What's next for the New Zealand dairy feed-base? Learnings from climate analogues

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Highlights

- The reviewed literature suggests that the likely main impact of climate change on New Zealand dairy systems will be a reduction in total annual rainfall and increased inter- and intra-season rainfall and associated soil moisture variability.
- Future climate analogues for New Zealand's current dairying regions are provided from both within New Zealand and Australia.
- Future climate scenarios for New Zealand dairy systems can be found within New Zealand with the exception of Northland whose most similar climate analogue is in Australia.
- A conceptual framework to increase the boundaries of the 'zone of system control' (ZSC) by the farmer is provided here for the first time. The ZSC is defined as the optimal range for a critical input (rainfall or soil moisture in this case) where productive and profitable farming can occur.
- Risk of failure increases as the frequency inputs fall above (excess) or below (deficit) the ZSC. Options to reduce the risk of system failure (outside of this zone) are provided with emphasis on soil moisture.
- This framework could be used to focus future research and development investment to make the New Zealand and Australian dairy industries more resilient to climate change.

Keywords: climate change, forages, milk, pasture, 'system control'

Background

Ruminants are vital contributors to agricultural production, protein food security, livelihoods, and socio-cultural values (Osei-Amponsah et al. 2019). In Australia, beef cattle, sheep and dairy cattle are respectively ranked first, second and third for the total value of Australia's livestock primary product. In 2018, they contributed AUD$17 billion to the Australian economy – one third of the country's entire gross domestic product. In New Zealand, red meat production (beef cattle and sheep) and processing and exporting (beef and dairy cattle and sheep) account for over $16B of value-added product and household income combined (Heilbron 2020); while the dairy industry alone contributes with over $20B in export value (www.dairynz.co.nz). However, climate change (CC) threatens the provision of ruminants as a global resource, affecting the animals directly (e.g., heat stress, health and welfare, parasites) and indirectly through the impact on pasture and forage crops.

There is already evidence of climatic changes in New Zealand and Australia. Extreme weather events, including extreme and prolonged drought, extreme rainfall and floods, more frequent and intense heatwave days, and bushfires have increased in frequency and intensity over the last decades. Sea levels are increasing following a decrease in glacier ice volumes, and the evidence suggests these changes are related to CC (CSIRO & Bureau of Meteorology 2020). These current and future changes in global and local climates pose a major risk to the sustainability of agricultural industries.

Australia has one of the most variable climates in the world. The country has been severely affected by extreme climate and unprecedented climatic catastrophes over just the last 5 years, including 1/100-year drought that lasted several years, the catastrophic bushfires of 2019-2020, and the 1/100-year flood in New South Wales (NSW) in 2021. The Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s State of the Climate 2020 report shows a steady decline in the 20-year running average of annual rainfall for Victoria and Southwest Western Australia, since about 1950 (CSIRO & Bureau of Meteorology 2020). The comparison of actual versus projected rainfall from 1995 to 2020 shows that, on average, rainfall has been tracking close to the driest end of the projected range, with no evidence of over or under estimation of projections (CSIRO & Bureau of Meteorology 2020).

New Zealand is also facing CC-driven challenges.

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A report published by the New Zealand Ministry for the Environment & Stats NZ (2020) shows increased winter temperatures across all 30 sites monitored around the country. Further anecdotal evidence suggests that northern New Zealand's climate is becoming more similar to central and southern Victoria's, and that, in the future, it may be more similar to current central/northern NSW. Moreover, climate variability between and within years is likely to impact more than global warming *per se* (Harrison et al. 2016).

The extent of impact on agricultural industries, and pasture-based livestock systems in particular, is unclear, although a recent modelling study using retrospective climate data suggests that pasture growth patterns have already changed in South East Australia over the last six decades (Perera et al. 2020). However, the climate-adjusted total factor productivity of the whole Australian agricultural sector has increased since the late 1970s (Huges et al. 2017), and crop productivity in dry years has also increased over the last two decades in Australia. This suggests that key agricultural industries like cropping for grain production can readily adapt to CC. An example of this is in the massive adoption of no-tillage agriculture in Australia over the last decades, with the resultant improvement in rainfall maintained in the soil accessible to plants and the associated increase in grain yields across dry years. It is noteworthy however that agricultural systems are usually quite complex, and the spread of no-till practices has also resulted in an increase in pest and weed management problems.

Effective adaptation mechanisms for the pasture-based livestock industries, particularly red meat and dairy, are less straightforward than for the grain industries. Questions as to how the different Australian dairy systems and regions have adapted to climate-exacerbated issues like persistence of perennial ryegrass (*Lolium perenne* L.), extreme variability in rainfall, incidence of insects and pests, among others, have not been fully addressed yet.

Modelling approaches

Many methods have been applied to try to understand the likely impacts of climatic changes on natural and human-dominated systems. These methods have ranged widely in complexity and aims. In many, perhaps most cases, authors have claimed to be predicting the future climates many decades into the future. Even a casual glance at the emissions scenarios used to drive the climate models reveals the uncomfortable truth that there are large, irreducible uncertainties in the rate of emission of greenhouse gases (GHGs), and consequently, no matter how good the biophysical climate models, the results are likewise plagued by uncertainty (IPCC 2014). Ironically, even the uncertainty's bounds are uncertain. Fortunately, there are some features of the CC observation and modelling effort that can be used to guide adaptation efforts. We know reasonably well what our present emission rate of GHGs has been, and how atmospheric temperature and concentration of CO_2 have grown, and we can relate this to the model scenarios to decide which ones could be arguably labelled as Business as Usual (BAU). We can then treat the future climate scenarios based on these BAU emission scenarios as a plausible benchmark. The scientific literature abounds in examples of where these future climate scenarios have been applied to biophysical models to create "predictions". This approach can mislead the application of the science as it can misrepresent the nature and extent of uncertainties, and consequently, can conceal the value of adaptation strategies based on proactive-monitoring and analysis.

The New Zealand dairy industry has undergone a massive expansion since the mid-2000s and is interested to understand the emerging challenges it faces due to CC so that it can prepare appropriately. One option to do this would be to take a biophysical mathematical model of the dairy industry such as DairyMod (Johnson et al. 2003) and then apply future climate scenarios and observe how the system changed. The strengths of this method would be the ease with which different adaptation strategies could be applied to test their benefits in the face of expected CC. One challenge with this method is that there may be many elements of the model system that are considered to be stationary in the face of the CC scenario. Another challenge is that the adaptation scenarios explored may be blinkered by the history of the analyst or the industry in the focal area.

