key to this is the design of pastoral systems that have an improved

synchronisation between soil supply and plant demand for nutrients. In the case of nitrogen (N), much research has identified where such improvements are needed, focussing particularly on mismatches between demand and supply for situations where large inputs from urine, soil mineralization or fertilisers and effluent can overwhelm the ability of plants to take up this N in the short- to medium-term (Whitehead 1995; Di & Cameron 2002; Cameron et al. 2013). Temporal considerations of when these imbalances between supply and demand occur are therefore a critical aspect of improved pasture performance. Spatial considerations are also important, particularly in the case of phosphorus (P) losses, which mostly occur from discrete parts of the landscape that are hydrologically connected to surface water networks.

Pasture replacement is one management activity that can result in large imbalances between soil N supply and demand, due in large part to the mineralization of potentially considerable amounts of soil organic N and, typically, the temporary removal of vegetation to allow new plants to establish. This can result in relatively large amounts of nitrate leaching if drainage occurs before newly established plants are able to take up mineralised N (Cameron & Wild 1984; Betteridge et al. 2011). Pasture renewal programmes that minimise the extent of soil disturbance and resulting flush of mineralization will therefore help to reduce this risk (Cameron et al. 2013). Reducing the area undergoing pasture replacement or the use of minimum tillage techniques are two strategies that can help to achieve this objective. Scheduling the timing of pasture re-establishment to maximise the opportunity for plant uptake of N before winter drainage commences is another management decision that can help reduce N leaching risk. Grazed forage crops can be an important component of pasture renewal programmes in New Zealand and therefore pose some degree of increased N-loss risk due to increased soil N mineralisation that is exacerbated by the return of urinary N deposited during grazing. Recent plot- (e.g., Malcolm et al. 2015, 2016) and field- (e.g., Hanly et al. 2017; Smith & Monaghan 2020) scale studies in New Zealand have quantified these losses and, by implication, emphasised the need for feed supply systems that maintain vegetative cover as long as possible, thus maximising the opportunity for plant uptake of soil and urinary N. Whilst established pastures are an obvious candidate for providing these features, there are some important challenges to be addressed (especially with autumn-winter pasture grazing management) to ensure that treading damage does not subsequently curtail N uptake too greatly and feed can be provided when it is most acutely needed, i.e., during winter and dry summers.

Synchronising urinary N returns with pasture sward demand remains a major challenge, due largely to the

relatively high rates of N return to urine patches (200–2000 kg N/ha, Selbie et al. 2015). A key design principle that can help to reduce N within the urine patch is selecting pastures that can extract more N from the soil profile. Enhanced cool season activity of species such as Italian ryegrass and plantain has been shown to significantly reduce N leaching from lysimeters treated with cow urine (Malcolm et al. 2014; Woods et al. 2018; Welten et al. 2019). Modelling analyses suggest that enhanced plant growth in summer may also help to reduce N leaching from pastures (Snow & White 2013), which may be achieved through the use of pasture species that have summer-dominance of growth or via irrigation inputs of water to ensure plant growth and N uptake are maximised. The use of deeper-rooting plants or swards that intercept more radiation may also help to capture more N than occurs in New Zealand's predominantly ryegrass-white clover swards, although more research is required to define the size of this potential benefit (Snow & White 2013). The harvesting of forages for hay or baleage is another strategy that can manipulate the amount and timing of urinary N returns to soil to achieve better synchronicity between N uptake and availability, particularly if scheduled for summer and autumn months when deposited urine N is at greatest risk of leaching (Cichota et al. 2012). Restricting pasture grazing hours per day during these times provides a similar (but smaller) benefit to this principle of improving synchronicity.

