Manaaki Whenua
Landcare Research

Quantifying resilience to drought and flooding in agricultural systems

Prepared for:

Our Land and Water National Science Challenge & the NEXT Foundation

May 2021

‘Think piece’ on Regenerative Agriculture in Aotearoa New Zealand: project overview and statement of purpose

Gwen Grelet & Sam Lang

Extracted from: Grelet GA, Lang S 2021. ‘Think piece’ on Regenerative Agriculture in Aotearoa New Zealand: project overview and statement of purpose. Manaaki Whenua – Landcare Research Contract Report LC3954 for Our Land and Water National Science Challenge & The NEXT Foundation.

Find the full project overview, white paper and topic reports at

ourlandandwater.nz/regenag and www.landcareresearch.co.nz/publications/regenag

This report is one of a series of topic reports written as part of a ‘think piece’ project on Regenerative Agriculture (RA) in Aotearoa New Zealand (NZ). This think piece aims to provide a framework that can be used to develop a scientific evidence base and research questions specific to RA. It is the result of a large collaborative effort across the New Zealand agri-food system over the course of 6 months in 2020 that included representatives of the research community, farming industry bodies, farmers and RA practitioners, consultants, governmental organisations, and the social/environmental entrepreneurial sector.

The think piece outputs included this series of topic reports and a white paper providing a high-level summary of the context and main outcomes from each topic report. All topic reports have been peer-reviewed by at least one named topic expert and the relevant research portfolio leader within MWLR.

Foreword from the project leads

Regenerative Agriculture (RA) is emerging as a grassroot-led movement that extends far beyond the farmgate. Underpinning the movement is a vision of agriculture that regenerates the natural world while producing ‘nutrient-dense’ food and providing farmers with good livelihoods. There are a growing number of farmers, NGOs, governmental institutions, and big corporations backing RA as a solution to many of the systemic challenges faced by humanity, including climate change, food system disfunction, biodiversity loss and human health (to name a few). It has now become a movement. Momentum is building at all levels of the food supply and value chain. Now is an exciting time for scientists and practitioners to work together towards a better understanding of RA, and what benefits may or not arise from the adoption of RA in NZ.

RA’s definitions are fluid and numerous – and vary depending on places and cultures. The lack of a crystal-clear definition makes it a challenging study subject. RA is not a ‘thing’ that can be put in a clearly defined experimental box nor be dissected methodically. In a way, RA calls for a more prominent acknowledgement of the diversity and creativity that is characteristic of farming – a call for reclaiming farming not only as a skilled profession but also as an art, constantly evolving and adapting, based on a multitude of theoretical and practical expertise.

RA research can similarly enact itself as a braided river of interlinked disciplines and knowledge types, spanning all aspects of health (planet, people, and economy) – where curiosity and open-mindedness prevail. The intent for this think piece was to explore and demonstrate what this braided river could look like in the context of a short-term (6 month) research project. It is with this intent that Sam Lang and Gwen Grelet have initially approached the many collaborators that contributed to this series of topic reports – for all bring their unique knowledge, expertise, values and worldviews or perspectives on the topic of RA.

How was the work stream of this think piece organised?

The project's structure was jointly designed by a project steering committee comprised of the two project leads (Dr Gwen Grelet[1] and Sam Lang[2]); a representative of the New Zealand Ministry for Primary Industries (Sustainable Food and Fibre Futures lead Jeremy Pos); OLW's Director (Dr Ken Taylor and then Dr Jenny Webster-Brown), chief scientist (Professor Rich McDowell), and Kaihāpai Māori (Naomi Aporo); NEXT's environmental director (Jan Hania); and MWLR's General Manager Science and knowledge translation (Graham Sevicke-Jones). OLW's science theme leader for the programme 'Incentives for change' (Dr Bill Kaye-Blake) oversaw the project from start to completion.

The work stream was modular and essentially inspired by theories underpinning agent-based modelling (Gilbert 2008) that have been developed to study coupled human and nature systems, by which the actions and interactions of multiple actors within a complex system are implicitly recognised as being autonomous, and characterised by unique traits (e.g. methodological approaches, world views, values, goals, etc.) while interacting with each other through prescribed rules (An 2012).

Multiple working groups were formed, each deliberately including a single type of actor (e.g. researchers and technical experts only or regenerative practitioners only) or as wide a variety of actors as possible (e.g. representatives of multiple professions within an agricultural sector). The groups were tasked with making specific contributions to the think piece. While the tasks performed by each group were prescribed by the project lead researchers, each group had a high level of autonomy in the manner it chose to assemble, operate, and deliver its contribution to the think piece. Typically, the groups deployed methods such as literature and website reviews, online focus groups, online workshops, thematic analyses, and iterative feedback between groups as time permitted (given the short duration of the project).

[1] Senior scientist at MWLR, with a background in soil ecology and plant ecophysiology - appointed as an un-paid member of Quorum Sense board of governors and part-time seconded to Toha Foundry while the think piece was being completed

[2] Sheep & beef farmer, independent social researcher, and project extension manager for Quorum Sense

Quantifying resilience to drought and flooding in agricultural systems

Contract Report: LC3954-14

Mitchell Donovan[1], Kate Orwin[2], Pierre Roudier[2], Stella Belliss[2]

[1]*AgResearch,* [2]*Manaaki Whenua – Landcare Research*

Please cite as follows: Donovan M, Orwin K, Roudier P, Belliss S 2021. Quantifying resilience to drought and flooding in agricultural systems. Manaaki Whenua – Landcare Research Contract Report LC3954-14 for Our Land and Water National Science Challenge & The NEXT Foundation.

Reviewed by:	*Approved for release by:*
Chris Phillips Senior Researcher Manaaki Whenua – Landcare Research	John Triantafilis Portfolio Leader – Managing Land & Water Manaaki Whenua – Landcare Research

Contents

1 Summary

Nearly every part of our planet has been exposed to, or is forecasted to experience, disruptions ranging from socio-political uprisings and economic crises to environmental disasters. Research is increasingly clear on the connections between human activities and environmental issues, with significant recognition of the current food system's role in the production of greenhouse gases, deforestation, and both degradation and loss of soil functions.

Understanding these connections and concerns about forecasted changes has brought awareness of the need for resilience: the capacity for a system to resist change and recover from external disturbances/stressors. Resilience can be broken down into:

- resistance – the capacity to mitigate internal change caused by an external stressor
- recovery or rebound – the ability to recover to a 'natural state' following a disturbance.

Resistance can be measured as the amount of change resulting from disturbance, and recovery can be measured as either a rate of change post-disturbance or as the length of time required to re-establish a baseline, undisturbed value.

In New Zealand and elsewhere, Regenerative Agriculture (RA) practices have been suggested as a way to increase resilience to flood and drought conditions. These two disturbance types are expected to increase in frequency and intensity over the coming decades (Melillo et al. 2014). To test this hypothesis, we suggest a framework for quantifying farm systems' resilience to flood and drought conditions using indirect and direct measurements of resilience at plot, field, farm, and landscape-scales. This framework consists of:

- measurements of soil properties (e.g. infiltration, macroporosity, aggregate stability, carbon, and biological communities) that are known to indirectly support resistance to, or recovery from, drought and flood
- direct measurements of productivity and quality throughout periods of disturbance
- remote sensing (RS) measurements of vegetation quality (through vegetation indices such as NDVI, SAVI, etc.) across regional scales to test whether farm-scale results are applicable across a broader New Zealand context.