A complementary method is to use analogue climates to identify areas that presently experience a climate that is similar to the future climate for the focal location or region. The analogue industry can be studied in its entirety to understand both the challenges being experienced in the warmer climate (e.g., the pest assemblage, the pasture species etc.) and the solutions that have been devised.

To address the concerns of the New Zealand dairy industry we model future climate scenarios for key dairy regions in New Zealand (Northland, Waikato, Manawatu, and Southland; Table 1) (Pers. comm. D. Chapman, DairyNZ) and compare them with New Zealand and Australian regions today to identify analogous climates. We then explore some of the approaches, research, techniques and adoption practices used in the different dairy regions of Australia to address, mitigate or overcome challenges directly or indirectly influenced by CC. We place emphasis on past and current research and development (R&D)-driven approaches and solutions to pasture and forage challenges faced in Australia with the view of anticipating future changes and needs in the dairy regions of New Zealand. Specifically, we address the following questions:

- What current regions of Australia can be considered analogues/equivalent to the above key dryland regions in New Zealand?
- How have the corresponding Australian regions dealt with pasture and feed base resilience challenges?
- What are the research gaps and opportunities for the New Zealand (and Australian) feed base?

Analogue climates and niche modelling

We used the CLIMEX Compare Locations to evaluate 'climate suitability' for dairy cattle, and CLIMEX Match Climates (Regional) model (Sutherst & Maywald 1985; Kriticos 2012; Kriticos et al. 2015) to match sets of locations for each region in New Zealand (i.e., 'climate similarity'). Briefly, the CLIMEX Compare Locations model calculates an Ecoclimatic Index (EI), which is the product of a 'growth' index that indicates suitability of the location for growth and development of a given species (plant or animal) during the favourable season(s), and a 'stress' index, which indicates the degree of unsuitability (too dry, wet, hot, cold, etc.) during the inclement season(s). The CLIMEX Match Climates model calculates a Composite Match Index (CMI; scale 0-1) from the similarities in climatic variables on a weekly basis, between different locations. By default, minimum and maximum temperatures, rainfall total and rainfall pattern are included in the match, with mean temperature, relative humidity and soil moisture available if desired. More details on the CLIMEX models can be found in Kriticos (2012) and Kriticos et al. (2015). A 0.5-degree fishnet spatial dataset was spatially intersected with the New Zealand local authority spatial dataset and centroids were generated for each resulting polygon. Four rain-fed dairy regions (Northland, Waikato, Manawatu and Southland) were selected in consultation with Dairy NZ (Pers. comm. D. Chapman, DairyNZ). For each selected region the Territorial Authority (Stats NZ 2020) class was used to select subsets of the centroids that were used as reference points for the 'Home' location set in each climate match analysis. For each region a bellwether station was chosen to illustrate the climate comparison.

Table 1 Target dairy regions of New Zealand, bellwether location reference and their geographic coordinates.

Region	Bellwether location	Corresponding Cell		
		Cell Location Code	Latitude	Longitude
Northland	Whangarei	66765	35.72°S	174.31°E
Waikato	Ngatea	66822	37.27°S	175.48°E
Manawatu	Palmerston North	66742	40.35°S	175.60°E
Southland	Invercargill	66803	46.41°S	168.36°E

To identify present day analogues of future climates for each of the regions we compared the future climate scenarios for each region as the home location set and compared each location with all locations in Australia and New Zealand under current climate. For all climate analyses the baseline climate dataset was the CliMond CM30 1995H V1.2 dataset centred on 1995 (Kriticos et al. 2012). This dataset was derived from the Climatic Research Unit dataset (Mitchell & Jones 2005). The future climate datasets were for 2050. The emission scenario was the RCP8.5. This is variously described as either an extreme scenario or BAU based on the similarity of results using this scenario to recent historical records of atmospheric [CO_2] and global temperatures (Rahmstorf et al. 2007). The results of four General Climate Models were applied (ACCESS, CNRM-CM5 [Voldoire et al. 2013], GFDL-ESM2M, and Nor-ESM1-M, https://pcmdi.llnl.gov/mips/cmip5/availability.html).

Summarised results of the analogue climates and niche modelling

Figure 1 shows the EI for the basal year (1995) and the year 2050 modelled with ACCESS and using RCP8.5 assumptions. The exercise was repeated using another three models, namely CNRM-CM5, GFDL-ESM2M, and Nor-ESM1-M, but results were very similar and consistent thus only ACCESS' results are shown. The EI gives an indication of the broad 'climatic suitability' of a given climate for, in this case, dairy production. The index is based only on climate factors, and it does not consider other determining factors such as soil type and topography. Based on CLIMEX results, climatic suitability for dairy changes little or in fact, increases in New Zealand, but it clearly reduces in Australia, particularly on the eastern coast.

More detailed changes are seen in Figure 2, which shows the EI for the difference between the basal situation and 2050 using the ACCESS model. According to this modelling, the climatic suitability for dairy of the mid and north coast of NSW (and South East Queensland) clearly decreases by 2050, while it improves markedly for Tasmania and Manawatu and even more so for Canterbury and part of Southland (red areas).

Figure 3 shows the CMIs for Manawatu, Northland, Southland and Waikato (a, b, c, d, respectively) as estimated by the climatic model ACCESS. The scenarios were also modelled with CNRM-CM5, GFDL-ESM2M, and Nor-ESM1-M, in all cases using