Another design principle that would help to increase nutrient cycling efficiency is the development of pasture swards that result in less accumulation of forms of N or P that are vulnerable to transport in drainage or surface runoff. In the case of N, this can be achieved via pasture diets that help to dilute urinary N and therefore spread urinary N more evenly or through the inclusion of pasture species that can exert some degree of biological nitrification inhibition (BNI) that slows the transformation of ammonium-N to the more mobile nitrate-N form. Recent studies indicate that plantain may provide both of these attributes and ultimately result in less N leaching (Woods et al. 2018; Carlton et al. 2019; Minnée et al. 2020), although further research is required to quantify its effect on annual N leaching losses from grazed pastoral systems. Forage diets that have a greater (and optimal) energy:protein ratio (e.g., higher C:N ratios of more mature pasture or in feed such as maize) will also help to lessen total urinary N excretion and thus N loss risk (Bryant et al. 2020). Strategies for reducing P-loss risk from grazed pastures place greater emphasis on spatial considerations that minimise areas where source and transport factors overlap to define Critical Source Areas (CSAs) of P loss. In practical terms this requires avoiding the accumulation of excessive levels of soil P in parts of

the landscape where surface runoff is likely, soil P retention is low, or artificial drainage pathways act as rapid conduits for the transfer of P between topsoil and surface water networks. McDowell et al. (2014) document a novel approach that used strategically placed grass and clover monocultures to reduce soil P concentrations in near-stream areas (CSAs) and consequently P loss from a small headwater catchment in south Otago. Mackay et al. (2011) noted how soil physical condition, as measured by soil bulk density, and soil P concentration can interact to influence pasture production. These studies indicate the importance of spatial considerations that help to protect soil physical condition and lower soil P concentrations in CSAs where P-loss risk is greatest.

Overall, resilient pastures can reduce adverse environmental impacts from nutrients if there is actively growing plant cover that maintains N and P uptake particularly during seasons with heightened risk of drainage or overland flow.

Soil erosion/loss

The resilience of a pasture and underlying soils are expected to impact both the rate and magnitude of soil loss from surface erosion based on both empirical and theoretical understandings of the mechanisms involved. By reducing soil losses, resilient pastures will convey multiple benefits to both environment and on-farm performance. Broadly, on-farm benefits of pasture management that improves resilience will reduce and/or minimize losses of topsoil, soil C, and other natural capital bound to sediments. Improved soil physical, chemical, and biological health will improve nutrient retention and increase pasture performance. Flow-on environmental benefits beyond the farm boundary include reduced sedimentation and nutrient losses to waterbodies, maintenance of C stocks, and improved nearby freshwater ecosystem functioning. We describe attributes of a resilient pasture that impact soil loss and the associated environmental benefits: increased ground cover and improved soil physical, chemical, and biological health.

Increasing ground cover is associated with decreasing surface erosion due to its beneficial roles in intercepting rainfall, impeding the velocity and quantity of overland flow, and reducing soil loss through increased tensile strength of the underlying root mat (Greene et al. 1994; Silburn 2011; Chen et al. 2021; Donovan & Monaghan 2021). The proportion, density, species type(s), and temporal extent of surface cover are the primary vegetative components involved in altering soil loss via surface erosion. Resilient pastures will exhibit higher/denser vegetation cover throughout periods of disturbance (e.g., drought, flooding, animal treading, pest or disease outbreak) relative to a pasture system

lacking resilience. Thus, on-farm benefits of resilient pastures that have increased ground cover include increased soil and soil C retention and reduced losses of nutrients, soil-bound metals and faecal microorganisms.

The second set of on-farm environmental benefits stem from positive feedback cycles between pasture resilience and soil health. Resilient pastures are likely to both reflect and support improved soil physical, chemical, and biological health. Specifically, soil physical health is tied to pasture resilience through soil permeability and porosity, which impact water retention and infiltration in periods of drought and times of intense and/or prolonged rainfall. Soils with low infiltration rates will generally be more susceptible to both infiltration- and saturation-excess overland flow during flooding events, thereby increasing surface erosion. Conversely, low infiltration rates may increase water retention time, thereby maintaining favourable conditions for grasses and crops for longer during periods of drought. Further improvements in soil water holding capacity may result from increased soil macrobiological activity (i.e., earthworms) and organic C content (Hudson 1994) which generally reduce bulk density and improve porosity and water transmission and storage (Soane 1990; Franzluebbers 2002). While these soil attributes are also tied to soil microbial properties, it is important to note that the strength and direction of this relationship and the connection to pasture resilience is variable (Mariotte et al. 2015).