In capturing all three approaches (indirect, direct, and RS), we can identify whether RA practices alter resilience to drought and flood compared to current management practices at field, farm, and landscape scales; and identify which mechanisms are supporting such resilience. For observational approaches we recommend that systems be monitored for at least 5 years in order to discern annual 'noise' from long-term resilience. Throughout this time, researchers should engage with farmers who practice 'regenerative' approaches, as well as farms not using such practices, to gain the fullest understanding of how management strategies differ and overlap throughout future disturbances. We suggest implementing research designed so that it includes sites that are known to be particularly

affected by drought and/or flooding (e.g. Hawke's Bay, Gisborne, Southland) or have recently experienced an extreme event; and sites that have less extreme disturbance regimes. In doing so, we can better understand how agricultural systems respond to a range of changes in weather patterns.

In brief, we recommend a paired study of farms applying practices and management labelled 'regenerative' alongside farms not using such practices in order to measure:

- indicators of a resilient system (i.e. physical, chemical and biological measures of soil health that lead to resilience)
- resilience to drought and flooding at a range of spatial and temporal scales.

2 Introduction and definitions

2.1 Resilience

Both New Zealand and global agro-ecosystems are expected to experience an increased frequency and intensity of drought and flooding events due to climate change (Reisinger et al. 2010; Melillo et al. 2014). This has led to an increasing desire to develop resilient agro-ecosystems to ensure that profitability and food production can be maintained despite these events becoming more frequent. Here we define *resilience* as the capacity to maintain and recover function in response to disturbance. A highly resilient system is one that exhibits a low disturbance impact and a fast recovery rate, 'low' and 'fast' being defined relative to the distribution of responses. Testing resilience to drought and flooding provides a more sensitive indicator of agricultural systems' performance than its ability to function under normal conditions, as resilience requires the physical, chemical, and biological properties of each farm system to work together to reduce the impact of the disturbance, and any limitations imposed by the low biological diversity associated with some management approaches are likely to be more evident (Isbell et al. 2015; Roesch-McNally et al. 2018).

The resilience of a system incorporates two main concepts: *resistance*, which is the ability of a system to minimise the impact of a disturbance, and *rebound* or *recovery* (Pimm 1984), which describes the ability of the system to recover to a pre-disturbance state following a disturbance (Figure 1.). Recovery can be thought of as a recovery rate, or as the total amount of time required to return to a pre-disturbance state (i.e. the return time). The response variable measured to quantify these components of resilience in agricultural systems can be any metric of interest, and might include production quantity and quality, or soil health parameters. Details of potential ways to measure these response variables are given in accompanying topic reports (Schon et al., 2021a, 2021b).

In this report we focus on discussing indirect and direct approaches to quantifying the resilience of production (of plant biomass or crops), and resistance to surface erosion in agro-ecosystems at a range of spatial and temporal scales. We also discuss remote sensing as a possible means for quantifying resilience.

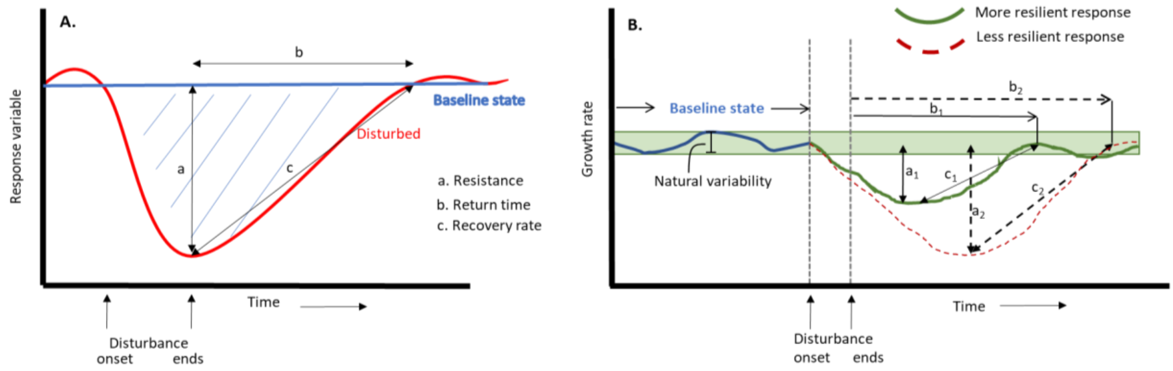

Figure 1. Resistance and recovery rates in response to disturbance (e.g., drought or flooding). A) provides a simplified overview of the different components of resilience, with the shaded area showing the overall impact of the disturbance. B) shows an example of possible responses in two systems (denoted by subscript 1 and 2 and red and green lines) with differing resilience. These figures are based on the concepts discussed in Ingrisch and Bahn (2018) and the references therein.

2.2 Drought

Droughts have been defined using a range of indicators across the globe (e.g. meteorological indicators such as, rainfall). For this study, 'agricultural drought' is best defined as the soil moisture deficit (SMD) in the root zone of the soil profile. SMD can be calculated using a simple water balance model, including water inputs (rainfall), outputs (evapotranspiration, evaporation, runoff), and physical characteristics of the soil (water-holding capacity). In New Zealand, NIWA calculates SMD from daily rainfall, daily potential evapotranspiration, and a standard water-holding capacity of 150 mm. Drought indicators are also available from SMD maps, based on the current SMD and the anomaly against long-term SMD records.

2.3 Flooding

Flooding can be described as excessively saturated soil conditions due to intense and/or prolonged rainfall. Saturated conditions occur when the quantity of rainfall exceeds the holding capacity of a soil. Taking a plant-centred view of flooding, we consider 'flood' to occur when soils drop below 10% air-filled pore space, at which point plants are typically stressed by lack of root-oxygen uptake. By volume, soils typically contain 15–30% air-filled pore space, and so the magnitude of precipitation required to 'flood' a soil will vary based on soil properties.

The amount and duration of precipitation required to induce stress on different crops and/or pasture species will vary and are not necessarily evident in ponding on the surface. Some plants may tolerate short-term flooding, while others respond drastically to such events.

The definition of flooding will differ along a river/floodplain, where flooding signifies overbank flow and inundation of the floodplain. Within this context, factors to consider would include the frequency, depth, and duration of inundation, as well as the amount and type of sediment that is eroded or deposited as floodwaters recede. For example, historical seasonal flooding of the River Nile deposited sediments valuable to agriculture; in contrast, silts deposited by the Whangaehu River, North Island, typically contain high heavy metal concentrations and stunt subsequent vegetation growth (Deely & Sheppard 1996).

3 Potential contribution of remote sensing

Remote sensing has the potential to be useful for helping understand differences in resilience between systems. Remote sensing is the acquisition of information about an object or phenomenon without making physical contact with the object (Jensen 2000). In current usage, the term 'remote sensing' generally refers to the use of satellite- or aircraft-based sensor technologies to detect and classify objects or phenomena on Earth's land surface, atmosphere and/or oceans. It may be split into *active* remote sensing, when a signal is emitted by a satellite or aircraft to the object and its reflection detected by the sensor (this includes synthetic aperture radar, or SAR), and *passive* remote sensing, when the reflection of sunlight is detected by the sensor (this includes the multispectral optical sensors that collect images at wavelengths varying from blue [visible] light through to short-wave and thermal infrared).

Optical remote sensing can record information on whether plants (and, indirectly, animals) benefit from different management approaches. Other types of remote-sensing sensors, such as synthetic aperture radar (SAR), can also sense the variations in soil moisture conditions. In terms of space-borne remote sensing, many environmental features can be mapped and monitored, but the main/most relevant and useful ones are:

- the type of land cover – sometimes to species level (e.g. fodder beet), but more frequently to a more generalised group (e.g. cereals, pasture)
- the state of this land cover and how healthy it is
- the persistence of the land cover through time – is a land cover/condition increasing or decreasing in area and/or in coverage (e.g. percentage bare soil vs crop coverage, forest and shrubland establishment or removal, extent of wetlands).