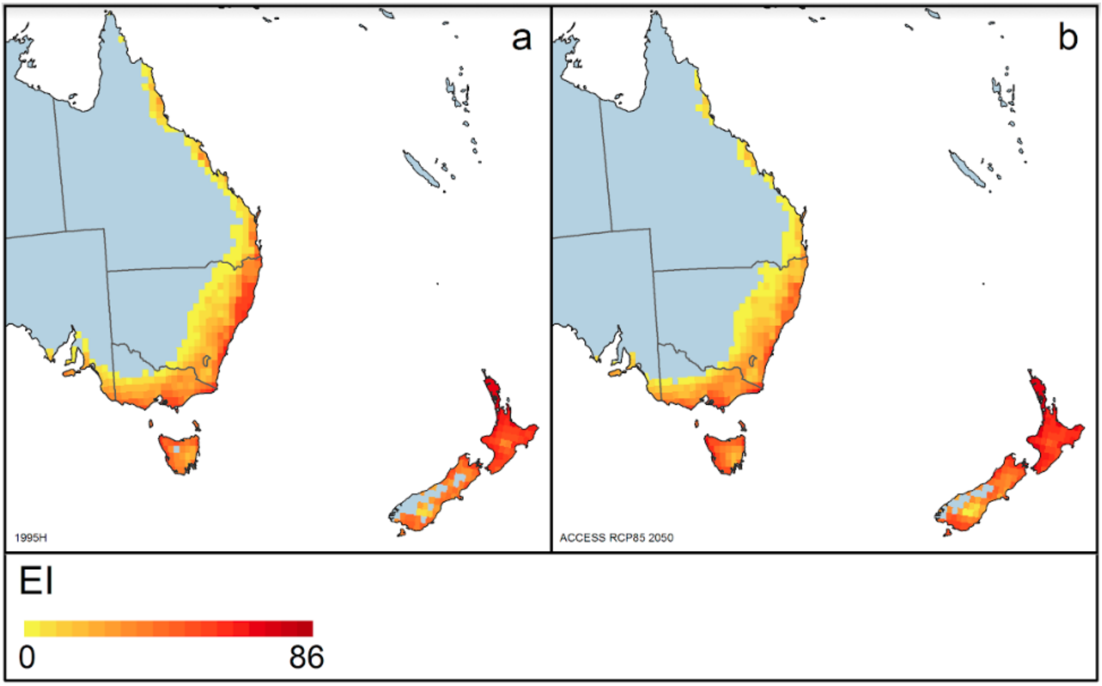

Figure 1 Baseline (1995, "a") and Future scenario (2050, "b") maps of 'climatic suitability' for dairy production in Australia and New Zealand. EI=ecoclimatic index; range 1 (climatically unsuitable) to 100 (optimal climatic suitability); 86 was the highest level of 'suitability' achieved in this modelling.

RCP8.5 emission scenario for 2050 and a cut-off value of 0.8. The CMIs depict the climate similarities between the selected region in New Zealand in 2050 in relation to New Zealand and Australian climate today. Although the model outputs allow for areas to be precisely defined, measured and their CMI quantified, for the purpose of this paper the graphical results are intended to be illustrative. Results across all four models were highly consistent, thus only ACCESS graphs are shown for simplicity.

For Northland (Figure 3a), the models indicate a similar climate to the Sydney Basin's today (strongest similarity, CMI> ~0.9) and to the NSW coast (literally just the coast) more generally (CMI ~0.8-0.9). Northland had been previously identified as one of the most negatively affected areas by CC (Kalaugher et al. 2017). The Waikato region, in 2050, also will likely have similarities with the coastal regions of NSW and Victoria (Gippsland in particular), but the strongest climate analogue (CMI ~1.0) is Northland (Figure 3b). This suggests that current climatic conditions in Northland today will be likely prevalent in Waikato in 2050. The future climate in Manawatu has strong similarities with current climates in South East Australia in general, and South East and South West Victoria and North East Tasmania, in particular (Figure 3c). Thus, current research, practices, challenges and solutions being applied in those regions today are likely to be applicable to Manawatu in the future. Lastly, our analysis shows that, in 2050, the climate in Southland might be an analogue to the northern areas of Southland, Canterbury and Manawatu (Figure 3d), with a slightly less similar match to the climates observed today in South East Victoria (Gippsland), the far south coast of NSW (Bega Valley) and central and North East Tasmania.

The results indicate that the analogue climates of the southern and central North Island regions in the near future are mostly to be found within New Zealand. Comparisons within New Zealand are relatively straightforward because the pest assemblages are likely only limited by their climatic patterns, and the external economic conditions are likely to be quite similar. Comparisons between New Zealand and Australia may be complicated by differences in these factors. Where there are suitable analogues in both New Zealand and Australia there is an opportunity to compare different solutions to similar challenges, as a way of stimulating more innovative thinking about adaptation options. For the dairy industry in Northland, the guidance for climate adaptation is mostly to be found in Australia. What the key dairy regions in Australia (Victoria, NSW coast, Tasmania) are facing today in terms of climate is likely to be seen in the warmer parts of New

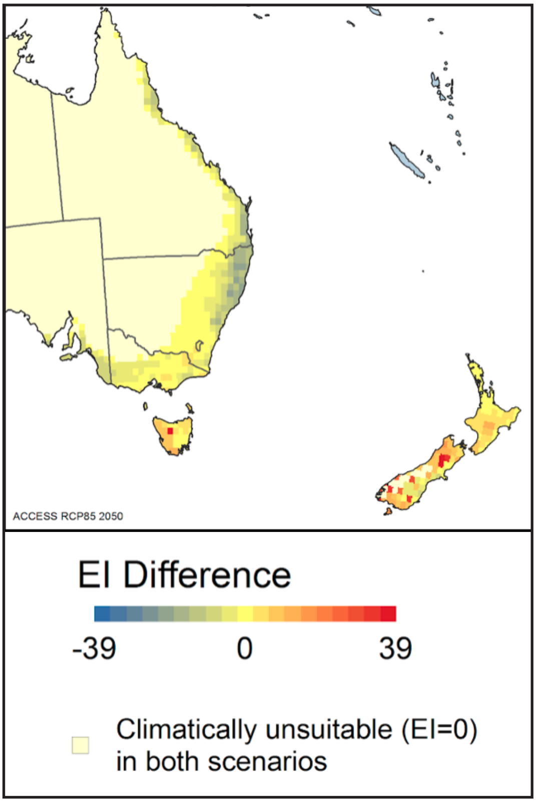

Figure 2 Difference ("change map") between Baseline (Figure 1a) and Future scenario (2050, Figure 1b) maps of 'climatic suitability' for dairy production in Australia and New Zealand. EI=ecoclimatic index. Red and blue colours indicate maximum level of difference (increase or decrease in suitability, respectively).

Zealand in just a few decades. Scanning beyond 2050, we would expect that the Australian analogues might become more useful as a harbinger of things to come later in the century. This longer-term perspective may be valuable for evaluation of future R&D investment and projections, and in particular for some producers who are considering major capital-intensive adaptation options that have very long payback periods.

