# A systems approach to understanding the connection between farm systems resilience and pasture resilience

David R. STEVENS[1,*], Marie J. CASEY[2], J. Paul EDWARDS[3] and Thomas M.R. MAXWELL[4]
[1] *AgResearch Ltd, Private Bag 50034 Mosgiel, New Zealand*
[2]*PGG Wrightson Ltd, Private Bag, Dunedin, New Zealand*
[3]*DairyNZ Ltd, PO Box 85066, Lincoln University, Lincoln 7647, New Zealand*
[4]*Department of Agricultural Sciences, PO Box 85084, Lincoln University, Lincoln 7647, Christchurch, New Zealand*
*Corresponding author: david.stevens@agresearch.co.nz

## Highlights
Farm systems resilience in New Zealand pasture-based farming is influenced by external drivers such as environmental regulation, and internal drivers such as existence, expressed as profitability. We examine ten published case studies of farm systems change to provide insight into management interventions to these drivers and their impacts on pasture resilience. Nutrient supply was key to increasing pasture longevity, water use efficiency and animal feed supply. Manipulating water use efficiency through irrigation and legume (predominantly lucerne) use increased nitrogen use efficiency and added pasture supply for animal consumption. Monitoring the pasture supply and animal response ensured both animal feed requirements and pasture conditions for future growth were met. The resilience of pastures was improved when monitoring guided adaptive management application to ensure whole-farm resilience.

**Keywords:** adaptation, complex systems, feedback, interactions, simple rules

## Introduction
Pastoral agriculture utilises many of the geo-climatic zones of New Zealand. The zones cover sub-tropical to cool temperate (Mackintosh 2001), and low to high rainfall, as well as low to high fertility soils (Hewitt 1998). These resources produce a wide array of both seasonal and total pasture production profiles around New Zealand (Radcliffe 1974). Therefore, there are many farming enterprises used to capture the pasture production from those resources. Farm systems have been developed to fit the winter trough and late spring peak in pasture production (McCall & Sheath 1993), utilising the natural seasonal breeding and lactation cycles to match pasture supply with animal demand. This vast array of both pasture production and animal enterprises supports approximately 25,000 farms whose primary income is from ruminant products, and provides partial support for another 10,000 farms (Beef and Lamb New Zealand 2020).

Resilience is the ability to recover from a disturbance event (Walker et al. 2004). Disturbance to pastures may be induced by internal or external factors. Internally, factors include livestock grazing demands (biomass removal, nutrient removal, treading), enterprise changes, and ethical choices such as organic farming. Externally, climatic variation and seasonal shocks (fire, drought, flooding), or capital availability and policy may force change. The timeframe of the disturbance must also be considered. This may be on a continuum from affecting the recovery from a single grazing event through to the continued perenniality of a pasture. Thus, pasture resilience is the ability to recover from shock to its previous state of meeting the goals of the farmer.

It is important to recognise that grazing systems are the intersection between pasture/plant communities and animal communities. Therefore, both the plant/pasture and the animal have a role in resilience. The farmer aims to employ a grazing system which optimises the outputs of product value to provide services to meet the needs of the farmer, their families and the wider community. Changes in the requirements and expectations of any of those parts then affects the ability of the underlying resource, the pasture, to be able to meet those needs, and to do so in a resilient fashion. Therefore, the management requirements and inputs of those resources must be altered to find a new resilience equilibrium when faced with change.

When pasture resilience is viewed as a response within the large range of farm configurations in New Zealand conditions then resilience of pasture is an intrinsic part of a unique system chosen by individual farmers. These systems are complex adaptive systems (Darnhofer et al. 2012). This means that they have many interactions, and that they change in response to both the internal and external influences.

All the elements of a system, both internal and external, are at play when we consider pasture resilience. “A system is resilient to the degree to which it rapidly and effectively protects its critical capabilities from disruption caused by adverse events and conditions” (Firesmith 2019). The pasture component of a farm system is vulnerable to adverse events that are both internal (such as grazing) and

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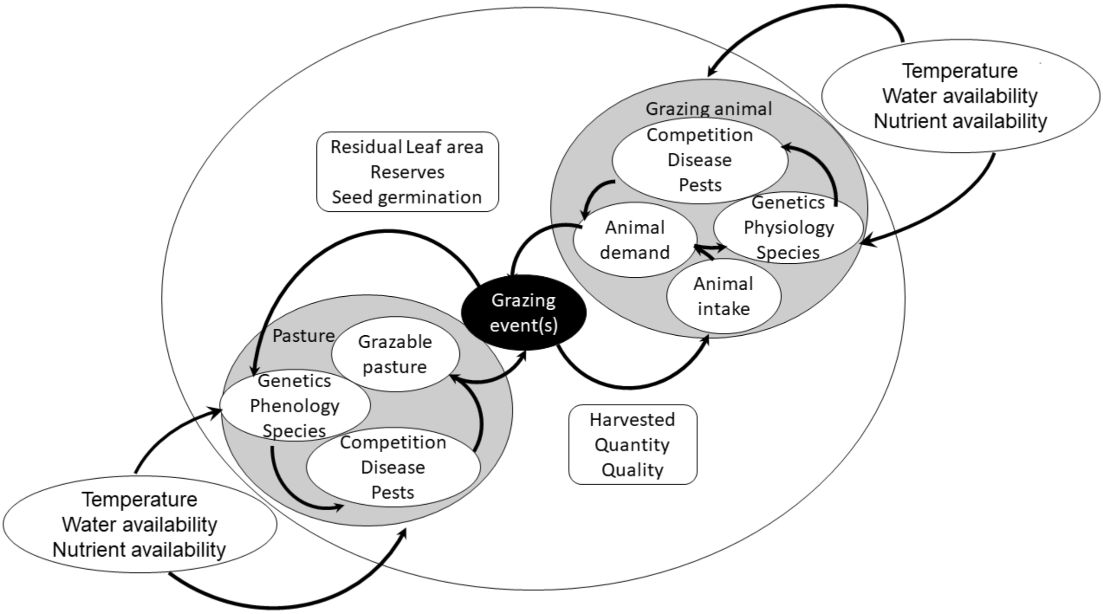