The state of land cover is typically monitored by some type of vegetation index (e.g. normalised difference vegetation index (NDVI) and variations thereof; Rouse et al. 1974). While vegetation condition is generally captured well in such indices, the specific cause and processes (climatic conditions, management of crop, weed, and/or pests) cannot typically be discerned using remote sensing. Further, although vegetation indices can provide useful information, there is a tendency for spectral signals from healthy, well-moistened vegetation to saturate well before maximum vegetation height and canopy coverage is attained. This limits the utility of these metrics in the New Zealand environment.

All primary sectors could benefit from the use of remote sensing and associated modelling as a means of understanding how resilience differs for farm systems implementing practices found within the regenerative framework. Remote-sensing approaches include a number of benefits.

- They are relatively cheap, and can be applied across broad spatiotemporal scales (Hilker et al. 2008; Harpold et al. 2015; Gerhards et al. 2019).
- They allow monitoring of past and present conditions for input into modelling and forecasting at an even wider range of sites.
- Remote-sensing data can be paired with ground truth measurements at farm and plot scales to reveal mechanistic understanding of what underlies field/farm-scale differences (Lawley et al. 2016).
- Uncertainty can generally be quantified to ascertain the variability in responses.

Of particular interest for vegetation studies is the spectral region of the red edge (around 700 nm). This spectral region can show up large variations in reflectance due to changes in chlorophyll absorption. The multispectral sensor on the Sentinel-2 satellites operated by the European Space Agency, which provides imagery every 5 days, includes three red-edge spectral bands. These data would be suitable for any proposed investigation into resilience in productive landscapes. In terms of measurements of pastures and arable crops, studies typically capture remote-sensing data from the mid-vegetation period (i.e. the optimal phenological stage) (Schmidt et al. 2014) and account for regional and local differences in rainfall, as well as grazing pressures (Bastin et al. 2012). In terms of the effects of, and rebound from, drought or flood conditions, the reflectance measurements should persist until the steady-state situation is regained.

It is also feasible to measure pasture biomass using remote sensing. This is one area where SAR can make a major contribution, especially if timely and consistent information is required (McNeill et. al. 2010). There are also existing proximally sensed solutions (C-DAX Pasture Meter, C-Dax Ltd, Palmerston North, New Zealand). Manaaki Whenua is currently completing some contracted work calibrating historical pasture quality samples against medium-resolution satellite imagery (Sentinel-2) and the results are encouraging (Stephen McNeill, pers. comm. 2020). However, we anticipate that, when applying remote-sensing approaches across diverse pastures compared to ryegrass/clover systems, issues will arise when distinguishing between actual pasture/crop resilience from unique optical traits of specific species compositions as opposed to individual species (Feilhauer et al. 2017).

As well as space-based remote-sensing satellite services, with their advantages of economy, repeatability, and scale, remote-sensing instruments can be mounted on, and used from, any number of platforms: fixed wing, UAV/RPA/drone, even hand-held. Each individual end use dictates the most appropriate platform, spectral information required, and temporal and spatial resolutions (e.g. Harpold et al. 2015). If intra-paddock-level metrics are sought, then hand-held or very high-resolution sensors are the most practical for direct plot–sensor relationships. If required, sampling from a series of plots could then be converged/averaged to provide paddock-level metrics.

The value of all remote-sensing solutions is that well-chosen, ground-based sampling can inform wide area analysis and information. If resilience studies are coupled with precision agriculture, then high-resolution topography (HRT), such as provided by LiDAR, is also very important (Tsoulias et al. 2019). In New Zealand, current LiDAR coverage is relatively minimal outside of major urban areas and floodplains, but release for several regions (Northland, Gisborne, Hawke’s Bay, and Marlborough) is scheduled for 2021 (see LINZ website, www.linz.govt.nz) and considerably more coverage is planned.

4 Indirect measures of resilience to drought and flooding

Indirect measures of resilience can include any single variable, or group of variables, that is known to be a key driver of resilience in the context of a farm system. A wide variety of soil and plant properties determine resilience, and many of these are influenced by management practices. These properties can be divided into physical, chemical and biological components, although it should be noted that these components interact with each other (Figure 2). A key advantage of this approach is that indirect measures are typically simple and well understood, can be used across all sectors, and are relatively cheap compared to experimental approaches.

While indirect approaches could incorporate a wide range of farms, soil types and climates, whether the amount of change in an indirect variable is sufficient to influence actual resilience in response to drought or flooding is often unknown and is likely to depend on the duration and intensity of the disturbance event. To be more certain of the relevance of these variables, it would be useful to validate them against actual responses to drought or flooding.

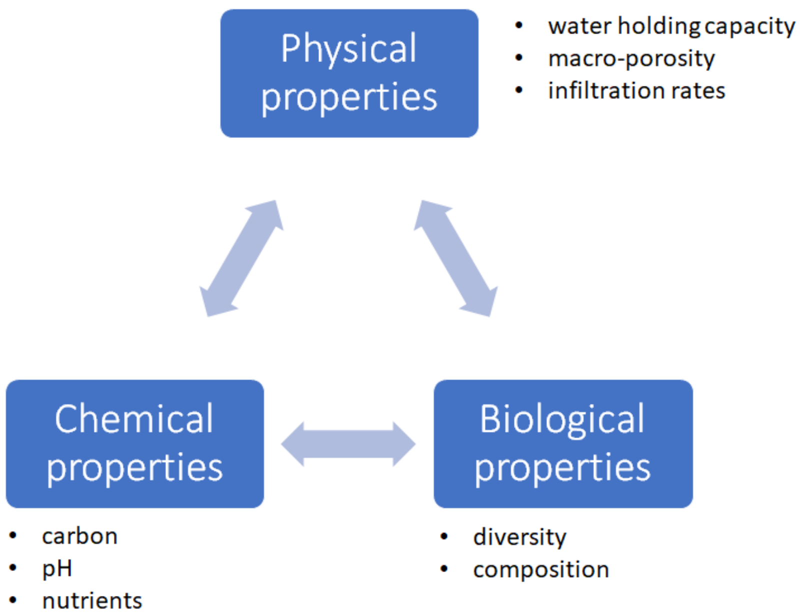

Figure 2. Example physical, chemical, and biological properties of a system that interact to support the functioning of agricultural systems.

4.1 Physical properties that promote resilience

4.1.1 Soil infiltration, porosity, permeability

A soil's physical properties affect its ability to retain water in periods of drought and infiltrate water in times of extreme or prolonged rainfall. Soil infiltration rate is the rate at which water drains through a soil profile. Rates vary in both vertical and horizontal dimensions. Soils with low infiltration rates will retain water longer, and thus will be able to maintain favourable conditions for grasses and crops for longer during periods of drought. Conversely, such soils will become waterlogged and oversaturated during periods of excess rainfall, possibly reducing the productivity of overlying grasses or crops. All measures of resilience for pasture and horticultural systems should account for differences in soil properties, such as particle size and permeability, since these factors mediate the storage capacity and position of available water within a soil column for root absorption.

Soil infiltration rates are partially a function of soil porosity: the interstitial pore space between sediment particles that is filled by air or water. The most common measure of porosity is macroporosity (pore spaces larger than 30 μm), as these macropores are the primary pathway through which water infiltrates. Macroporosity is influenced by the parent rock material (i.e. geology), plant root density, organic matter, compaction from grazing, tillage, and numerous other factors. As macropores are reduced, so is the transmission of water through the soil profile (i.e. soil permeability), which has been shown to increase soil loss via surficial erosion (Donovan & Monaghan, 2021).