The results also suggest that key and traditional dairy regions in New Zealand, particularly Waikato, may need to be prepared for the lower and more variable rainfall of Northland currently. Combined, these results provide some validation for the relevance of using climate analogues to explore what and how current climate-driven factors influencing some regions today (e.g., key dairy regions in Australia) may provide clues for some or all of the key dairy regions of New Zealand into the future. The discussion of climate-driven factors and research approaches or strategies that can be used to address these issues is the focus of the next sections.

Climate-driven factors affecting pasture-based systems in the last decades

While the extent of global warming increase in the future remains highly uncertain due to the incertitude in the rate of emissions of GHGs, consensus is building amongst scientists on its likely consequences, namely, for South East Australia, a decrease in total and winter-spring rainfall, milder winters and an increase in rainfall variability between and within years (CSIRO & Bureau of Meteorology 2020).

As evapotranspiration from pastures and sequential annual forage crops can reach ~1.2-1.4 ML/ha/yr to maximise above-ground biomass production in temperate areas (Garcia et al. 2008), it follows that soil moisture stress is likely the greatest challenge faced by farming systems in South East Australia. This extends to dryland areas in South West Victoria, NSW mid and northern coasts, part of Gippsland, and irrigated dairy regions with limited access to water in Northern Victoria, the Riverina and the Hunter Valley in NSW.

Prolonged soil moisture deficits, or severe drought can have devastating effects on pastures and forage crops; as regions of Australia – Victoria, NSW and Queensland in particular – have seen during the two unprecedented and extreme droughts that occurred within the last two decades. Severe drought results in nil (or extreme reduction in) biomass growth over months or entire seasons, which, for dairy systems, are typically associated with substantial increase in feed costs and reduced farm profitability.

A less extreme reduction in water availability with intermittent soil-moisture stress can have variable but serious effects on pastures and crops, by affecting not only biomass yield but also persistency for perennial forages; weed and pest infestation; and forage quality (Islam et al. 2012). All this, in turn, increases uncertainty for feed-base planning, with the associated risk of greater feed costs and reduced profitability.

Research-based strategies to help address climate-driven challenges

A search on Web of Science narrowed to the keywords "pasture" or "forage" or "crop" with "CC", "dairy" or "milk" and "Australia" or "New Zealand" resulted in 102 papers published since 2000. As expected, most research undertaken in the last decades associated with CC was based on modelling, with the remainder focussed on Forage and Management options, Environmental impact of dairy production, or the Animal/production field.

Modelling research

Modelling-based research is necessarily at the core of most CC-related research. In Australia and New Zealand in particular, biophysical models have been

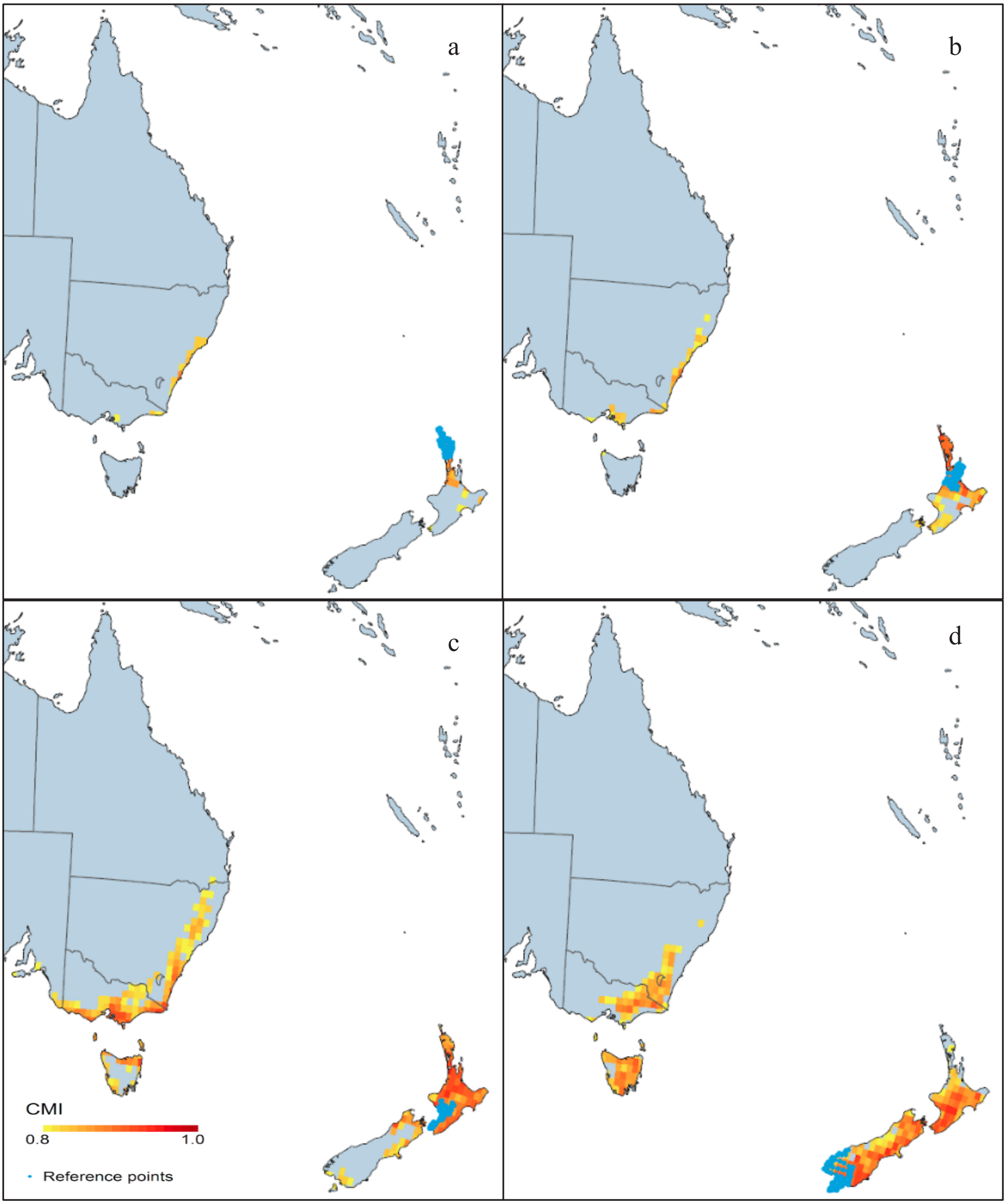

Figure 3 Climate Match Index (CMI) for a) Northland, b) Waikato, c) Manawatu, and d) Southland as predicted by the climatic model ACCESS. Blue sectors represent the actual region being compared.

widely used to evaluate the performance of pasture and crops under a variety of past, current and future climatic scenarios.