**Figure 1** A diagrammatic depiction of the biophysical system components of a grazing animal and a pasture, including their interaction through a grazing event.

external (such as drought). This raises the question of the role of pasture resilience within the framework of farm system resilience. The resilience of the farm system is measured by its continued profitability. This paper uses systems principles to identify management interventions at the strategic, tactical and operational level that may alter pasture resilience. We examine ten case studies of farmers who have reported changes in the resilience of their farm systems.

## Systems principles

Principles that define complex adaptive systems (Holland 2014) are used here to represent the potential for change. These include simple rules, interactions, nested and multiple sub-systems, feedback and adaptation/evolution.

*Simple rules of pasture growth and interactions with the grazing animal*

The first is *simple rules* (Figure 1). This enables the identification of what is critical to protect and assist in devising controls to detect adverse events (Firesmith 2019). A few simple rules that govern pasture growth can be identified. When simple pasture growth rules are broken, for example, the original function of the pasture is compromised and the system must come to a new equilibrium. In this case, the pasture would be unable to recover to the state that supported previous production levels, and therefore its current function/ resilience would change to a new, potentially lower level of functionality.

The second is the principle of *interaction* (Figure 1). We need to identify how the pasture growth rules interact with the animal and therefore how the farmer can influence those interactions. Understanding these interactions provides insight into the responses that may be needed to correct the impacts of adverse effects.

We begin with two inherent factors of the interaction between plants and animals in a grazing system – the animal demand and the plant growth (Figure 1). The internal factors, governed by simple rules, determine feed demand of the animal and are translated into feed intake through a grazing event. This feed intake comprises energy, protein and other nutrients to meet the potential animal demand generated by the species of animal, its genetic merit and its physiological state. This potential demand is modified by external factors such as the presence or absence of animal pests, disease and competition with other grazers.

The simple rules that govern the state of the pasture (internal factors) include the species present, their genetic merit and the phenology of the plant. These respond to the conditions that are created by the grazing event, the potential growth is modified by external factors such as competition with other plants, and the presence or absence of insect pests and diseases. The external conditions of soil water availability, nutrients and temperature provide the raw materials for growth.

This demonstrates the layering of simple rules (internal factors), responding to various raw materials

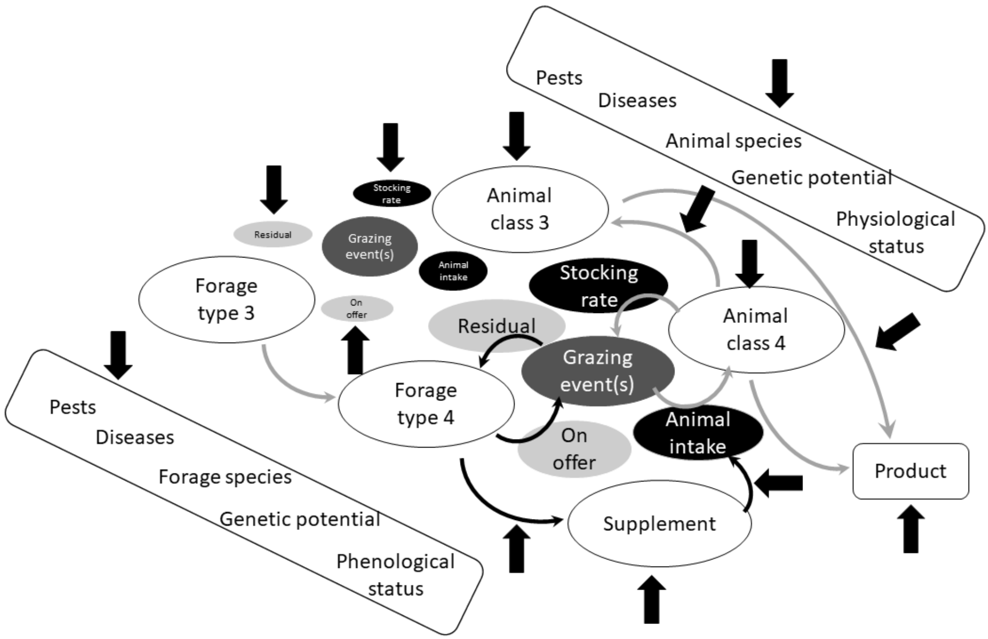


**Figure 2** A simplified farm systems model identifying multiple nested systems and the feedback process indicated by points of monitoring and intervention (black arrows) available to the farmer.

and conditions (external factors) to firstly produce a grazable pasture, then generate an animal intake, and the interactions that influence the re-creation of those conditions in the future.