Through these mechanisms and feedbacks, resilient pastures provide on-farm environmental benefits in the form of favourable soil-water retention/infiltration, increased resistance to soil compaction and pugging, improved regulation of soil chemistry, and enhanced below-ground biological activity. The flow-on impacts to other aspects of the farm system are extensive. For example, the combination of improved soil infiltration and reduced pugging and compaction will likely result in improved animal welfare due to reductions in mud and oversaturated soil conditions. Further, pastures with resilience to drought conditions will help to maintain feed supply from pastures and therefore reduce reliance on forage crops and imported feeds, thereby mitigating soil and contaminant losses from farms when soils are cultivated for cropping (Donovan & Monaghan 2021). Over sufficiently long timescales, retaining soil on farm could result in greater long term C sequestration within pastoral lands, thereby helping to mitigate the C footprint of pastoral farming activities.

Greenhouse gas emissions

The two main GHGs emitted from pastoral systems are enteric methane (CH_4) from grazing ruminants and nitrous oxide (N_2O) from animal excreta deposited onto pasture (van der Weerden et al. 2018). Net conversion

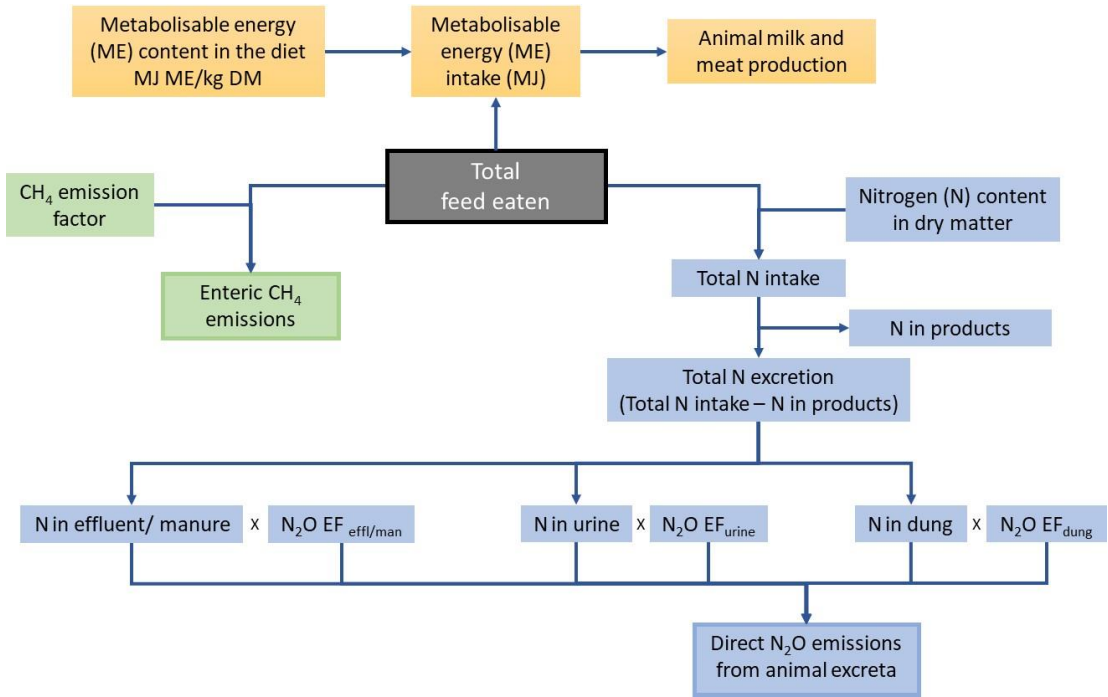


Figure 1 Schematic representation of how 'total feed eaten' directly affects animal production and enteric methane (CH_4) and nitrous oxide (N_2O) emissions from pastoral livestock production systems. MJ = mega joules; EF = emission factor.

of soil C to CO_2 also contributes to the atmospheric GHG burden and is dealt with in the following section. As CH_4 loss per unit DM intake is generally similar for all pasture species, enteric CH_4 emissions from pasture-based systems are largely controlled by the amount of feed eaten (van der Weerden et al. 2018; Jonker et al. 2020), which, combined with the energy content of the DM, affects animal production (Figure 1). Although maintaining DM production is a key element of pasture resilience, maintaining or increasing pasture quality (metabolisable energy (ME) content) is arguably more important for reducing CH_4 emissions (intensity) from pastoral systems. If the ME content of pasture declines, animals produce less milk or meat for the same DM intake, so total CH_4 will not be reduced and emissions per unit of production will increase. Therefore, a key factor of pasture resilience for reducing CH_4 losses per kg DM intake or kg product is to maintain or increase the energy content of the DM, either through selection of high-quality pasture species, improved genetics and/or improved pasture management. Cosgrove et al. (2018) suggested that differences in ME content in perennial ryegrass cultivars were due to genetic variation, rather than management factors such as N fertilisation and clover content. There is increasing recognition of the need to shift the efforts of improving forage genetics from solely focussing on productivity

traits to including attributes associated with improved resource use efficiency and energy content (Barrett et al. 2015).