Pembleton et al. (2021) used the biophysical models DairyMod and APSIM to assess the performance of annual cropping systems and perennial pastures for three dairy regions of south-eastern Australia, using historical climate data and two future climate scenarios. In all three sites (Elliot, Tasmania, partial irrigation; Terang, South West Victoria, dryland; Dookie, Northern Victoria, full irrigation), forage production increased in winter and decreased in summer. Interestingly, under irrigation (Northern Victoria), yields of both pasture and forage crops increased in the future climates, although more irrigation water was required. This aligns with recent work by Cleverly et al. (2020), who, using wavelet-statistics (for time-series analysis) showed that high irrigation and fertilisation practices (i.e., intense management) can provide better protection against heat stress, particularly for irrigated crops in dry regions. This is also supported by the potentially greater yields of commonly used forage crops in South East Australia under future climate scenarios with increased concentration of CO_2 due to global warming.

Perera et al. (2020) determined changes in annual and seasonal pasture growth rates using DairyMod for five sites (high and medium rainfall, irrigation) in South East Australia since 1960. They found very little or no differences in total pasture yield, but a steady increase of pasture growth rate in winter, and a decrease in spring, highlighting the current impact of CC. In New Zealand, Kalaugher et al. (2017) modelled six dairy farms located in different major dairy regions and reported that change in total annual pasture production could range between 0 and -18% due to CC.

As opposed to the relatively milder impact of global warming trends on the feed base, there is increasing consensus among scientists that the projected increases in rainfall inter- and intra-annual variability will be much more detrimental than the long-term effects of an increased average global temperature *per se*. The work by Harrison et al. (2016, 2017) suggests that this is already the case with our recent and current climate. The authors showed that 'current' (recent decades) inter- and intra-annual variability in climate (including the already higher incidence of extreme climatic events (ECE), i.e., heatwaves, droughts, extreme rainfall) is adversely impacting pasture-based production more than the consequences of global warming *per se* (Harrison et al. 2016, 2017). They conclude that focus should be on management strategies to address short-term climatic variability versus long-term warming (Harrison et al. 2017).

Overall, the most recent modelling research for South East Australia collectively points to extreme variability as the biggest challenge to resilience.

Pasture persistency and resilience

Modelling research combined with experimental data has also provided insights into the cause-consequence effects of CC on pasture and forage production. The recent work by Woodward et al. (2020) provides an example. They used a process-based pasture model (BASGRA) to replicate, by simulation, the differences in tiller number observed in field experiments for perennial ryegrass pastures in New Zealand. Data ranged from dryland (lower persistency and biomass production after the second-year post establishment), to irrigated pastures (where losses in neither tiller numbers nor yield were observed). Tiller mortality was positively associated with soil-moisture deficit and as such was the key explanatory factor of the observed differences in pasture yield. Their conclusion suggests that some of the proposed mitigation strategies against CC such as plant breeding for heat tolerance, or more lenient grazing management, may not be as effective as breeding for plants with increased soil moisture resilience.

There is an opportunity for pastures to buffer against intermittent moisture deficits, maintain tillers and persist, by having larger root systems enabling exploitation of a greater volume of soil. Typically, short-term pasture grasses (e.g., annual ryegrass, *Lolium multiflorum* Lam.) and shallow-rooted species such as perennial ryegrass are sown on dairy farms. These produce dense but shallow root systems with fewer roots at depth compared to species such as tall fescue (*Festuca arundinacea* Schreb.), cocksfoot (*Dactylis glomerata* L.) and phalaris (*Phalaris arundinacea* L.) (Ridley & Simpson 1994). When perennial ryegrass experiences moisture deficits, it responds first by extending roots further down the soil profile, presumably in search of moisture, and then if moisture deficits continue it rapidly sheds roots, particularly those nearer to the surface (Wedderburn et al. 2010). In perennial ryegrass, recovery from moisture deficits is initially driven by carbohydrate reserves and it can take a month for root production to begin recovering rapidly (Wedderburn et al. 2010), allowing greater above-ground biomass growth. Deep-rooted pasture species such as tall fescue (Garwood & Sinclair 1979), cocksfoot and phalaris experience less root death under moisture deficits (Huang & Gao 2000; Wang et al. 2008; Skinner & Comas 2010) than perennial ryegrass. Their greater rooting depth gives the plants access to a much larger soil volume from which to draw moisture. These deep-rooted species are less likely to be affected by intermittent moisture deficits, can provide an extended growth period (Nie et al. 2004a; Tharmaraj et al. 2008; Lee et al. 2013), and are more persistent than perennial ryegrass (Nie et al. 2004b). There is potential therefore for deep-rooted perennial species to be a key strategy in adapting our dairy farm systems to increased climate variability.

At the farming system level, it could be argued that reduced persistency (e.g., perennial ryegrass in South East Australia) could be managed simply by increasing the frequency of pasture renewal. This, however, can not only increase cost but also reduce soil organic carbon (SOC) content, as each pasture renewal cycle is associated with a net decrease in SOC, particularly if using cultivation for seed bed preparation instead of direct drilling (Rutledge et al. 2017).

Soil carbon as potential adaptation strategy

Soil organic carbon can potentially help to address CC-derived challenges in two ways. First, grasslands account for about 26% of the planet's land and about 70% of total agricultural area, with content of SOC that varies substantially (e.g., from 2 to 239 t C/ha in the first 30 cm of soil in Victoria, Robertson et al. 2016). Clearly increasing soil C in grasslands can potentially offset GHG emissions and improve the world's ability to produce food sustainably in the future. In fact, increasing C sequestration in the soil has been proposed as possibly the most effective way of reducing global net C emissions in the short term (the '4 per mille' initiative; Minasny et al. 2017). Second, SOC improves soil structure, increasing the water retention capacity of the soil and its potential fertility (Whitehead et al. 2018). Thus, with the expectation of reduced rainfall in warmer months in South East Australia and New Zealand in the future, in addition to offset total emissions, increasing SOC could help improve soil moisture balance in localised soils and therefore the ability of pastures and crops to cope with shortfalls in rainfall.