Macroporosity is a widely accepted and simple measure of a soil's physical health and would also provide an indirect measure of the resilience to flooding, drought and surface erosion when combined with infiltration rates or particle size density. For example, soil macroporosity and infiltration rates have been measured before and after grazing events under saturated and unsaturated soil moisture conditions to understand how resistance and recovery times of soil physical properties vary (Houlbrooke et al. 2009; Laurenson et al. 2016). These results demonstrated much lower resilience (both resistance and recovery) of physical properties for grazed soils directly after precipitation events because the soils had exceeded the plastic limit (Houlbrooke et al. 2009; Laurenson et al. 2016).

4.1.2 Topography

Topographical metrics – such as slope angle, slope length, curvature, and aspect – are significant drivers of resistance to surface erosion across a farm system. As slope angle increases, so does the shear stress of overland flow as it makes its way downhill. Thus, avoiding grazing or tilling on steeper slopes will reduce soil loss via surface erosion by minimizing exacerbated soil disturbance on areas with inherently low resistance to erosion. Further, the shear stress from overland flow will increase as flow volume increases via convergence and accumulation at the foot of hillslopes. Flow converges when the curvature of a hillslope is concave, and diverges (i.e. spreads) on convex terrain, thereby reducing erosional forces. Generally, the productivity of pastures are limited by water availability at the tops of hillslopes, while being dampened by excess moisture conditions at the bottoms of slopes.

Finally, terrain aspect influences surface erosion via differences in soil moisture content on north- and south-facing slopes (Zheng et al. 2020). While topography is an inherent factor that cannot be managed and plays a pivotal role in the landscape's resilience to erosion, drought, and oversaturated conditions, the decision of which terrain will be grazed or cropped remains. Management decisions can be made that avoid or minimise the use of steep and concave land areas in order to proactively increase the retention of soils. The spatial and temporal variability of land's resilience to surface erosion is best captured using a combination of remote sensing and modelling. Together, these tools can capture finescale variability while encompassing broad spatial coverage. The universal soil loss equation and/or derivatives is one model that can be applied at broad spatial scales to evaluate relative susceptibility to surface erosion across space and time (Donovan & Monaghan, 2021; Donovan, 2021).

4.2 Chemical properties that promote resilience

An increase in soil organic carbon has been widely associated with improved physical soil properties, particularly for water-holding capacity (Hudson 1994). The principles driving this correlation are that (i) the addition of lighter organic matter decreases the overall bulk density of soil, improving porosity (Soane 1990), or (ii) the effects of increased soil aggregates help control water infiltration, transmission, and storage in soils (Franzluebbers 2002). However, in their meta-analysis study, Minansy and McBratney (2018) found a large variation in reported effects of increased organic carbon on water-holding capacity. They concluded that this positive effect is more important when soil is close to or at saturation, and the magnitude of this effect decreases for field capacity, and permanent wilting point. These authors also note that the effect increases with particle size distribution (i.e. the positive effect is more significant for sandy soils, while almost null for clayey soils).

There is also some suggestion that the supply of limiting nutrients can determine recovery rates (Gessler et al. 2017). Identifying the most limiting nutrients in a system may be difficult, but measuring changes in nutrient availability after drought or flooding may provide a mechanistic understanding of why systems differ in their responses.

4.3 Biological properties that promote resilience

Many RA approaches aim to support above- and below-ground biological diversity and health. Measurements of plant community structure have been shown to influence resistance and recovery in response to drought and flooding. For example, species richness, community composition, and traits that influence disturbance tolerance (e.g. growth rate, rooting depth, aerenchyma) have all been linked to plant responses to drought and flooding (Lepš et al. 1982; MacGillivray et al. 1995; Mariotte et al. 2013; Gaudin et al. 2015; Striker & Colmer 2017; Wright et al. 2017; Oram et al. 2020). These measurements have also been linked to several physical and chemical soil properties that influence the ability of the system to resist erosion and cope with flooding, such as soil aggregate stability (Pérès et al. 2013; Gould et al. 2016); along with infiltration rates, porosity, and soil carbon (Fischer et al. 2015).

Measurements of plant community composition, diversity and traits could therefore provide information on potential resilience. If used in conjunction with direct measurements of resilience, they could also provide mechanistic insights. Plant community composition can be quantified using standard vegetation survey approaches (Hurst & Allen 2007) and at least some trait values will be available in existing databases (e.g. the TRY database; Kattge et al. 2020). However, additional trait measurements are likely to be required to cover the specific varieties used in New Zealand and for less commonly measured traits.

The influence of plant communities on ground cover is also significantly correlated with the proportion of surface erosion (Green et al. 1994). This is the simplest and cheapest plant-based measurement and could be measured by farmers. Ground cover reduces surface erosion by intercepting rainfall that would otherwise dislodge exposed soils, and by reducing the velocity and quantity of overland flow. The proportion, density, species types, and temporal extent of surface cover are the four primary components necessary for understanding how above-ground plant communities influence resistance to surface erosion. In agricultural systems all these components are controlled through decisions on pasture community composition, grazing management, crop type(s), and the use of cover crops during fallow periods. For example, within grasslands, the inclusion of rhizomatous species and low forb-grass ratios tend to be associated with increased tensile strength to resist surface erosion (Löbmann et al. 2020).

Soil biology can also have a significant impact on the response of both the above- and below-ground system to drought and flooding by influencing soil physical properties (e.g. via the effects of fungi, arbuscular mycorrhizal fungi, and earthworms on soil structure), directly influencing access to water via mycorrhizal fungi, and by determining the availability of nutrients during recovery. Fungal and gram-positive bacterial dominance may be good indicators of microbial drought resistance (Schimel et al. 2007) and have been indirectly linked to the resilience of the above-ground system (Mariotte et al. 2015). However, the strength and direction of relationships of these soil microbial properties to resistance and recovery is highly variable (Lambie et al. 2017), which means these indicators may be relatively unreliable. The use of soil biological indicators to estimate soil structure or water availability is also likely to be more expensive and less reliable than direct measurements of these soil properties.

5 Direct measures of resilience to drought and flooding

Direct measurement of resilience requires monitoring responses to experimentally imposed or naturally occurring drought or flooding events. Such responses can be quantified at a range of spatial and temporal scales, from plot to national scale, and from single disturbance events on a daily timeframe to multiple disturbance events spread across many years. The data requirements and most appropriate approaches for each scale are different and are discussed below.

5.1 Resilience in response to single disturbances at a local spatial scale

Responses to single disturbance events, where the intensity and duration of the disturbance are the same across systems, can be quantified using experimental and observational approaches. The most direct and accurate way to measure resilience is to impose an experimental drought and/or flooding event in the field. Drought can be imposed using rain-out shelters, and this has been successfully deployed elsewhere (e.g. Kreyling et al. 2017; Jung et al. 2020). Flooding is more difficult to impose in the field as it would require more infrastructure to ensure that water remained in place; this would be simplest to impose on flat fields. An alternative experimental approach is to take intact cores from farms and impose drought and flooding in the laboratory (Oram et al. 2020). Experimental approaches require a stringent paired approach, where two farms with different management strategies that are on the same topography and soil type can be compared. Due to the relatively high cost, an experimental approach can only be practically implemented at a small number of sites, and plot size will be small.