*Nested and multiple sub-systems: translation from simple rules to a farm system*

A third principle, *nested and multiple sub-systems* (Figure 2)*,* is introduced to highlight the change in focus when the pasture system and animal enterprise exist within a farm system comprising of many forage sub-systems (beyond pasture) and animal enterprises to utilise that forage resource. Further to that, the nesting of systems changes the locus of control and potential intervention.

As we transition into a farm system, and as the farmer assumes control, we see the nesting and multiplication of systems. Elements that were within the plant and animal sub-systems (Figure 1) are now relocated outside the sub-system into the broader farm system (Figure 2). Items like insect pests, disease, and genetics can be controlled by the farmer. What was depicted as a pasture in Figure 1 is now replaced by a range of forage types that may change in response to grazing. Supplement may also be added as a feed source. Even the animal species and physiological status are a choice made by the farmer. Within each enterprise there may be several animal classes (breeding ewes, lambs, milking cows etc.). Each animal class has a specific set of nutritional requirements. The farm system has a requirement to create products. These may be generated direct from one or more animal classes, or potentially transferred between animal classes as they mature or change physiological status. For example, the lambs produced by the ewe breeding flock may be sold at weaning, becoming a direct product, or be transferred to a finishing mob, becoming a new animal class.

The knowledge of simple rules and their potential interactions becomes magnified many times when elevated from a single grazing event to the farm system scale. This is also related to farm type. In a dairy cow system that operates a farm as a milking platform there is only one animal class, and this may translate into two herds of different physiological need (early or late calvers/low or high condition score cows). In a sheep, beef and deer system there may be upwards of 20 animal classes, and many more herds/mobs. This then translates into multiple grazing events that may be all happening simultaneously. This is where the complexity happens.

*Feedback: monitoring, intervention and control*

A fourth principle is the role of feedback throughout the system on decision-making and intervention (Figure 2). There are many potential feedback points within the forage type and animal class sub-systems, between the sub-systems and beyond, into the wider farm system. While feedback happens at the biological level, between plant and animal, during and after a grazing event, feedback to the farmer must be explicit for a decision to be made. The black arrows (Figure 2) provide an indicator of the places within the farm grazing system that direct feedback can be gathered. The farmer can monitor the condition and liveweight of their livestock and use tools to predict their feed requirement. They can monitor the state of disease and insect pest incursion, and the physiological and phenological status of their livestock and pasture. They can use the output of product as an indicator of the adequacy of the system. At the finer level they can adjust instantaneous stocking rate, monitor feed on offer and the residual pasture after grazing. The amount of forage being conserved can be monitored, as well as the amount in the supplement inventory, and that fed to meet animal demand.

*Adaptation and evolution: External events and the impacts of different timeframes*

The final principle is *adaptation/evolution*, which is explored further in ten case studies (Table 1). The potential for evolution comes as a response to perturbation. A new equilibrium may result at a higher or lower level of pasture system functioning. This is driven by the response to external influencers, such as climate, that may modify the internal workings of the system. These may explain why our perceptions of resilience are changing or are directing the need for future change.

By understanding the effect and extent of an adverse event we can begin to understand the likely direction of change, or the potential and timeframe for recovery. We need to recognise the impact of different time scales and examine the adaptive element of pasture systems. The element of time is crucial to resilience, as different mechanisms (e.g., tiller production vs. seed germination) may be at play. Events occur over a continuum of timeframes and can be grouped into three broad categories that match the operational, tactical, and strategic decision-making timeframes (Parker et al. 1997). These reflect the potential ability of the pasture to recover in the short, medium and long terms. The aim of the farmer is to optimise the conditions of recovery over these timeframes to maximise the likelihood of achieving their goals from a social, economic, environmental and cultural perspective. The farmer's responses then depend on the relative occurrence rate and severity of events over each of those timeframes. So, while there are underlying biophysical principles to be considered, a major influencer on resilience is the farmer, through their chosen management interventions.

We use these systems parameters to identify the links between farm systems resilience and pasture resilience using a set of ten case studies to identify significant management interventions that farmers have used to enable or improve the resilience of their pasture system.

