Manaaki Whenua
Landcare Research

Research strategies relevant to Regenerative Agriculture in New Zealand

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

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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, hereafter referred to as ‘RA 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 RA 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 a complex profession, constantly evolving and adapting, based on a multitude of theoretical and practical experiments and 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 RA 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 RA Think Piece 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).

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[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, and to the NZ Merino Company few days before the release of this report.

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

Research strategies relevant to Regenerative Agriculture in New Zealand

Contract Report: LC3954-4

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1 Executive summary

A 'think piece' project was undertaken in 2020/2021, funded by Our Land and Water National Science Challenge, The NEXT foundation and Manaaki Whenua – Landcare Research. It brought together several groups of experts to identify knowledge gaps about Regenerative Agriculture (RA) in Aotearoa New Zealand. This report synthesises their findings.

More than 60 individual knowledge gaps were identified, across 11 aspects of RA: productivity, food nutrient density & quality, animal welfare, freshwater health, soil health, economics, biodiversity, greenhouse gas emissions, resilience to extreme weather events, adaptation to climate change, and well-being/mindset/culture.

Methodological considerations to close these knowledge gaps include types of methods, research partnerships and experimental designs.

Research on RA can have three purposes: (1) testing RA claimed benefits (does RA work), (2) understanding how RA works, and (3) innovation within RA to optimise its practices and/or principles within the NZ context and increase its adaptability to future environmental and trade conditions. Given the growing backup of RA by food corporates and the urgency of future-proofing the NZ agri-food system, we would argue NZ agricultural sectors should combine public and private research funding to test and co-develop RA principles & practices that fit the NZ context and achieve NZ's long-term goals.

Research strategies to meet all three purposes require the establishment or strengthening of research partnerships with landowners/farmers/RA practitioners, deployment of methodological approaches intersecting agricultural, environmental, and social change research, accounting for blurred boundaries between RA and other farm management philosophies, and greater recognition of evidence derived from landowners' observational knowledge.

Partnership with iwi, with influential farming networks/levy bodies/cooperatives but also with entities that operate 'at the edge' of social, agricultural/environmental and digital innovation (green & social entrepreneurs, small start-up companies) is critical to meet the third research purpose (innovation within RA).

Research strategies delivering on all three research purposes across all aspects of RA considered include: farm system research; pairwise comparisons; repeated assessment of outcomes across social, economic, environmental domains (cross-sectional/longitudinal studies); citizen science supported by crowdsourcing and digital technologies, place-based research (case-studies); Living Labs/Real World Labs.

All research strategies can be designed to embed partnership with iwi and address their interests/research goals, but not all can be built as per kaupapa Māori. Hence the choice of strategy for any given research question will determine the extent to which the research can be embedded in Te Tiriti o Waitangi.

2 Introduction

This report should be read as one of the last synthesis reports produced by the RA think piece. Previous reports and a white paper have already addressed issues with RA's definition (or lack of definition) and the lack of clear boundaries between RA management and farm management systems; discussed RA claims, practices, and principles; provided insights on what RA might mean for NZ (compared with overseas); and touched upon the current state of relationship between RA and Te Ao Māori (Grelet et al. 2021a, 2021b, 2021c; Lang 2021; Letica 2021; Merfield 2021).

This report should also be read in its 2021 context and the global and national events that preceded the time it was written. This is a time of change, almost 2 years since the start of the COVID19 pandemic, a few days after the long-awaited COP26 summit that led to ambitious pledges for emission reduction and accelerating transition to sustainable agriculture,[1] but much uncertainty on their effective implementation;[2] and a few weeks after the release of New Zealand (NZ) Ministry of Business, Innovation & Employment (MBIE) Te Ara Paerangi Future pathways green paper 2021,[3] highlighting the need to make NZ's research system 'more connected, adaptive and resilient'. This is also a time when a groundswell of farmers and land managers, are transitioning to management systems that seek to deliver more positive environmental and social outcomes – including, but not exclusively, Regenerative Agriculture (RA).

This report has two key aims:

- To summarise the main knowledge gaps about Regenerative Agriculture (RA) highlighted in previous reports. These include gaps in data/evidence, gaps in understandings about processes/mechanisms or gaps in methodologies hindering data & understanding gaps to be filled. Consideration of gaps commonly described as unknown unknowns were outside the scope of these previous reports. All reports were also primarily focussed on knowledge gaps emerging from considering the impact of RA **within the farm gate**.
- To propose research strategies that would most effectively meet RA research needs, promote a 'more connected, adaptive and resilient' research and practice culture, and serve New Zealanders – in the context of 2021 and beyond.

In addition, a comprehensive appendix section provides information about the theories underpinning some of these research strategies.