Observational approaches can also be used to quantify responses to a single natural disturbance event, and this could be used across more farms and at larger within-farm spatial scales than experimental approaches. For past events, farmer records of production or remote sensing could be used to quantify resilience to specific drought or flooding events. For future events, monitoring of sites that are prone to flooding or drought could be undertaken, either by scientists or based on data collected by farmers (e.g. change in grape, milk, pasture biomass estimates or crop production over a relevant time scale). That approach is useful for systems that are already managed to cope with such disturbances, but may not capture responses to the more extreme events projected to increase in frequency with climate change (Reisinger et al. 2010). For that, investing in monitoring recovery in greater detail in the field after extreme events (e.g. the recent flooding in Napier) would provide highly valuable information. As for experimental approaches, the most robust approach is to compare paired farming systems that differ in management but have the same soil type, climate, and topography.

5.1.1 Metrics for quantifying resilience to single disturbances

Because resilience incorporates change over time, a variety of metrics have been developed to summarise those changes. There continues to be considerable debate as to which are the best (Orwin & Wardle 2004; Ingrisch & Bahn 2018). Here we discuss how the common features of these metrics can be applied to resilience in agricultural systems.

Quantifying baselines

Most methods recommend comparing disturbed systems to a baseline (i.e. undisturbed) state, which can be quantified in three ways:

- Measuring the response variable in an undisturbed but equivalent soil and plant community throughout the same time frame as the disturbance and recovery period (e.g. along the blue line in Figure 1A)
- Estimating the baseline value based on measurements in previous years without those disturbances, and/or modelling based on this data
- Using the value of the response variable from immediately before the disturbance started (disturbance onset in Figure 1).

Because baseline values vary over time (Drewry et al. 2004; Yeung & Richardson 2018) in response to drivers such as seasonality and management (e.g. grazing, pruning, fertiliser addition), the most accurate baseline is the first option. However, this is typically only available for experimental approaches. Using modelling to estimate baseline values is the next most accurate approach, but this requires access to long-term data sets and investment in modelling and validation. Using pre-disturbance values as the baseline is the least accurate but simplest approach.

Quantifying resilience

After establishing which baseline value will be used, resilience can be calculated. A simple and cost-effective approach to quantifying resilience across all sectors is to calculate the percentage loss in production between the baseline system and the disturbed system over an appropriate time scale for the disturbance studied (e.g. seasonal, crop life span, annual). This metric quantifies the size of the perturbation caused by a disturbance and is equivalent to the shaded area in Figure 1A. Quantifying the different components of resilience (e.g. resistance, recovery rate, return time) provides greater detail of the impact of, and response to, the disturbance. If this approach is taken, overall resilience can be visualised by plotting resistance versus recovery rates for each site (Hodgson et al. 2015; Ingrisch & Bahn 2018).

Quantifying resistance

Resistance can be quantified as the immediate effect of, or the peak amount of change in, a response variable caused by a disturbance (Todman et al. 2016; Ingrisch & Bahn 2018). Where a long time-series of data can be measured or obtained, the point of maximum deviation from the baseline can be more easily defined. However, where this is not practical or available, resistance is often measured as the amount of change at the time point where the disturbance ends (Orwin & Wardle 2004). For drought, the end of the disturbance could be defined based on the Standardised Precipitation Index, the Soil Moisture Deficit, the Soil Moisture Deficit Anomaly, the potential evaporation deficit, the New Zealand Drought Index developed by NIWA (https://niwa.co.nz/sites/niwa.co.nz/files/NZDI_more_info.pdf), or a site- and plant community-specific estimate of the point where adequate soil moisture levels are attained. The end of the flooding period could be defined as the point where the soil returns to field capacity (McDowell & Houlbrooke 2009).

Quantifying recovery

The extent of recovery can be expressed relative to the baseline pre-disturbance state (baseline-normalised) or relative to the amount of change caused by the disturbance (impact-normalised). Ingrisch and Bahn (2018) advocate for the use of baseline-normalised indices because this allows, in combination with baseline-normalised measures of resistance, an estimate of overall recovery time, impact-normalised recovery, and perturbation size. As for resistance, detailed time series data allows the point of full recovery to be identified. Where this is not practical or available, a relative measure or estimate of recovery can be obtained by comparing a minimum of two data points (e.g. measurements made at the end of the disturbance and at some point during recovery; Orwin & Wardle 2004). The timing of the second measurement will depend on the response variable focused on and the duration and intensity of the disturbance. For example, soil microbial respiration rates can return to baseline within days (Orwin & Wardle 2004), whereas plant biomass may take weeks or months to recover (Wright et al. 2017). Ideally, more than two measurements would be made to increase the accuracy of recovery estimates, but this is more expensive to implement.

5.2 Resilience over larger temporal and spatial scales

The observational approaches described above can be extended to cover larger spatial and temporal scales. This means that different systems will be subjected to different disturbance timing, intensity and frequency, and systems will have inherent different underlying properties (e.g. soil type, topography, background climate), all of which will have an impact on farm system responses. For example, a disturbance event just after planting crops, during pasture spring growth or at bud burst for grape vines, could have a more devastating effect than one that occurs later in the season, and more intense disturbances usually have larger impacts. This variability will need to be statistically controlled for, as this allows effects arising solely from management to be quantified (Ingrisch & Bahn 2018). This could be done by including variables such as soil type, climate, plant growth stage at the time of disturbance, maximum soil water deficit, flooding depth, and disturbance duration in models; some of these variables are already available in existing maps or databases. This approach would also allow some assessment of the circumstances under which management practices influence resilience. Experimental approaches could also be implemented at multiple sites across New Zealand, but due to cost this would only be practical for a limited number of sites.

A final option for quantifying resilience is to estimate variability in the quantity and quality of food or plant biomass produced over time (e.g. using the coefficient of variance; CV). This would provide a coarse indicator of the impact of natural environmental variability on production, incorporate multiple systems and management approaches, and allow a longer-term view of system resilience, but would provide little information on resilience to extreme events. Results would be dependent on how much variation in climate has occurred during the period for which data are available. This approach could utilise farmer data or remote sensing to measure biomass and areas planted in different crops and so would be cost-effective to implement.

6 Sector context

In this section we discuss options and limitations for measuring resilience that apply to specific sectors. Because all indirect measures are relevant to all sectors, they are not explicitly included here.

6.1 Pastoral

The resilience of production in pastoral systems can be measured using any of the approaches described above. Quantifying both resistance and recovery may be more important for pastoral systems than the other systems discussed here, as the balance between these two variables has implications for stocking rates. The main challenge with pastoral systems is assessing what the most relevant baseline value is due to the impacts of grazing on biomass and productivity. For observational assessments of the resilience of production, variability in management practices such as pasture resowing, animal movement between farms, and the impact of importing feed will need to be accounted for.

Field measurements, remote sensing, and modelling of soil loss from pastures all suggest the primary managed indicators of resilience to surface erosion are cover and soil conditions/properties, along with slope, which is an inherited/environmental condition. Because grazing intensity (density and duration) will primarily affect surface cover and soil properties, while slope will remain consistent, modelling changes to cover and soil properties are a way to evaluate how grazing management will affect surface erosion (Donovan & Monaghan, in review).

AgResearch is currently modelling the impacts of grazing on ground cover, soil physical properties, and soil losses at national scales to be used in national erosion modelling efforts, in collaboration with Manaaki Whenua – Landcare Research (Donovan, in review). Such models could be adjusted and updated to incorporate different grazing strategies that retain cover or reduce mob densities to mitigate soil compaction. At finer scales, field measurements of site-specific soil losses will be highly accurate when comparing paddocks with varying durations of bare period. The erosional resilience of a paddock might be increased if it is direct-drilled instead of ploughed.