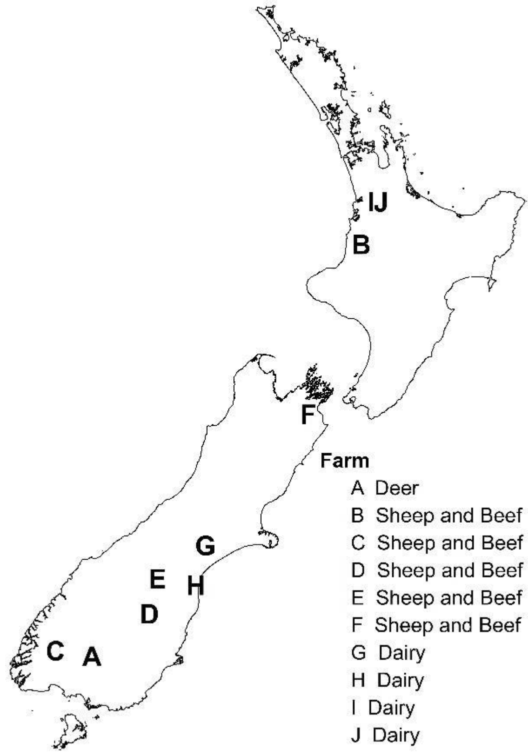


**Figure 3** Case study sites and enterprises around New Zealand.

## Case studies of dairy, sheep and beef and deer enterprises

Ten case studies with either published, or available data were identified. These case studies represented the range of livestock enterprises and geo-climatic conditions in New Zealand (Table 1, Figure 3). The threat that each case study was responding to is also noted. The options used to manage pasture supply and animal demand were categorised as either strategic, tactical or operational (Parker et al. 1997). Pasture eaten was calculated from documented animal numbers and performance records, using the factorial approach to energy requirements and equations published by Rattray et al. (2007), or retrieved from the literature. Main pasture types are described as pasture associations identified by Field (1989) and republished by Cosgrove & Field (2016).

*Case study analysis*

Solutions were grouped into the management framework of strategic (long term), tactical (medium term) and operational (day-to-day, Parker et al. 1997).

Key controls and changes implemented by the farmers were also characterised by whether they influenced the animal or forage enterprises, or both. Further grouping was used to identify the *simple rules, interactions, feedback* and *adaptations* that were represented.

## Case study insights

A wide range of management approaches were implemented to increase the resilience of pasture-based animal production systems (Table 2). Each of these solutions depended on the context of both the animal

**Table 1** Descriptions of ten case studies examining pasture resilience in a systems context.

| Case study[1] | Initial livestock enterprises | Environment | Climatic data[2] | | | Pasture and forage type | Source | Threat to systems resilience[3] |
|---|---|---|---|---|---|---|---|---|
| | | | Annual rainfall (mm) | Average winter temperature (ºC) | Average summer temperature (ºC) | | | |
| A | Deer breeding/ finishing<br>Replacement heifer grazing<br>Beef finishing | Cool temperate | 810 | 4.9 | 14.3 | Ryegrass/white clover/browntop<br>Winter brassica<br>Summer brassica | Focus on Deer Sustainable Farming Fund project;<br>Payne et al. 2009 | 1,2 |
| B | Sheep breeding/finishing<br>Beef breeding/finishing<br>Bull beef finishing<br>Winter lamb finishing | Warm temperate | 1585 | 8.7 | 17.1 | Ryegrass/white clover/Yorkshire Fog<br>Red clover-plantain<br>Winter brassica | Fraser et al. 2016;<br>Stevens & Casey 2017 | 2,3 |
| C | Sheep breeding/finishing<br>Beef breeding/finishing<br>Sheep genetics | Cold temperate | 1135 | 4.3 | 12.2 | Ryegrass/white clover/sweet vernal<br>Lucerne<br>Winter brassica | Johns et al. 2016 | 4 |
| D | Sheep breeding/finishing | Cool arid | 425 | 3.3 | 15.4 | Cluster clover/ haresfoot trefoil<br>Lucerne<br>Winter brassica | Casey et al. 2015;<br>Stevens & Casey 2017<br>Stevens et al. 2012 | 2,5 |
| E | Sheep breeding/finishing<br>Beef breeding | Cool arid | 480 | 5.6 | 17.4 | HieraciumRyegrass/ tall fescue/ clover<br>Lucerne<br>Winter grazing cereal | Anderson et al. 2014;<br>Moot et al. 2019 | 2 |
| F | Sheep breeding/finishing<br>Beef breeding/finishing | Warm arid | 610 | 7.1 | 17.3 | Browntop<br>Winter brassica<br>Subterranean clover | Grigg et al. 2008 | 2 |
| G | Milking cows | Cool temperate (free draining) | 680 | 6.5 | 16.6 | Ryegrass/ white clover<br>Plantain | Pinxterhuis & Edwards 2018 | 1 |
| H | Milking cows | Cool temperate (impeded drainage) | 660 | 5.8 | 15.7 | Ryegrass/ white clover<br>Plantain | Pinxterhuis & Edwards 2018 | 1 |
| I | Milking cows<br>Replacement heifer grazing | Warm temperate | 1130 | 7.7 | 17.0 | Ryegrass/ white clover | Jensen et al. 2005;<br>Clark 2011 | 1 |
| J | Milking cows | Warm temperate | 1130 | 7.7 | 17.0 | Ryegrass/ white clover | Jensen et al. 2005;<br>Clark 2011 | 6 |

[1] See Figure 3 for location in New Zealand
[2] Source: National Institute of Water and Atmospheric Research. The National Climate Database. https://cliflo.niwa.co.nz/ (Retrieved 27 November 2020).
[3] Threats to systems resilience: 1-Environmental regulation, 2-Existence (profitability), 3-Land use change, 4-Animal welfare, 5-Family succession, 6-Resource use efficiency.

enterprise and the environmental conditions. Threats to resilience of the farm system included external drivers of environmental regulation/impacts (cases A, G, H, and I), animal welfare (case C), and land use change (case B), and internal drivers of existence/profitability (cases A, B, D, E and F), and resource use efficiency (case J).