Thus, increasing SOC could be considered a mitigation strategy to attenuate the main adverse effects of CC, i.e., the increase in global temperature (though reduced emissions) and the lower and more variable rainfall through improved water retention of localised soils. In practice, however, factors like irrigation, fertilisation, forage options, animal supplementation, presence of invertebrates, and grazing management, among others, all interact and affect SOC directly or indirectly, limiting the scope of adjusting SOC as a mitigation strategy.

Annual rainfall explained about 80% of the variation in SOC in Victoria (Robertson et al. 2016). Thus, it follows that irrigation can increase soil C in dry climates due to an increase in C inputs and root biomass from a low base but decreases or does not change soil C in humid climates, possibly due to increased or accelerated decomposition and turnover rates (Whitehead et al. 2018). Fertilisation with nitrogen (N) can increase soil C stock, particularly in low-fertility grasslands, but both cost and environmental impact of producing N need to be considered. Moreover, while N use efficiency can be increased particularly through the use of precision technologies (Rawnsley et al. 2019), it is unlikely an option for New Zealand given the current trends in regulations limiting its use.

Intensive cropping, particularly maize (*Zea maize L.*) for silage, can deplete C due to the high extraction rate through the harvested biomass. This effect can be partially offset by minimising 'dead times' between crops, zero-tillage, and incorporation of organic residues such as with double or triple cropping. In fact, complementary forage (crop) rotations (CFR), a concept developed by FutureDairy (García et al. 2007) can increase total C removal (harvested areal biomass), and potentially also total C inputs. The latter is due to the greater volume of soil explored by the roots of complementary crops (Whitehead et al. 2018), more total biomass grown below ground level, and less unproductive or 'dead time' between crops (Garcia et al. 2008).

Management factors such as grazing management can also affect soil C balance. In this regard, overgrazing can deplete soil C due to reduced C input (i.e., photosynthesis) and reduced partition of C to the roots. However, the net effect of grazing management has not been fully elucidated yet, possibly because of the many factors and interactions involved (Whitehead et al. 2018). Other factors such as imported feed (Kirschbaum et al. 2017) and invertebrates can also affect SOC, but the magnitude of the effect is very small (Whitehead et al. 2018).

With all the above factors combined, opportunities exist to increase C sequestration globally to help mitigate about one quarter of current global CO_2-equivalent emissions (Minasny et al. 2017). However, the potential to improve soil moisture retention due to increased C content at paddock/farm level, which, in theory would help to mitigate the impact of rainfall variability, appears to be more difficult to be achieved in practice.

Forage crops and management options

A dramatic example of farm system adaptation to climate-induced challenges such as drought has been observed in Northern Victoria over the last 10-15 years. In the southern Murray Darling Basin in particular, dairy systems have evolved from the typical combination of perennial (e.g., perennial ryegrass; *Paspalum* spp.) and annual grasses (mainly annual ryegrass), generally dominated in proportion by the perennials, to a common use of forage crops and herbs (Rogers et al. 2017). This review by Rogers et al. (2017) shows a large range in water use efficiency (defined as milk output/water input) and water productivity (WP, t MS/ML water), as well in total irrigation water required by different annual and perennial forage options (from less than 2 for short-season annual species to over 13 ML/ha/yr for perennial pasture). Average water productivity of irrigated water ranged from ~1.0 t dry matter (DM)/ML for perennial ryegrass-white clover pasture to ~2.6 t DM/ML for annual clover (Persian clover [*Trifolium resupinatum L.*]; subterranean clover [*Trifolium subterraneum L.*])-Italian ryegrass [*Lolium multiflorum L.*] mix; while the double cropping of oats (*Avena sativa L.*) in winter and millet (*Panicum milliaceum L.*) in summer achieved ~2.0 t DM/ML (Rogers et al. 2017). These figures are well below the potential demonstrated experimentally in other regions of Australia, for example with the triple cropping CFR of FutureDairy, which achieved over 5 t DM/ML of irrigation water for several sites in NSW (Garcia et al. 2008).

The Rogers et al. (2017) review discusses strategies to improve productivity with limited water in Northern Victoria as it is likely to be increasingly the case in that region in the future. They compared the suitability of different forage options including perennial (C_3 and C_4) and annual forage grasses and legumes; winter and summer fodder crops; and herbs, concluding that despite WP being a key factor to focus on, it is not the only one. Better irrigation practices and strategies combined with improved management practices of perennial species should go jointly with the choice of appropriate forages. The authors went on further, identifying the need for farmers to include economic analysis in the decision process, and to be flexible when selecting forage mixes, given the already large inter- and intra-annual variability in soil moisture and water availability (due to the water allocation system) in that region. The authors noted that farming systems with a greater proportion of perennial pastures may see this flexibility greatly reduced.

Can cropping increase dairy system flexibility?

Planned (strategic) and/or opportunistic use of forage crops for grazing, harvest, or dual purposes both open up a window of opportunities for famers to address inter- and intra-season climate variability, particularly in rainfall. Triple-crop CFR with maize for silage as the base crop can yield consistently over 40 t DM/ha under irrigation (Garcia et al. 2008), which is more than double the potential of temperate pastures. However, they are complex to manage and therefore have not been extensively adopted (www.futuredairy.com). Flexibility at the system level, together with the ability of a farm to address climate variability, can be maximised with forage crop rotations. Such rotations allow for many combinations of forage crop options for different regions and soils; within and between seasons in a region; the possibility of mixing green crops and nutrient-capturing crops (e.g., *Brassica* spp.); and the possibility of changing the destination (grazing, harvest, or both). The latter, i.e., combining harvestable crops (e.g., maize for silage) with grazable crops (brassicas, annual legumes) in the same forage rotation can increase the flexibility of a dairy system, but it may also limit utilisation of the land close to the dairy.

For instance, summer and annual legumes, alone or intercropped with C_4 grasses (e.g., maize) can provide additional options for dairy farms in regions with limited irrigation water or variable rainfall. A series of field experiments conducted by FutureDairy at Camden, NSW investigated double-crop CFR forage options for grazing only (G), and for both grazing and conservation (GC). In G, four legumes (cowpea, *Vigna unguiculata* L. Walp; fababean, *Vicia faba* L.; lablab. *Lablab purpureus* L.; and soybean, *Glycine max* L.) were grown during summer. Then maize only, or maize intercropped with either forage rape (*Brassica napus* L.) or Persian clover, were grown in autumn-winter. In GC, maize was grown as a sole crop or intercropped either with soybean or lablab in summer followed by another maize intercropped either with forage rape, ryegrass or soybean in autumn-winter.