[1] https://ukcop26.org/the-conference/cop26-outcomes/;

[2] https://www.unep.org/news-and-stories/story/cop26-ends-agreement-falls-short-climate-action; https://www.theguardian.com/world/commentisfree/2021/nov/20/yes-cop26-could-have-gone-further-but-it-still-brought-us-closer-to-a-15c-world

[3] https://www.mbie.govt.nz/dmsdocument/17637-future-pathways-green-paper

3 Summary from other reports

This section brings together key findings presented in previous reports published as part of the ‘RA Think Piece’ project – from here on these reports will be referred to as ‘topic reports’. These topic reports were written by small groups of experts (including no more than 10 experts per group), who were tasked with identifying key knowledge gaps about RA in their particular field of expertise, along with the methodologies to close these gaps.

Two additional topic reports are still being finalised. They will address the knowledge gaps, metrics, and methodologies to assess the impact of RA on the health and quality of NZ’s freshwater, and on the well-being and mindset of farmers/growers. The main knowledge gaps and methodologies discussed in these additional topic reports have also been taken into account in the preparation of this present report.

Each topic report drew on the expertise of a small groups of scientists and technical experts often operating within the realm of a single scientific discipline. As such, taken together, these reports were organised based on a reductionist view of agroecosystems. Here, an attempt is made to bring together the conclusions from each of these reports and build propositions for more holistic research frameworks.

3.1 Summary of Knowledge gaps identified in other reports

Table 1 lists the knowledge gaps identified in the topic reports as part of the RA think-piece project. Each knowledge gap is marked against the aspects of RA to which it is relevant (among the aspects investigated in this project). The readers are asked to note that other aspects of RA, not examined as part of the RA Think Piece project, might need to be considered to fully appraise the impact RA might have on New Zealand. For example, aspects pertaining to mātauranga Māori, structure of the supply and value chain, transfer of knowledge and practices across disciplines including farming, barriers to adoption and relationship to policies were not in scope and have not been examined as part of this project (see Grelet et al. 2021a, 2021b, Grelet & Lang 2021; Letica 2021).

Knowledge gaps fall into three categories:

- Fundamental knowledge gaps: these correspond to gaps that will require an investigation of the effects/impacts of RA as well as the deciphering of processes and mechanism by which effects/impacts are mediated.
- Knowledge gaps about magnitude/direction of effect(s): some of the knowledge gaps can be closed by solely quantifying the magnitude of the effect/impact of RA management and its direction (increase/ decrease)
- Tools: many of these topic reports have identified technological gaps, which need to be solved to subsequently or more comprehensively close the other types of knowledge gaps. These reports have focused on technological gaps that also hinder adequate decision making on-farm (i.e. technological developments required to primarily to advance any particular field of research have not been examined/listed in these reports).

Table 1. Key knowledge gaps by scientific discipline – summarised from other reports published as part of this project

Knowledge type	Scale(*)	Knowledge gap (**)	Aspect of RA *('y' indicates where there are knowledge gaps)*: *Productivity*	*Food nutrient density & quality*	*Animal welfare*	*Freshwater health*	*Soil health*	*Economics*	*Biodiversity*	*Greenhouse gas emissions*	*Resilience to extreme weather events*	*Adaptation to climate change*	*Wellbeing/Mindset/ Culture*
Fundamental	*Multiple*	Role of RA in the resilience to drought and flood at field, farm, and landscape scales[7]	y			y	y	y			y	y	
		Relationship between RA in NZ and Māori food sovereignty[8,9]	y	y		y		y	Y			y	y
		Relationship between RA in NZ and Māori sovereignty for kaitiakitanga[8,9]	y			y		y	Y			y	y
		Impact of RA on the well-being of Farming communities[13]									y	y	y
	Country	Impact of RA on the true cost of food / fibre production[2]		y	y	y	y	y	y	y	y	y	
		RA-mediated Nature's contribution to adaptation services (latent/sustained/novel)[6]	y			y	y	y	y	Y	y	y	
		Impact of blockchain technologies on access to markets / premium[2]						y					
		Role of labels / certification schemes on access to markets / premium[2,9,3]						y			(y)	(y)	
		Role of RA in defending existing value / market share[2]						y			(y)	(y)	
		Role of RA in generating a premium price[2,3]						y			(y)	(y)	
		Role of RA in generating new intangible commercial advantages[2]						y					
		RA-mediated understanding of human-centric and eco-centric adaptation services[6]									y	y	
		Impact of RA on the well-being of 4ers/growers[13]									y	y	y
		RA adopters / innovators archetypes[13]									y	y	y
		Health-relevant impact of RA on the human microbiome[5]		y					y				y