Nitrous oxide emissions from pastoral systems are driven by the total amount of excess N (i.e., the difference between N supply and demand) in the soil and the proportion of this N that is converted to N_2O (i.e., the N_2O emission factor, Figure 1; Selbie et al. 2015; de Klein et al. 2020). As discussed previously, urine patches are hotspots for excess soil N and the amount of urinary N is controlled by the amount of feed eaten and the N content of this feed. Feed characteristics such as low protein to energy ratio and high condensed tannin content can increase the partitioning of N excretion into dung, thus also reducing the amount of urinary N excretion (de Klein & Eckard 2008). Mineralisation of organic matter (OM) following pasture renewal and cultivation also increases excess soil N and N_2O emissions (Schils et al. 2013; Buchen et al. 2018). To minimise the risk of N_2O loss (and N leaching) from excess soil N, pasture species should be selected that can extract more of this N from the soil profile. Maintenance of vegetative cover, to ensure increased N uptake, has been shown to reduce N_2O emissions from urine patches (Bowatte et al. 2018; Chirinda et al. 2019). Furthermore, using pasture species with complementary root morphologies

to increase plant N uptake capacity can also reduce N_2O emissions from urine patches (Abalos et al. 2014). Although no direct evidence exists that species with seasonal complementarity (winter vs. summer activity) can reduce N_2O emissions from urine patches (de Klein et al. 2020), seasonal complementarity has been shown to reduce N leaching (Malcolm et al. 2014; Woods et al. 2018; Welten et al. 2019), thus reducing indirect N_2O emissions. Therefore, key pasture resilience attributes for reducing excess soil N include: low N pastures to reduce urinary N excretion; species that can partition more dietary N into dung; species with diverse and complementary root systems and/or seasonal activity to increase N uptake/demand; pastures that can maintain vegetative cover and avoid bare patches; and pastures that persist so that the renewal frequency can be reduced.

The N_2O emission factor of urinary N is highest under warm and anaerobic soil conditions, i.e., in wet or compacted soils, and when excess N occurs as the nitrate-N form (Selbie et al. 2015). Key attributes for reducing the N_2O emission factor may include plant morphological characteristics that affect the soil microclimate (especially soil moisture, aeration and temperature conditions) and the ability to inhibit the transformation of ammonium-N to nitrate-N (biological nitrification inhibition, BNI). This BNI trait has been found in tropical pasture species (Subbarao et al. 2012) and recent studies have shown that plantain may also exhibit this trait (Gardiner et al. 2018; Judson et al. 2018; Pijlman et al. 2019; Simon et al. 2019).

A recent modelling study investigated the potential of three of these attributes for reducing N_2O emissions from grazed pastures (Giltrap et al. 2021): N content in animal feed; plant-excreted nitrification inhibitors; and rooting depth. These authors concluded that reducing the N content of animal feed provided the most promising results for reducing N_2O emissions and (N leaching loss). The simulations suggested that the effect of plant-excreted nitrification inhibitors was mixed, with N_2O emissions only reduced at assumed high rates of nitrification inhibition. At lower rates of inhibition, there was little effect on N_2O emissions. Plant-rooting depth scenarios suggested that N was more effectively intercepted and prevented from loss by greater root proliferation in the upper soil layers rather than by deeper rooting *per se*.