In G, yield of cowpea (7.4 t DM/ha) in summer and maize-forage rape (17.9 t DM/ha) in autumn-winter was the best combination, providing 25.3 t DM/ha grazeable forages in a 9-month growing cycle. In GC, yield of maize-lablab intercropped (27.5 t DM/ha) in summer for conservation followed by maize-forage rape (18.7 t DM/ha) for grazing in autumn-winter provided 46.2 t DM/ha from double-intercrop forage rotation in a 12-month period.

Irrigation water use efficiency (or water productivity, expressed as unit of DM per unit of irrigation water) of these grazeable forages in G, and grazeable plus conserved forages in GC, was also greater (56 and 51 kg DM/mm, respectively) than other options (soybean, fababean, lablab in summer followed by maize-clover or maize-ryegrass in autumn for G; maize alone or maize soybean in summer followed by maize-ryegrass or maize-soybean/ryegrass in autumn-winter for GC). These efficiencies in the use of irrigation water are 4-times greater than the average WP of perennial ryegrass pasture in Northern Victoria farms (Armstrong et al. 2000) and 2- or 3-times greater than those achieved by Rogers et al. (2017) with mixes of Italian ryegrass and annual clovers. The nutritive value of these high-yielding grazeable forages in G, and grazeable plus conserved forages in GC was also higher or similar to other options. These results demonstrate the feasibility of achieving over 25 t DM/ha of wholly grazeable forages and over 45 t DM for both grazing (autumn-winter) and conserved high nutritive value forages for dairy production from a double-crop rotation of forages. Therefore, there is a potential for future dairy systems in temperate and subtropical regions to strategically and opportunistically incorporate forage crops to increase supply and nutritive value of grazeable and conserved forages. Such potential can help to address, anticipate, or take advantage of, current and future variability in climate, particularly the predicted lower and more extreme rainfall in temperate regions of Australia and New Zealand.

Adaptive management to climate change: the opportunity to be strategically opportunistic?

In combining our analogue climates with research-based strategies and approaches to deal with CC-driven challenges, we highlight the following points.

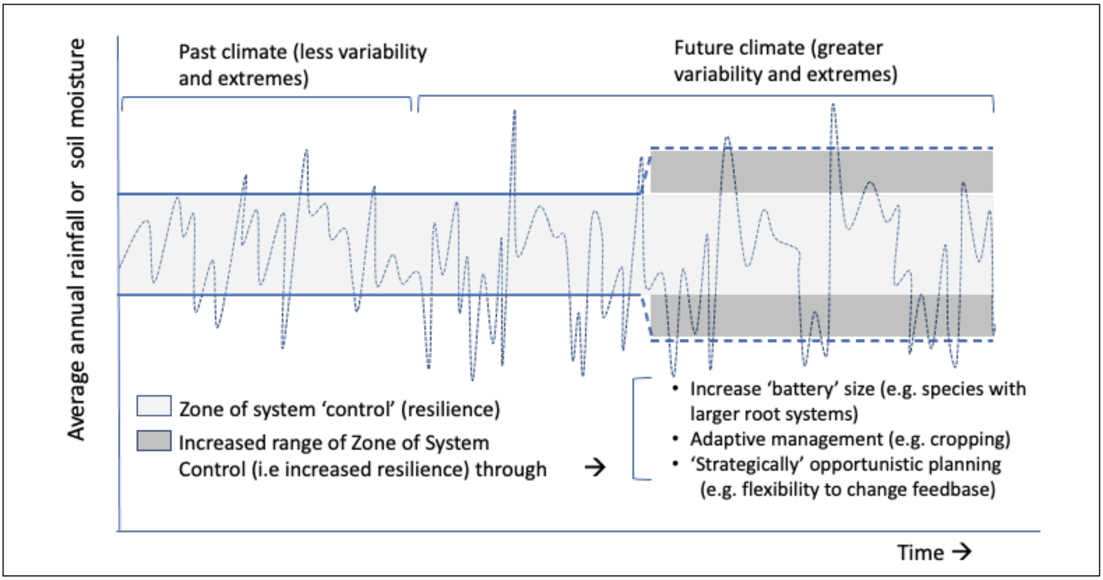

Figure 4 A diagrammatic representation of potential system adaptation to climate change (CC). The main effect of CC is represented by the increased magnitude and frequency of rainfall (or soil moisture content). The light grey area represents the zone of system 'control' i.e., the level of rainfall or soil moisture where productive and profitable farming can occur. As time progresses, both the frequency and mangitude of extreme years increase due to CC. Farmers can not control those changes, but they can potentially increase the 'boundaries' of the zone of system 'control' (dark grey areas) through adaptive management and other techniques, reducing the adverser impact of CC and increasing resilience.

First, extreme variability in weather patterns, particularly inter- and intra-annual rainfall variability, holds the key to present and future pressures on farming systems. The consequences of long-term, gradual increased temperature and CO_2 will likely exacerbate that variability, increasing the probability for farming systems escaping the zone of 'system resilience' (Figure 4).

The increased variability due to CC is likely to result in an increased number of 'peaks' (extreme effects = out of farmers' control) occurring in the future, particularly for dryland systems. The unprecedented sequence of dramatic and extreme climatic events hitting South East Australia in the last 5 years appear to provide clear and present evidence of this.

These changes are diagrammatically represented in Figure 4. The actual extremes, in terms of both size and frequency, are out of farmers' control. But the 'Zone of System Control', i.e., the range (of rainfall or soil moisture content) where an individual farmer can manage to produce and grow sustainably and profitably, is movable. Farmers and dairy producers will have to develop new strategies to increase the size of this zone of 'process or system control'. They can do this by basically three ways.

a) Increase the size of the system's reserve or 'coping' range. An analogy of this is to increase the size or capacity of a 'battery' in an electrical system. For dairy farming, it means to cushion the impact of lower and more variable rainfall by developing strategies that can alleviate the adverse effects. An example is the use of temperate species that can explore much greater and deeper soil volume than perennial ryegrass (see above).
b) Adaptive management. A change from the more traditional and typical dairy farming practices and management, to a more holistic, business-oriented way of enterprising dairy production. This can include, for instance, management practices perhaps unthinkable today in the context of New Zealand dairying, like double- or triple- cropping or the replacement of perennial ryegrass by other grasses, legumes or herbs.
c) Increased preparedness to better capture the advantages and opportunities of good seasons and years, for example by purposely leaving paddocks free and ready for very quick sowing or interventions, like a system's 'trump' card. We call this 'strategically opportunistic planning'.