At each timeframe of management/control there were an equal number of interventions relating to the animal or the forage enterprise (Table 2). The number of interventions recorded were 52, 60 and 52 at the operational, tactical and strategic timeframes, respectively (Table 2).

Every intervention point of the farm system (Figure 2) was represented for at least one of the timeframes. Plant phenology was represented as a forage intervention in the lucerne and subterranean clover studies. Interventions regarding surplus pasture, such as closing times for silage, were made to meet supplement requirements and maximise feed quality for the grazing animal, therefore an animal decision.

There were 116 interventions targeted at animal performance. These included the manipulation of forage supply through nitrogen (N) fertiliser use, grazing triggers such as pre-and post-grazing herbage mass and the use of supplement making to transfer feed into the future, and to return pastures to a high feed-quality state. There were 99 interventions aimed at pasture management. The manipulation of animal product flow, choice of animal species to match pasture supply and managing stocking rate and pre- and post-grazing herbage mass, were included in this set of interventions.

These case studies highlight the range of themes which were employed by the farmers to develop systems resilience. We discuss a set of themes which emerged from the examination of the case studies and relate them to farm systems characteristics.

**Table 2** Management interventions applied at operational, tactical and strategic levels and the priority to manage animal demand or pasture supply to increase the resilience of pasture-based animal production in case studies of sheep, beef and deer (A-F) and dairy farm (G-J) systems.

| | Operational | | | Tactical | | | Strategic | | | Priority | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Within a grazing round (up to 30 days) | | | Within a season (30-90 days) | | | Beyond a season (>90 days) | | | | |
| **Control/intervention** | Sheep, beef and deer[1] | Dairy[2] | Total | Sheep, beef and deer | Dairy | Total | Sheep, beef and deer | Dairy | Total | Animal | Plant |
| Animal performance | 6 | 0 | 6 | 4 | 0 | 4 | 2 | 2 | 4 | 14 | |
| Stocking rate | 5 | 1 | 6 | 2 | 1 | 3 | 4 | 4 | 8 | 17 | 17 |
| Residual forage mass | 5 | 4 | 9 | 2 | 0 | 2 | 0 | 0 | 0 | 11 | 11 |
| On-offer forage mass | 6 | 4 | 10 | 3 | 1 | 4 | 1 | 0 | 1 | 15 | 15 |
| Transfers between animal classes | 0 | 0 | 0 | 4 | 2 | 6 | 2 | 0 | 2 | 8 | |
| Transfers between forage types | 3 | 0 | 3 | 5 | 0 | 5 | 1 | 2 | 3 | 11 | |
| Supplement use/making | 1 | 2 | 3 | 4 | 3 | 7 | 1 | 0 | 1 | 11 | 11 |
| Supplement importation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | |
| Product flow | 2 | 0 | 2 | 5 | 3 | 8 | 2 | 0 | 2 | | 12 |
| Animal genetic potential | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 2 | |
| Animal physiological status | 0 | 0 | 0 | 2 | 2 | 4 | 3 | 1 | 4 | | 4 |
| Plant genetic potential | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | |
| Plant phenological status | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 0 | 0 | | 4 |
| Animal species | 2 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 2 | | 6 |
| Forage species | 0 | 2 | 2 | 4 | 0 | 4 | 6 | 2 | 8 | 14 | |
| Weeds | 3 | 0 | 3 | 1 | 0 | 1 | 0 | 0 | 0 | | 4 |
| Diseases | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | 1 |
| Irrigation | 1 | 1 | 2 | 1 | 3 | 4 | 1 | 3 | 4 | | 10 |
| Stock water | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | |
| Soil nutrient supply | 0 | 3 | 3 | 3 | 0 | 3 | 4 | 1 | 5 | 7 | 4 |

[1] Case studies A-F, six in total – refer to Table 1 and Figure 3 for details
[2] Case studies G-J, four in total – refer to Table 1 and Figure 3 for details

**Simple rules**

Underlying changes that influenced the simple rules within the system were a significant source of increased resilience. Of greatest significance were the nutrient supplies, both to the forage sub-system and the animal sub-system. Also, of significance in some environments was water supply (through irrigation and stock water) and water use efficiency (through legume introduction and N fertiliser use).

*Nutrient supply*

The supply of nutrients, both to the forage and the animal sub-systems, from external sources, was a feature of 9 out of 10 case studies. This supply of nutrients was an underlying enabler to maximise potential feed supply to meet animal demand, and in turn influenced animal enterprise management.

*a) Forage sub-system*

For the forage systems the manipulation of nutrient supply took two forms. One was to change the nutrient supply for legumes to indirectly increase N supply through fixation of atmospheric N. This option was applied in systems that were chronically deficient in N, usually having low soil organic matter content, and hence N reserves (cases C, D and E). The targeting of specific legume systems, rather than overall changes in the grass-legume balance of a pasture, is a departure from traditional pasture practices in New Zealand (McCall & Sheath 1993). The targeting of legumes (white and red clover) where soil organic matter was greater (cases B and I), was much harder to both implement and capture benefits (Clark 2011; Fraser et al. 2016).