Soil carbon

Carbon cycling in pasture-based agricultural systems is primarily controlled by two key factors: (1) the exchange of CO_2 between the atmosphere and ecosystem; and (2) the management of the pasture system. Pastures take up C from the atmosphere through photosynthesis, with this C stored in above- and below-ground biomass

or respired back to the atmosphere by the plants themselves. Although not tied directly to plant uptake, decomposition of soil OM by microorganisms releases additional C back to the atmosphere (often referred to as soil respiration). For New Zealand pastures, around 90% of photosynthetic CO_2 uptake is returned to the atmosphere as either plant or soil respiration. Carbon allocated to above-ground biomass that is utilised for animal feed (whether grazed or harvested) is mostly lost from the system, either to the atmosphere as animal respiration and CH_4 , or as product (milk/meat). Consequently, the C available for storage in the soil in a simple grazed system is from below-ground inputs (i.e., roots), above-ground stubble and pasture that is trampled and wasted by grazing animals, and C excreted by the grazers following consumption of the pasture.

At the farm scale, both pasture-related management decisions and overall management philosophies influence soil C stocks. Use of inputs (e.g., supplementary feed, water (irrigation), fertiliser, etc.) to compensate for pasture shortages, or for the primary aim of boosting production and/or profitability, can affect soil C stocks in different ways. Importing supplemental feed can increase soil C stocks (Wall et al. 2019), irrigation likely decreases soil C stocks (Mudge et al. 2017), and fertiliser has limited effect for most New Zealand grasslands (Whitehead et al. 2018). Pasture renewal, whereby the existing pasture is eradicated and a new sward is sown, involves a period when there are no or limited photosynthetic C inputs but continued soil respiration losses resulting in a net loss of C (Rutledge et al. 2014, 2017). How long, if at all, it takes to recapture this lost C due to pasture renewal is uncertain. Inclusion of an arable crop produced for supplemental feed (e.g., maize silage) can result in even larger losses of soil C (Wall et al. 2020).

Resilient pastures with traits that are beneficial for soil C can take different forms. Pastures that allocate more C below-ground can increase the inputs of C to the soil, particularly if the roots penetrate deeper into the soil profile, thus providing the potential for increased soil C stocks. Increasing the diversity of a sward can lead to increased below-ground C inputs (McNally et al. 2015), although benefits will only occur if diversity is maintained. Resilience of pastures to climatic variability can influence soil C stocks in two key ways: (1) by providing a continuous input of C to the soil; and (2) by reducing the need for management interventions (e.g., the use of irrigation, supplemental feed, etc.) to overcome pasture feed deficits, which may be detrimental to soil C. Whilst the use of supplemental feed can increase soil C, production of that feed, whether on-farm or elsewhere, is likely detrimental to C stocks, and any small gains during use are likely cancelled out by losses during production. Increased persistence of a

pasture can reduce the need for pasture renewal and its associated soil C loss. Pastures that are beneficial for soil C are those that reduce the need for external inputs through resilience to climate extremes and/or change, and interventions that decrease C inputs to the soil, such as harvest and removal of above-ground biomass.

Discussion

Resilient pastures need to support farm continuity by maintaining production and quality, as well as achieving increasingly challenging environmental outcomes. In this paper we discussed key attributes of resilient plants and pasture management to minimise soil erosion and nutrient, GHG and soil C losses (Table 1). Many of these attributes have multiple beneficial environmental outcomes, with key examples being maintaining an actively growing plant cover, low N species, species diversity with complementary root morphology and/or seasonal complementarity, and greater persistence. These attributes are also likely to have positive benefits for production and productivity. An important exception to this is the potential tension between productivity outcomes and CH₄ emissions, where CH₄ production per hectare increases with increased growth and feed intake. If ongoing improvements in forage genetics and/or pasture management to achieve pasture resilience means ongoing focus on maximising harvestable yield, then total CH₄ emissions are not likely to be reduced from our pastoral systems. With currently available options, on-farm CH₄ emissions will only be reduced if the total amount of feed eaten by the herd is reduced (van der Weerden et al. 2018). This can be achieved by (1) reducing fertiliser or irrigation inputs to grow less DM per hectare (but with higher feed quality to maintain animal production), (2) maintaining or increasing DM per hectare but reducing the total area of pastoral land and/or (3) maintaining or increasing DM per hectare but harvesting less. The first option has the added advantage that if N fertiliser is reduced to reduce DM production, N₂O emissions will also be reduced. Similarly, the last option has the added benefit of providing extra C inputs to the soil, in particular young soil OM that can play an important role in pasture resilience (Shepherd et al. 2021). As the amount of feed eaten is also directly related to animal production, pasture species or management that can maintain or increase the ME content of the sward is an important driver of farm-scale resilience (Cosgrove et al. 2104, 2018).