Opportunities for future research

In this paper we emphasise that, from a pasture-based dairy production viewpoint, the key and largest effect of CC impacting farmers will be through the increased inter- and intra-annual variability in rainfall, and its main consequence, soil moisture content. The extremes can occur, and will occur, at both sides of the equation (as Figure 4 represents), but it seems unequivocal that CC will result in a greater incidence of soil moisture deficits than surpluses.

The focus of future research and future solutions should, therefore, be placed on how to either reduce soil moisture deficit, reduce water losses, or increase the ability of plants to not only tolerate but also grow and produce, under more limiting soil moisture. We have presented here a conceptual framework to represent this, that is, the notion of increasing the area or zone under 'system control' (Figure 4).

Following this framework, some opportunities and research gaps can be identified.

Drought and heat tolerance through genetics

It seems unlikely, as previously discussed, that increased heat tolerance in plants could have a large beneficial impact on farming resilience to CC, given that the main challenge is soil moisture deficit and extreme variability in rainfall. Conversely, increased drought tolerance has a much larger potentially beneficial impact. A discussion of this is outside the scope of this work, but some tangible opportunities could exists through, e.g., i) the adaptation and use of naturally-stress resistant plants (NSRP, Zhang et al. 2018), including the potential domestication of exotic NSRP through gene editing; ii) the development of 'drought resistant' C_4 plants (e.g., millets), which are typically higher in water use efficiency or productivity; and iii) the use of newer techniques like "speed breeding" which enables breeders to accelerate forage and crops research and breeding by shortening generation time (e.g., up to 6 generations of wheat, barley, and peas per year) (Watson et al. 2018).

Soil organic carbon

Although difficult to be achieved in practice (as discussed above), increasing SOC on individual paddocks and farms can increase the soil capacity to retain moisture and the availability of nutrients for plant growth. There is an enormous amount of research on SOC, C sequestration and mitigation strategies, as well as the effect of plant roots on C sequestration, stabilisation and destabilisation. These topics are grossly beyond the scope of the present work, but recent research (Dijkstra et al. 2021) indicates that the actual net or true effect of plant roots on SOC is subject to an apparent paradox from opposite-acting mechanisms, namely those causing C accrual (stabilisation) and those causing C loss (destabilisation). The authors have proposed a new conceptual framework called "Rhizo-Engine" that highlights the 'double-sword' nature of the effects playing, allowing for better understanding of these effects and their interactions under particular changes due to land use or CC (Dijkstra et al. 2021). A specific gap in knowledge becomes apparent in relation to the interaction between pasture- (or forage-) based dairy systems, including the large variety of annual, biennial and perennial grasses, legumes and herbs, and soil carbon.

Improved management through remote sensing and technologies

Earlier we argued that double, triple and intercropping can provide solutions to future CC-driven challenges, particularly through increased WP, water use efficiency (WUE), total DM yield, relative yield in relation to water and nutrient inputs, and reduced cost of production (www.futuredairy.com). However, there are two main barriers to overcome: increased production system complexity and the availability of land, water and resources to maximise, or better, optimise, their use. Intensive cropping adds complexity into a system, particularly for the more traditional pasture-based 'grazier' famers of New Zealand and Australia. The management of time, inputs, and human and physical resources becomes critical for success, as the window of opportunity for establishing crops (particularly in 3-crop CFRs) is counted, ideally in hours, not days. A 1-day delay between (e.g.,) harvesting maize for silage and sowing a clover, annual grass or a brassica, with the bad luck of a rain event can delay sowing for 1 or 2 weeks, sealing the failure of what was going to be a top yielding 3-crop CFR (FutureDairy Feedbase technotes; www.futuredairy.com).

However, while complexity cannot be avoided, it can be addressed, overcome, or at least minimised, by the use and application of new technologies and automation, precision farming and digital agriculture. These include, among others, application of remote sensing to pasture and feeding management; animal behaviour (e.g., heat stress) and productivity; and the use of digital agriculture (digital soil mapping, digital sampling, decomposed digital data, digital monitoring of water and N). The potential of all this is, on paper, enormous. But there is clearly a need for coordinated R&D programs between regions (and countries) to assess the true complexity (or reduction in), applicability and impact of these technologies for dairy production systems.

Conclusions

Key dairy regions in New Zealand and Australia will be increasingly affected by CC over the next decades. The main effects will be a reduction in total annual rainfall and distribution, and increased inter- and intra-season variability in rainfall, and consequently, in soil moisture content.

For most of New Zealand dryland dairy regions, the analogue climates of the southern and central North Island regions in the foreseeable future are mostly to be found within New Zealand. Northland is the exception, with an increased likelihood of facing in a few decades what Victoria, NSW coast, and Tasmania are facing currently in terms of climate.

In both countries, tomorrow's dairy farmers will have to be prepared to develop new ways, approaches, and systems that allow profitable production of feed, and milk, under much more challenging climatic conditions impacting directly and indirectly on soil moisture content.

We have presented here a conceptual framework to increase the boundaries of the 'Zone of System Control', i.e., increasing resilience and reducing risks of failure due to soil moisture deficit, by means of three groups of strategies: i) increasing the size of the soil moisture reserve or 'coping range' (the 'battery' analogy) by, for example, increasing C sequestration or using species with better capacity to explore and extract soil moisture; ii) implementing adaptive management strategies, for example, using forage crop rotations to increase flexibility of management and maximise WP and WUE; and iii) be better prepared to maximise opportunities arising from good climatic seasons by planning for increased flexibility and readiness (strategically opportunistic planning).

Whether or not this framework and its associated strategies can indeed result in tangible changes in the zone under control by the farmers warrants further collaborative, interdisciplinary, and translational research. In particular, research is needed to explore and quantify: the impact of SOC on localised soils (farms), the true ability of different forage species to explore greater volumes of soil (the 'battery' analogy), the opportunities arising from plant genetics, and the use and application of AgTech (including technologies, automation, digital agriculture and artificial intelligence) to reduce the apparent complexity of the truly more complex systems of the future. In addition, all the above would need to be tested and quantified at the whole-farm system level; perhaps a real opportunity for the Australian and New Zealand dairy industries to work together today to increase their chances of remaining sustainable beyond 2050.

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