6.2 Arable

Most of the approaches identified above can be applied to arable systems. Baseline values for particular crops can be estimated using space-based remote sensing to measure or predict arable crop yield. This normally relies on field measurements of the arable crop under consideration and the area over which it has been sown. From this, estimates of yield and the uncertainty/variability of those estimates can be made. With adequate information on soil properties and expected precipitation or irrigation, this information can be estimated as early as at the planning stage. Modifications to the estimated yields can be made as the crop grows, based on updated/improved model inputs such as weather events and irrigation, among other factors. Recursive/iterative modelling processes that incorporate 'hindcasting' can help improve forecasting modelling scenarios. The most difficult approach to apply in arable systems is assessing resilience over multiple years and disturbance events using a coefficient of variation or similar metric, as variation in responses caused by crop rotation and cover crop practices would need to be accounted for.

Within arable systems the best indicators for evaluating resilience to surface erosion are typically vegetation cover and slope, followed by inherent soil properties. Because land management of arable lands will predominantly affect surface cover and soil properties, modelling the impact of management decisions (i.e. tillage and crop type/density) to cover and soil properties is one way to evaluate the change in surface erosion. Current erosion models could be adjusted and updated to incorporate management practices of arable lands, such as ploughing strategies. For example, there are differing impacts from ploughing across slope as opposed to downslope ploughing (e.g. Marques da Silva et al. 2004). At a minimum, and without specific land management decision information, the fraction and density of ground cover throughout the year can be used to assess resistance to surface erosion using models based on empirical measurements.

6.3 Viticulture

Most approaches described above can also be applied to measure resilience of production in viticultural systems. The main exception to this is that imposing a drought or flooding on intact cores from these systems is unlikely to yield relevant information, as the vines themselves cannot be removed. Measuring variability over multiple years and disturbance events would best be achieved using site-specific data of grape production and quality (e.g. farmer-collected data), as it may be difficult to distinguish vine biomass, which is the primary variable of interest, from inter-row vegetation using satellite-based remotely sensed data. Geospatial modelling solutions can be applied for estimating changes to surface erosion arising from ground cover changes, as in the other sectors.

7 Conclusion

Across all sectors, indirect measurements are relatively inexpensive and can be implemented over a wide spatial scale (Table 1), especially if collaborating with farmers to collect data or soil samples. However, the extent to which indirect measurements can accurately predict actual resilience remains uncertain, particularly for productivity . Using indirect measures to estimate resistance to surface erosion (e.g. ground cover) provides a greater degree of certainty for estimating the net impact on soil loss from farm systems arising from surface erosion and can be modelled at broad scales. In both cases, it would be beneficial to validate the indirect variables with direct measurements of resilience and soil loss.

Experimental approaches to understand plot-scale resilience provide accurate results (Table 1), with the downside being that they can be expensive and are largely reliant on scientists rather than farmers. While it is more difficult to scale up to other climates, experimental work can be valuable for establishing or validating the usefulness of indirect and observational approaches and is more likely to gain insight into mechanistic relationships.

Local-scale observational approaches to specific flooding or drought events tend to be less accurate than experimental approaches, but they do provide broad insight into trends across a wider range of systems and disturbance types (Table 1). In doing so, the results are more scalable and easily translated to societal relevance. Further, they are used on farm systems that have not been modified or adjusted for experimental purposes. We suggest such approaches should be based on remote sensing in combination with data collected by farmers, thereby providing relatively inexpensive and reproducible methods. Extending these approaches across larger temporal and spatial scales to include all environmental variation provides limited information on extreme events but would give a different indication of whether management influences resilience on an inter-annual scale. Broad-scale observational approaches can also include modelling to project various scenarios, such as land-use scenarios or changes in precipitation modelling to understand differences in soil loss.

Based on our analysis, we suggest a series of measurements to understand the impact of regenerative management practices on resilience. Measurements of soil health properties (e.g. soil macroporosity, infiltration rates, aggregate stability, soil carbon, plant cover) that are known to indirectly support resistance to, or recovery from, drought and flood could serve as useful and comparable indicators of resilience across sectors. Direct measurements of productivity and quality throughout periods of disturbance will be necessary to fully understand a farm system's ability to resist and rebound from flood and drought conditions.

These direct measurements of system resilience could be supplemented by measures of soil health (e.g. porosity, aggregate size and stability, nutrient availability, and food webs) over time, to provide information on the resilience of the soil system and mechanistic understanding of why systems differ in their responses. To improve the scalability of results, we also recommend incorporating the use of remote-sensing measurements at larger spatial and temporal scales (e.g. over 5 years to account for inter-annual variability and long-term resilience). Site selection should ensure that inherent properties that influence resilience (e.g. slope and soil type) can be controlled for, and that comparisons across both less and more extreme events can be investigated. Together, this hierarchy of measurements would provide a comprehensive understanding of (1) whether RA practices alter resilience to drought and flood compared to current management practices under a range of disturbances, and (2) what mechanisms support such resilience.

Table 1. Summary of potential approaches to measuring resilience

Indicator	*Method*	*Use: C = cheap; A = accurate; S = scalable; R = more research req.* A	C	S	R	*Reference*	*Priority: 1 = Must; 2 = Maybe; na = not applicable. In D = dairy; S = sheep & beef; A = arable; V = viticulture* D	S	A	V	*Potential issues under regen. agriculture*
Indirect indicators of resilience											
Soil physical measurements											
Porosity		✓	✓	✓	✓	Hirmas et al. 2018	1	1	1	1	
Infiltration		✓	✓	✓	✓	Hirmas et al. 2018	1	1	1	1	
Water-holding capacity			✓		✓	Saetre 1998	1	1	1	1	
Stable aggregates					✓	Franzluebbers 2002; Gould et al. 2016; Pérès et al. 2013	1	1	1	1	
Soil chemical measurements											
Soil organic matter content	% carbon	✓			✓	Hudson 1994; Minasny & McBratney 2018	1	1	1	1	
	Loss on ignition		✓		✓	Ball 1964	2	2	2	2	
Soil nutrients	Mineralisable nitrogen, Olsen P etc	✓			✓	Gessler et al. 2017	2	2	2	2	
Biological measurements											
Microbial indicators	PLFA	✓			✓	Bardgett et al. 1996; Bligh & Dyer 1959	2	2	2	2	
	Metabarcoding				✓	Wood et al. 2017	2	2	2	2	
Plant community	Vegetation survey			✓	✓	Hurst & Allen 2007	2	2	2	2	
	Plant cover		✓	✓		Jung et al., 2020	1	1	1	1	
	Biomass/quality					See Schon et al., 2021a					

Indicator	*Method*	*Use: C = cheap; A = accurate; S = scalable; R = more research req.*				*Reference*	*Priority: 1 = Must; 2 = Maybe; na = not applicable. In D = dairy; S = sheep & beef; A = arable; V = viticulture*				*Potential issues under regen. agriculture*
		A	*C*	*S*	*R*		*D*	*S*	*A*	*V*	
	Remote sensing		✓	✓	✓	Jensen 2000	2	2	2	2	Currently unable to distinguish some plant community compositions
Direct measurements of resilience – multiple measurements made through time											
Local scale, single disturbance, experimental											
	Biomass/quality measures	✓				See Schon et al., 2021a	1	1	1	1	
	Soil physical measurements	✓				See Schon et al., 2021b	1	1	1	1	
	Soil chemical measurements	✓				See Schon et al., 2021b	1	1	1	1	
	Soil biological measurements	✓				See Schon et al., 2021b	1	1	1	1	
Local scale, single disturbance, observational											
	Biomass/quality measures		✓	✓		McNeill et al. 2010	1	1	1	1	
	Soil physical measurements	✓			✓	See Schon et al., 2021b	2	2	2	2	
	Soil chemical measurements	✓			✓	See Schon et al., 2021b	2	2	2	2	
	Soil biological measurements	✓			✓	See Schon et al., 2021b	2	2	2	2	
	Remote sensing		✓	✓	✓		1	1	1	1	
	Proximal sensing	✓		✓	✓		1	1	1	1	
Larger spatial and temporal scales, multiple disturbances											
	Biomass/quality measures		✓				2	2	2	2	
	Remote sensing		✓	✓	✓		1	1	1	1	
	Proximal sensing	✓		✓	✓		2	2	2	2	

8 References

An L 2012. Modeling human decisions in coupled human and natural systems: review of agent-based models. Ecological Modelling 229: 25–36. doi:10.1016/j.ecolmodel.2011.07.010

Ball DF 1964. Loss-on-ignition as estimate of organic matter + organic carbon in non-calcareous soils. Journal of Soil Science 15: 84–92. doi: 10.1111/j.1365-2389.1964.tb00247.x

Bardgett RD, Hobbs PJ, Frostegård Å 1996. Changes in soil fungal:bacterial ratios following reductions in the intensity and management of an alpine grassland. Biology and Fertility of Soils 22: 261–264.