Another potential tension between productivity and environmental outcomes of resilient pastures is less need for pasture renewal. Although a reduced pasture renewal rate has many beneficial environmental (reduced N leaching, P and sediment loss; decreased soil OM turnover) and financial outcomes (reduced cost), it could also result in a lower need or ‘incentive’ for

a farmer to improve pasture genetics or use emerging novel pasture species that have a lower environmental impact. Furthermore, from a farm systems perspective a key consideration of pasture resilience is that although plant cover may be maintained, thus providing attributes that are beneficial for environmental outcomes, the pasture may not be producing to the quantity and quality targets that the farmer intended. To enhance overall farm resilience it is therefore important that desired species persist in the sward. An example where persistence and desirability are in conflict is kikuyu on Northland farms. Kikuyu is a persistent forage, but produces less, especially over the cool season, and its quality is lower than that of ryegrasses (Crush & Rowarth 2007). Similarly, Tozer et al. (2011a) presented farmer observations on persistence and many commented that persistency means that the sown (i.e., desired) species continue to be dominant in the sward and that these species provide significant DM for up to 10 or more years after sowing. Farm practices that can improve pasture persistence should ensure that the vigour of sown species is maintained, and bare patches and weed propagule pressure are minimised (Tozer et al. 2011b).

As stated earlier, our definition of ‘resilient pasture’ includes environmental outcomes as an integral part of pasture resilience, rather than just as co-benefits. The choice of pasture species should reflect the desired outcomes for both productivity and the environment, and incorporate species that include all or some of the attributes summarised in Table 1. Finally, we note that whilst there are numerous attributes and managements documented in Table 1, none are likely to deliver major improvements on their own at the scale of a whole-farm system; progress will instead be more likely achieved through incremental improvements associated with the implementation of a range of these attributes and actions.

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Table 1 Summary of the key aims, attributes and managements of resilient pastures that deliver improved environmental outcomes (highlighted in grey).

Aim	Plant or management attribute	Environmental impact			
		Nutrient losses	Greenhouse gas loss	Soil loss	Soil carbon loss
Maintaining actively growing vegetative cover/minimise bare soil	Increase sward persistence; reduce susceptibility to drought, flooding (via soil infiltration), pest incursion	Reduced N leaching and P-loss risk	Reduced N ₂ O	Reduced surface soil erosion susceptibility	Reduced soil C loss by maintaining root inputs of C
Minimise excess soil N	Lower N content; increased condensed tannin content; diuretic traits that increase the spread of urinary N; tactical use of N fertiliser and effluent; optimal irrigation; reduced grazing duration	Reduced N leaching risk	Reduced N ₂ O	No effect	No known effect but limited data
Improved synchronisation between nutrient supply and demand to ensure high nutrient uptake capacity	Increased persistence to reduce pasture renewal rates; minimum tillage; renewal in spring	Reduced N leaching risk	Reduced N ₂ O	Reduced surface soil erosion susceptibility	Reduced risk of soil C loss
Maintain soil integrity; avoid soil degradation (i.e., soil structure and losses)	High root biomass; deep-rooting species; diversity of species that occupy different spatial and temporal niches; targeted harvesting of forages (cut-and-carry, silage); restricted grazing during autumn/early winter	Reduced N leaching and P-loss risk	Reduced N ₂ O	Reduced surface soil erosion susceptibility	Reduced risk of soil C loss; potential for soil C gain from greater root inputs
Reduce feed eaten whilst maintaining animal production	Biological nitrification inhibition capacity	Reduced N leaching risk	Reduced N ₂ O	No effect	No known effect but limited data
	Minimise pugging and compaction damage; optimise irrigation and soil infiltration/retention; increased root mass; high-C (organic) fertilisers; targeted protection of soils in CSAs ¹	Reduced P-loss risk	Reduced N ₂ O	Reduced surface soil erosion susceptibility	Maintained inputs of C and reduced loss of topsoil C
	Increased energy content and increased overall DM production	Reduced N leaching risk	Reduced CH ₄ and N ₂ O	No effect	No known effect but limited data
	Increased energy content; maintained overall DM production but less grazed	Reduced N leaching risk	Reduced CH ₄ and N ₂ O	No effect	Reduced loss risk/potential gains in soil C

¹ Critical Source Area

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