The second approach was to use N fertiliser, either as a long-term strategy or a medium-term tactical decision. In dairy systems N use as fertiliser was both strategic (case J) and tactical (cases G and H). However, strategic use of N to enhance pasture growth has been documented to increase the N surplus in a system (Serra 2020), with a change to appropriate tactical use reducing potential nitrate leaching (Serra 2020).

*b) Animal sub-system*

Manipulating the nutrient supply to the animal sub-system, beyond the direct grazing event, was achieved through pasture conservation, additional forages, imported supplements and the identification and management interventions to achieve target pasture covers. Thus, there are elements which are managed within the system and additions from outside the system. All of these are initially designed to support the nutrition of the animal, with a secondary target of ensuring that pastures are not overgrazed. None of the documented cases used the closing for feed conservation as a method of using plant phenology, for example to increase tiller production (Waller & Sale 2001), to support pasture resilience.

*Water supply and use*

Water supply was addressed at a strategic level through infrastructure investment, the tactical level when deciding when to begin irrigation, and at the operational level through variable rate application. It was also addressed through supply of stock water in one case.

Water use efficiency was addressed through the variable rate application of irrigation water, the use of N fertiliser (cases G and H) and through the introduction of legumes (cases D, E and F). As a legume, the amount of dry matter (DM) produced per mm of water used is between 2- and 3-times greater than perennial pasture, mainly due to its associated N fixation (Moot et al. 2003). Therefore, the introduction of lucerne on farms with low rainfall, and the use of N fertiliser on irrigated farms maximises water use efficiency, demonstrating management interventions used to capture the interaction between two simple rules.

**Interactions**

*Forage resource management*

This included elements such as wintering-off (cases G and H), fast or variable rotations (cases A, G, H, I and J), feed pads and self-fed silage (cases A, H), cropping options (cases A-F), target covers (all cases), extended grazing intervals (cases A, D, E, and F) and irrigation (cases D, E, G and H). These options again covered strategic and tactical timeframes.

These options interact strongly with the supply of nutrients to the animal. The elements chosen depended on the requirements of the system and the potential of each system to meet the capital and seasonal finance to implement change. Target pasture covers, for example, were chosen to attempt to optimise both forage and animal performance.

*Animal enterprise management*

Once enterprises are chosen at a strategic level, management interventions can be applied to those enterprises. Variations at the tactical level included the choice to retain young stock for finishing (cases D, E and F), the timing of sales and purchases of livestock (cases A-F), culling decisions (cases G, H and I) and the match of species/stock classes to forage conditions (cases A, B and C). These management changes were either to utilise extra pasture production or to release pasture as a feed for other enterprises, operating to optimise the outcomes from several nested sub-systems.

*Animal physiology management*

This was implemented at tactical and operational timeframes. Tactical decisions to dry off cows were a feature of case studies H and I, while varying milking interval was mentioned in case H. Variable weaning times are a feature of animal demand management in sheep and beef systems (e.g., Gray et al. 2011), though these were not mentioned as specific changes to current practice. They also noted that this decision was based on ewe condition rather than pasture overgrazing.

**Feedback**

*Measurement and Tools*

The use of measurement and tools to guide the application of management decisions was a constant feature throughout these case studies. These can be assigned to either monitoring to know the state of the resource or understanding the outcomes of decision-making. Often a single measurement may provide both. For example, a post-grazing herbage mass will provide insight into the potential intake of the animal which has just grazed that pasture while also providing insight into potential future pasture growth.

Operational tools used included options such as pre-winter and pre-spring pasture cover targets (cases A-H), forage measurement and management tools such as feed wedges (DairyNZ 2016) and pasture cover estimates (cases A, B and G-J), and animal management tools such as feed budgeting (cases A, B and G-J), animal liveweight (cases A-C and E) and body condition scoring (cases B, C and G-J).

Measurement types and intensity differed from other elements as they differed between animal enterprises. Herbage measurement of individual grazing events was most often practised in dairy systems (cases G-J), while sheep, beef and deer systems (cases A-F) were more likely to use an inventory approach at monthly or longer intervals. Sheep, beef and deer systems were more likely to target ranges of pasture covers at specific times of the year rather than on-going measurement. Animal measurements of liveweight and liveweight change were practised in sheep, beef and deer systems (cases A-F), while body condition score was used more universally (cases A-J).

These differences may reflect the complexity of the system and both the spatial scale of the properties and the temporal scale of grazing management. As previously stated, a sheep and beef farm may have greater than 20 or 30 mobs of animals while a dairy farm may have two to four, therefore the amount of effort to monitor these events is an order of magnitude apart. Sheep and beef farmers implement continuous grazing practices at relatively low stocking densities and slow forage harvesting rates while dairy farmers most often rotationally graze at high stocking densities with fast forage harvesting rates. The changes being detected by daily monitoring are measurable and meaningful in a dairy farm but are not on a sheep and beef farm. Therefore, the monitoring of a single grazing event is appropriate for a dairy enterprise, while the monitoring of changes in inventory is appropriate for a sheep and beef farm.