Bastin G, Scarth P, Chewings V, Sparrow A, Denham R, Schmidt M, O'Reagain P, Shepherd R, Abbott B 2012. Separating grazing and rainfall effects at regional scale using remote sensing imagery: a dynamic reference-cover method. Remote Sensing of Environment 121: 443–457. doi: 10.1016/j.rse.2012.02.021.

Bligh EG, Dyer WG 1959. A rapid method of total lipid extraction and purification. Canadian Journal of Biochemistry and Physiology 37: 911–917.

Deely JM, Sheppard DS 1996. Whangaehu River, New Zealand: geochemistry of a river discharging from an active crater lake. Applied Geochemistry 11(3): 447–460.

Donovan M (accepted). Modelling soil loss from surface erosion at high-resolution to better understand sources and drivers across land uses and catchments; a national-scale assessment of Aotearoa, New Zealand. Environmental Software and Modelling: 35p.

Donovan M, Monaghan RM 2021. Impacts of grazing and treading on ground cover, soil physical properties and soil loss via surface erosion: a novel geospatial modelling approach. Journal of Environmental Management oi: 10.1016/j.jenvman. 2021.112206.

Drewry JJ, Paton RJ, Monaghan RM 2004. Soil compaction and recovery cycle on a Southland dairy farm: implications for soil monitoring. Soil Research 42: 851. doi: 10.1071/SR03169.

Fischer C, Tischer J, Roscher C, Eisenhauer N, Ravenek J, Gleixner G, Attinger S, Jensen B, de Kroon H, Mommer L, et al. 2015. Plant species diversity affects infiltration capacity in an experimental grassland through changes in soil properties. Plant and Soil 397: 1–16. doi:10.1007/s11104-014-2373-5

Franzluebbers AJ 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Research 66(2): 197−205.

Gaudin ACM, Tolhurst TN, Ker AP, Janovicek K, Tortora C, Martin RC, Deen W 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLOS ONE doi:10e0113261. doi: 10.1371/journal.pone.0113261.

Gerhards M, Schlerf M, Mallick K, Udelhoven T 2019. Challenges and future perspectives of multi-/hyperspectral thermal infrared remote sensing for crop water-stress detection: a review. Remote Sensing 11: 1240. doi: 10.3390/rs11101240.

Gessler A, Schaub M, McDowell NG 2017. The role of nutrients in drought-induced tree mortality and recovery. New Phytologist 214: 513–520. doi:10.1111/nph.14340

Gilbert N 2008. Agent-based models. Quantitative Applications in the Social Sciences. Number 07-153. Los Angeles, CA: Sage.

Gould IJ, Quinton JN, Weigelt A, De Deyn GB, Bardgett RD 2016. Plant diversity and root traits benefit physical properties key to soil function in grasslands. Ecology Letters 19: doi:1140–1149. 10.1111/ele.12652

Greene R, Kinnell P, Wood J 1994. Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. Soil Research 32: 953. doi:10.1071/SR9940953

Harpold AA, Marshall JA, Lyon SW, Barnhart TB, Fisher B, Donovan M, Brubaker KM, Crosby CJ, Glenn NF, Glennie CL, et al. 2015. Laser vision: lidar as a transformative tool to advance critical zone science. Hydrology and Earth System Sciences Discussions 12: 1017–1058. doi:10.5194/hessd-12-1017-2015.

Hilker T, Coops NC, Wulder MA, Black TA, Guy RD 2008. The use of remote sensing in light use efficiency based models of gross primary production: a review of current status and future requirements. Science of the Total Environment 404: 411–423. doi:10.1016/j.scitotenv.2007.11.007.

Hirmas DR, Giménez D, Nemes A, Kerry R, Brunsell NA, Wilson CJ 2018. Climate-induced changes in continental-scale soil macroporosity may intensify water cycle. Nature 561: 100–103. doi: 10.1038/s41586-018-0463-x.

Hodgson D, McDonald JL, Hosken DJ 2015. What do you mean, 'resilient'? Trends in Ecology & Evolution 30: 503–506. doi:10.1016/j.tree.2015.06.010

Houlbrooke DJ, Drewry JJ, Monaghan RM, Paton RJ, Smith LC, Littlejohn RP 2009. Grazing strategies to protect soil physical properties and maximise pasture yield on a Southland dairy farm. New Zealand Journal of Agricultural Research 52: 323–336. doi:10.1080/00288230909510517.

Hudson BD 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49(2): 189–194.

Hurst JM, Allen RB 2007. A permanent plot method for monitoring indigenous forests: field protocols. Lincoln: Manaaki Whenua – Landcare Research.

Ingrisch J, Bahn M 2018. Towards a comparable quantification of resilience. Trends in Ecology & Evolution 33: 251–259. doi:10.1016/j.tree.2018.01.013

Isbell F, Craven D, Connolly J, Loreau M, Schmid B, Beierkuhnlein C, Bezemer TM, Bonin C, Bruelheide H, de Luca E, et al. 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature 526: 574–U263. doi:10.1038/nature15374

Jensen JR. 2000. Remote sensing of the environment: an earth resource perspective. Upper Saddle River, NJ: Prentice-Hall, Inc.

Jung EY, Gaviria J, Sun SW, Engelbrecht BMJ 2020. Comparative drought resistance of temperate grassland species: testing performance trade-offs and the relation to distribution. Oecologia 192: 1023–1036. doi:10.1007/s00442-020-04625-9

Kattge J, Bönisch G, Diaz S, Lavorel S, Prentice IC, Leadley P, Tautenhahn S, Werner G, et al. 2020. TRY plant database – enhanced coverage and open access. Global Change Biology 26: 119–188.

Kreyling J, Arfin Khan MAS, Sultans F, Babel W, Beierkuhnlein C, Foken T, Walter J, Jentsch A 2017. Drought effects in climate change manipulation experiments: quantifying the influence of ambient weather conditions and rain-out shelter artifacts. Ecosystems 20: 301–315.

Lawley V, Lewis M, Clarke K, Ostendorf B 2016. Site-based and remote sensing methods for monitoring indicators of vegetation condition: an Australian review. Ecological Indicators 60: 1273–1283. doi:10.1016/j.ecolind.2015.03.021.

Lambie S, Lear G, Muller K, Wakelin SA, Smaill SJ, Orwin KH 2017. Microbial function and adaptation in response to climate-change-driven drought and the resulting effects on plant production and nutrient cycling. Landcare Research Contract Report LC3054.