Measurement was much greater in some instances. In case J, for example, measurement was frequent and detailed as the relative tolerance for error was much less than in some other systems, due to the very high stocking rates that were tested. Sheep and beef farmers were more likely to set strategic decisions (such as the introduction of lucerne or lambing date changes) and then rely on broad principles at critical times, rather than precision measurement. Systems with greater variability and scale (cases A and D-F) were more likely to have a limited set of measurements and management tool use. This may be due to the lower labour availability, the greater variability and the greater complexity. This concept is developed further in the discussion. All the case studies had some external assistance when developing and monitoring the systems changes that were implemented.

**Adaptation**

The case studies illustrate the wide range of red meat and dairy farm enterprises that are commercially viable (Table 1). This range may be due to climatic variation, both across seasons and years, resource and input parameters (including capital), regulatory and social factors, and to farmer management skills including experience and risk profile. Several elements were present that indicated adaptation.

*Systems fit*

While pasture is key to providing most of the feed, the inherent variability means that optimal configuration to capture pasture productivity as animal product is rarely achieved, and often not aimed for in developing a resilient farming system. Resilience, when viewed in systems thinking frameworks, by definition, comes from configurations that aim to optimise a range of objectives, of which production is only one. In these case studies we can see the development of resilience by adjusting enterprise mix and sale policies using strategic and tactical timeframes.

Cases G and H used the milking platform as a specific enterprise that improved systems fit. In these cases, winter pasture production may be only 5% of that recorded at the spring peak. Thus, high stocking rates to capture the spring pasture as milk production cannot be readily accommodated in the same system over winter. Further, the provision of irrigation provides a more assured water supply towards more predictable pasture production.

The improvement of systems fit using forage species choice such as lucerne, red clover and subterranean clover (cases B, D-F) also increased productivity and profitability of these enterprises (Grigg et al. 2008; Fraser et al. 2016; Stevens & Casey 2017; Moot et al. 2019). These changes were applied to create greater opportunities to utilise the climatic resources at critical production times, for example, to provide high quality forage for lactating ewes in spring.

Changes introduced through shifting animal demand by altering the timing of animal physiological changes (cases B, C, D and H), such as the change in lambing or calving dates, may appear minor. However, their cumulative effects can be significant, as a strategic change such as this alters the demand of feed at a time when supply and demand may be critical. The ability to control the demand during early spring, for example, results in greater leaf area and pseudo-stem reserves, and thus can increase subsequent pasture production (e.g., Stevens et al. 2003). This then alters the availability of pasture in the medium term, and so increases the feed intake of the animal, resulting in both more pasture grown, and greater animal productivity, as demonstrated in case A, amongst others. These examples illustrate how the addressing of underlying simple rules can influence the opportunity for adaptation.

*Genetics*

Farmers identified that the genetic potential of the ewe flock was not being met in cases B and C. This directed changes in the timing of both feed supply and demand (Fraser et al. 2016, Johns et al. 2016), including additional forage resource, supplementation and changing lambing date.

Genetic gains in the sheep (Fennessey et al. 2016), beef (Anon 2010), deer (Ward et al. 2016) and dairy (Clark 2011) industries have been significant. Those gains in genetic potential have been matched by gains in nutritional understanding which capture much of that gain. The case studies all incorporated some elements of altering feed supply to continue to meet the increased feed demand from genetic gain.

Genetic advances should recognise the increased feed demand where appropriate and adjust grazing pressure accordingly. The genetics of higher milk yield in dairy cows, for example, increase feed demand by approximately 0.3% per annum. Thus, herd numbers should be reduced by 1 cow for every 300 cows per annum (Bryant 2017) or feed supply should be increased, possibly through pasture renewal with genetically improved pastures. If feed supply is not adjusted to meet this demand, the overall grazing pressure at each grazing event will increase, altering the equilibrium of the grazing system, thereby changing the potential resilience of the system.

Pasture renewal was a feature of several case studies, though often as an adjunct to a winter cropping programme, and to change to alternative forages such as lucerne. The choice of pasture genetics was much less important than the choice to renew pastures generally. Pasture renewal appeared to be regarded as a standard practice. Case A reduced rates of pasture renewal. The choice of pasture species was a significant mitigation in 7 of the 10 case studies. However, cases G and H chose alternative species (plantain) to improve environmental outcomes, increasing their resilience to regulatory change, rather than to increase pasture resilience. In fact, the species chosen in cases B, G, and H reduced pasture resilience as an increase in pasture renewal was required due to the lack of perenniality in the species chosen.

**What was missing?**

Documented interventions did not include insect pest or disease control, except for weed spraying in lucerne as a standard practice. This may be due to either the acute nature of insect pest and disease incursions, or to a chronic state where their presence is undetected. Farmers may feel that they have little control over these elements, perhaps without economic solutions, impacts that occur too quickly or collateral damage that is too great. When collateral damage is too great resilience is lost and requires post-event intervention such as full pasture renewal.

## Discussion: systems change alters resilience of pastures

These case studies provide the background for examining the role of systems choice, and potential changes, on pasture resilience. Each example presents a different configuration of complexity, and different resulting grazing management strategies, along with a different base resource of pasture/forage species.

Are there systems that have degraded over time? Absolutely! Are they then non-resilient consequently, or have they just not met an equilibrium point where the system is resilient? Take, for example, the invasion of *Hieracium* in the high country (case E). A *Hieracium* system is very resilient in the face of the stressors applied – high grazing pressure (grazing pressure greater than the pasture resource could recover from in a timely fashion), low soil fertility and low soil moisture status. Case E (Moot et al. 2019) reported the recovery of the hill pastures from *Hieracium* to a grass and legume sward when grazing pressure was alleviated through the provision of lucerne to meet spring feed demands. This example demonstrates the restoration of a productive pasture in one part of the system by altering another forage element.

At the other end of the scale there are the irrigated dairy pastures of Canterbury (cases G and H). These systems are highly fertile with a grazing regime that optimises conditions for high pasture production systems. In this relatively benign climate, with soil moisture deficits removed through irrigation, external nutrients are supplied by N and phosphate (P) fertilisers to support the potential extra demand from improved pasture genetics. For example, for every 1 t/ha increase in DM production, the soil needs to supply approximately 35 kg each of potassium and N, and 3.5 kg P. Thus, the system responds to the supply of extra nutrients to create the new resilience equilibrium. Insect pest control through interventions such as the use of endophyte and seed treatment and potential further interventions such as artificially applied plant growth regulators are often used though not noted by farmers. In these systems the environment is heavily modified to support the apex species, ryegrass, to maintain both pasture and system resilience. Many farms in the South Island, for example, were converted to dairy farming in the 1990s and early 2000s and so are designed to meet the needs of current dairy cow genetics.

The climatic data indicates that meteorological drought is increasing in frequency and intensity in Waikato (Stats NZ 2020), with associated commentary regarding a lack of pasture persistence in this environment (Clark 2011). Case studies I and J demonstrated a range of interventions and options that retained adequate levels of profitability, productivity and pasture species stability (Clark 2011). Their success may result from the intense measurement and management tool use. This feedback was used to manage the application of tools such as irrigation and imported supplement to support the pasture in meeting animal feed requirements (case J), while reducing stocking rate and costs at the other end of the scale (case I). This may illustrate the concept of adaptation under slowly changing conditions. Dryland farmers exhibit high degrees of flexibility in their management policies and stock choices (Gray et al. 2011). When faced with slowly changing climatic conditions, these systems evolve in step with that flexibility. Dairy systems, which rely on a single product, are often in areas with more reliable pasture production and have fewer options for flexibility due to the inability to restart lactation, and as such the current systems configuration has been developed in response to previous conditions, rather than being configured for future conditions. Therefore, changing climatic conditions may challenge these systems and put pressure on pastures through over-grazing before the need for change is recognised. High degrees of monitoring may help accelerate the development of newly adapted systems.

Direct measures of the nature of the pasture, such as desirable species, were only available for the cases I and J. The contribution of ryegrass, the noted desirable species, remained high, and similar for the 5 years recorded (Clark 2011), regardless of case J having approximately three times the stocking rate, and half of its feed externally sourced compared with case I. The productivity of hill pastures was anecdotally reported as increasing in cases D-F. Soil and nutrient losses from case A were also reported as low (McDowell & Stevens 2006).

## Conclusions

When responding to both internal threats such as existence and external threats such as environmental regulation similar principles were employed to generate resilience. Underlying attention to simple rules and their interactions within the farm system were utilised to affect the resilience of pastures. These simple rules included:

- Nutrient supply for forages through N fertiliser and the introduction of legumes such as lucerne which fix their own N alongside capital P application and changing soil pH;
- Water supply for forages through irrigation and animals through stock water installation; and
- Nutrient supply for animals through augmenting pasture supply by the introduction of crops, supplement making and importation of supplements.

Interactions being used were:

- Using N to increase water use efficiency, either as fertiliser or the introduction of legumes such as lucerne, red clover and subterranean clover;
- Using target pasture covers to optimise both pasture production and animal intake;
- Forage resource management to shift demand to alternative forages when animal demand may exceed pasture growth;
- Animal enterprise management to increase or reduce demand to match with pasture supply, or to direct feed resources to the most appropriate animal enterprise; and
- Manipulating animal physiological demand through varying milking interval, weaning dates and drying-off to reduce or maintain pasture consumption.

Feedback was used to:

- Set target pasture covers strategically (upper and lower average pasture cover boundaries), tactically (at the start of spring, for example) and operationally (pre- and post-grazing pasture cover);
- Monitor pre- and post-grazing pasture cover; and
- Monitor animal liveweight and condition score.

Adaptation was represented as:

- Systems fit where the advantages and deficiencies of the soil and plant resources were identified, modified and animal enterprises chosen to utilise those resources; and

- Identification of changes in feed demand induced by genetic gain and adapting feeding options to capture those benefits.

Several potential elements of disruption were not expressed fully. These included insect pest and disease management, pasture genetics (beyond species choice), inclusion of consideration of plant phenology (beyond lucerne in autumn and subterranean clover seeding management) and grazing management technique (e.g., continuous or rotational grazing).

The control of nutrient flows through the systems and their interaction with water supply were the most critical elements determining the resilience of the farm system. When applied appropriately to meet the demand of grazing livestock, many animal enterprises were able to capture the productive outcomes of a pasture-based forage supply system. On-going resilience of the farm system then enabled pasture resilience through monitoring and adaptive management.

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