Lepš J, Osbornová-Kosinová J, Rejmánek M 1982. Community stability, complexity, and species life history strategies. Vegetatio 50: 53–63.

Laurenson S, Houlbrooke DJ, Beukes PC 2016. Assessing the production and economic benefits from preventing cows grazing on wet soils in New Zealand: managing wet soils in a pasture-based dairy system. Journal of the Science of Food and Agriculture 96: 4584–4593. doi:10.1002/jsfa.7676.

Löbmann MT, Tonin R, Stegemann J, Zerbe S, Geitner C, Mayr A, Wellstein C 2020. Towards a better understanding of shallow erosion resistance of subalpine grasslands. Journal of Environmental Management 276: 111267. doi:10.1016/j.jenvman.2020.111267.

MacGillivray CW, Grime JP, and the Integrated Screening Programme Team 1995. Testing predictions of the resistance and resilience of vegetation subjected to extreme events. Functional Ecology 9: 640–649.

Marques da Silva JR, Soarea JMC, Karlen DL 2004. Implement and soil condition effects on tillage-induced erosion. Soil and Tillage Research 78(2): 207–216.

Mariotte P, Robroek BJM, Jassey VEJ, Buttler A 2015. Subordinate plants mitigate drought effects on soil ecosystem processes by stimulating fungi. Functional Ecology 29: 1578–1586. doi:10.1111/1365-2435.12467

Mariotte P, Vandenberghe C, Kardol P, Hagedorn F, Buttler A 2013. Subordinate plant species enhance community resistance against drought in semi-natural grasslands. Journal of Ecology 101: 763-773. doi:10.1111/1365-2745.12064

McDowell RW, Houlbrooke DJ 2009. Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. Soil Use and Management 25: 224–233. doi:10.1111/j.1475-2743.2009.00231.x.

McNeill SJ, Pairman D, Belliss SE, Dalley DE, Dynes RA 2010. Robust estimation of pasture biomass using dual-polarisation TerraSAR-X imagery. Presented at IEEE International Geoscience and Remote Sensing Symposium, Honolulu, Hawaii, USA, 25–30 July 2010.

Melillo JM, Richmond T, Yohe GW 2014. Climate change impacts in the United States: The Third National Climate Assessment. US Global Change Research Program. doi:10.7930/J0Z31WJ2.

Minasny B, McBratney AB 2018. Limited effect of organic matter on soil available water capacity. European Journal of Soil Science 69(1): 39–47.

Oram NJ, De Deyn GB, Bodelier PLE, Cornelissen JHC, van Groenigen JW, Abalos D 2020. Plant community flood resilience in intensively managed grasslands and the role of the plant economic spectrum. Journal of Applied Ecology 57: 1524–1534. doi:10.1111/1365-2664.13667

Orwin KH, Wardle DA 2004. New indices for quantifying the resistance and resilience of soil biota to exogenous disturbances. Soil Biology & Biochemistry 36: 1907–1912. doi:10.1016/j.soilbio.2004.04.036

Pérès G, Cluzeau D, Menasseri S, Soussana J, Bessler H, Engels C, Habekost M, Gleixner G, Weigelt A, Weisser W, et al. 2013. Mechanisms linking plant community properties to soil aggregate stability in an experimental grassland plant diversity gradient. Plant and Soil 373: 285–299. doi:10.1007/s11104-013-1791-0

Pimm SL 1984. The complexity and the stability of ecosystems. Nature 307: 321–326.

Reisinger A, Mullan AB, Manning M, Wratt DW, Nottage RAC 2010. Global and local climate change scenarios to support adaptation in New Zealand. In: Nottage RAC, Wratt DS, Bornman JF, Jones KC eds. Climate change adaptation in New Zealand: future scenarios and some sectoral perspectives. Wellington: New Zealand Climate Change Centre. Pp. 26–43.

Roesch-McNally GE, Arbuckle JG, Tyndall JC 2018. Barriers to implementing climate resilient agricultural strategies: the case of crop diversification in the US Corn Belt. Global Environmental Change – Human and Policy Dimensions 48: 206–215. doi:10.1016/j.gloenvcha.2017.12.002

Rouse JW, Haas RH, Schell JA, Deering DW 1974. Monitoring vegetation systems in the Great Plains with ERTS. In: Fraden SC, Marcanti EP, Becker MA eds. Third ERTS-1 Symposium, 10–14 Dec. 1973, NASA SP-351. Washington DC, NASA. Pp. 309–317.

Saetre P 1998. Decomposition, microbial community structure, and earthworm effects along a birch-spruce soil gradient. Ecology 79: 834–846.

Schimel J, Balser TC, Wallenstein M 2007. Microbial stress-response physiology and its implications for ecosystem function. Ecology 88: 1386–1394. doi:10.1890/06-0219

Schmidt T, Schuster C, Kleinschmit B, Forster M 2014. Evaluating an intra-annual time series for grassland classification—how many acquisitions and what seasonal origin are optimal? IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 7: 3428–3439. doi:10.1109/JSTARS.2014.2347203.

Schon N, Donovan M, King W, Gregorini P, Dynes R, Selbie D 2021a. Quantifying productivity of regenerative farming systems. Manaaki Whenua - Landcare Research Contract Report LC3954-9, for Our Land and Water National Science Challenge and The NEXT foundation. Downloadable at: https://ourlandandwater.nz/regenag and https://www.landcareresearch.co.nz/publications/regenag

Schon N, Fraser T, Masters N, Stevenson B, Cavanagh J, Harmsworth G, Grelet GA 2021b. Soil health research in the context of regenerative agriculture. Manaaki Whenua - Landcare Research Contract Report LC3954-13, for Our Land and Water National Science Challenge and The NEXT foundation. Downloadable at: https://ourlandandwater.nz/regenag and https://www.landcareresearch.co.nz/publications/regenag

Soane BD 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil and Tillage Research 16(1–2): 179–201.

Striker GG, Colmer TD 2017. Flooding tolerance of forage legumes. Journal of Experimental Botany 68: 1851–1872. doi:10.1093/jxb/erw239

Todman LC, Fraser FC, Corstanje R, Deeks LK, Harris JA, Pawlett M, Ritz K, Whitmore AP 2016. Defining and quantifying the resilience of responses to disturbance: a conceptual and modelling approach from soil science. Scientific Reports 6, Article number 28426.

Tsoulias N, Paraforos DS, Fountas S, Zude-Sasse M 2019. Calculating the water deficit spatially using LiDAR laser scanner in an apple orchard. Proceedings of the Precision Agriculture Conference 2019. Pp. 115–121. doi:10.3920/978-90-8686-888-9

Wood JR, Holdaway RJ, Orwin KH, Morse C, Bonner KI, Davis C, Bolstridge N, Dickie IA 2017. No single driver of biodiversity: divergent responses of multiple taxa across land use types. Ecosphere 8. doi:10.1002/ecs2.1997

Wright AJ, de Kroon H, Visser EJW, Buchmann T, Ebeling A, Eisenhauer N, Fischer C, Hildebrandt A, Ravenek J, Roscher C, et al. 2017. Plants are less negatively affected by flooding when growing in species-rich plant communities. New Phytologist 213: 645–656. doi:10.1111/nph.14185

Yeung ACY, Richardson JS 2018. Expanding resilience comparisons to address management needs: a response to Ingrisch and Bahn. Trends in Ecology & Evolution 33: 647–649. doi:10.1016/j.tree.2018.06.005

Zheng M, Liao Y, Liang C, Huang B, Yuan Z 2020. Erosion-induced spatial uniformity of surface runoff over an extremely degraded catchment on the Chinese Loess Plateau. CATENA: 105001. doi:10.1016/j.catena.2020.105001.