Knowledge type	Scale(*)	Knowledge gap (**)	Productivity	Food nutrient density & quality	Animal welfare	Freshwater health	Soil health	Economics	Biodiversity	Greenhouse gas emissions	Resilience to extreme weather events	Adaptation to climate change	Wellbeing/Mindset/ Culture
			Aspect of RA *('y' indicates where there are knowledge gaps)*										
Fundamental, cont.	*Region*	Role of RA for pest control[11][3]	y		y			Y	y		y	y	
		Role of RA on habitat connectivity for NZ native species (establishment of nodes / corridors)[11][12]							y			y	
		Impact of bio-stimulants and bio-amendments on fertilisers and herbicides efficiency[10]	y				y	y					
		Impact of RA on the linkages between soil nutrient retention and indicators of freshwater health[14]				y					y		
		Impact of RA animal management on freshwater health[4]			y	y							
		Impact of adverse climate events on the productivity of RA farming systems[9][3]	y					y		y	y	y	
		Link between mineral balance and resistance/resilience to pest/disease[10]	y				y	y					
		Role of RA on weed naturalisation[3][12][9]							y				
		Seed contamination / weed risks to neighbouring production systems from increased pasture and crop diversity[9][3]	y						y				
	Farm	Impact of RA on methane emission from grazed ecosystems[1]			y		y	y		y		y	
		Feed conversion efficiency under RA management in pastoral farming[3]	y		y			y					
		Grazing principles applicable to highly diverse pasture swards[3][4]	y		y								
		Impact of increased plant diversity on crop / pasture quality[3][5]	y	y	y				y	y			
		Impact of RA grazing management on animal wellbeing[4]	y		y								
		Potential of RA to increase monetary gains from Environmental credits[2]						y	y				
		Role of RA for 'green financing' of farms[2]						y			(y)	(y)	

Knowledge type	**Scale(*)**	**Knowledge gap (**)**	*Productivity*	*Food nutrient density & quality*	*Animal welfare*	*Freshwater health*	*Soil health*	*Economics*	*Biodiversity*	*Greenhouse gas emissions*	*Resilience to extreme weather events*	*Adaptation to climate change*	*Wellbeing/Mindset/ Culture*
			Aspect of RA *('y' indicates where there are knowledge gaps)*										
Fundamental, cont.	*Farm, cont.*	RA potential to improve soil water cycle(10)(7)(14)	y			y	y	y		y	y	y	
		Link between soil water cycle & aeration and plant minerals / vitamins concentrations(10)(5)	y	y		y	y			y		y	
		Impact of RA on soil biological activity and diversity(10)(12)					y		y	y	y		
		Potential of RA to increase soil organic matter/carbon concentration(10)	y				y	Y		y	y		
		Ability of RA management to maintain N and P with less synthetic fertiliser(10)	y			y	y	y					
Magnitude / direction of effect	*Farm*	Impact of mixing ages and livestock types on the production of young/low social order animals(3)	y		y			y	y				
		Impact of RA grazing management on pasture performance and persistence(3)	y		y			y	y				
		Impact of RA on animal disease(4)	y		y			y					
		Impact of RA on animal welfare in wintering Livestock(4)	y		y			y					
		Impact of RA on recovery from stressors post-calving/lambing(4)	y		y			y					
		Impact of RA on soil carbon sequestration(1)				y	y	y		y		y	
		Impact of RA on farm's compliance costs & regulatory taxes(2)						y					
		Impact of RA on farm's profitable use of resources(2)						y					
		Impact of RA management on soil structure(10)(7)				y	y			y	y	y	
		Impact of bio-stimulants and bio-amendments on production(10)	y				y	y		y			
		Impact of RA farm management on product quality and quantity(3)(5)	y					y					
		Impact of RA soil health management on pasture/crop quality (protein content, nutrient density, mineral balance, harmful minerals)(3)(5)	y	y	y	y				y			
		Impact of RA soil health management on pasture/crop production (quantity)(3)(5)	y	y			y	y		y			

Knowledge type	Scale(*)	Knowledge gap (**)	Aspect of RA ('y' indicates where there are knowledge gaps)										
			Productivity	Food nutrient density & quality	Animal welfare	Freshwater health	Soil health	Economics	Biodiversity	Greenhouse gas emissions	Resilience to extreme weather events	Adaptation to climate change	Wellbeing/Mindset/ Culture
Tool	Multiple	Magnitude of errors in measurement & data processing for sensor data[14]			y	y	y		Y	y	y	y	
		Technology and measurement devises for collecting high frequency of dynamic animal data[4]			y			y					
		Biodiversity monitoring schemes at relevant spatial and temporal scale[12][11]							y			y	
		eDNA-based monitoring of terrestrial biodiversity[12][11]							y			y	
		Rapid diagnostic methods for monitoring invertebrate bioindicators of ecosystem response to management / environmental change[11]							y		y	y	
	Country	National disease surveillance and treatment programmes[4]			y			y	Y				
		App to assess farmers' mindset/wellbeing for many farmers[13]									y	y	y
		Calibration for key biological indicators for soil health[10]				(y)	y		y	(y)	y		
		NZ-specific calibration for non-standard soil tests used by RA practitioners[10]				(y)	y				(y)		
		NZ-specific commercial availability for non-standard soil/sap tests used by RA practitioners[10]				(y)	y				(y)		
	Farm	Economic Metrics to quantify trade-offs between farm's profitability and environmental impacts[2][3]	y			y		y	y	y	y	y	
		Economic Metrics to quantify impact of RA management over farm's long-term profitability[2]	y					y					
		Brix as a potential proxy of plant- based food quality[5]		y									
		Chlorophyll as a possible indicator of plant health[5]		y									
		Tools to determine production and quality of highly diverse pastures[3][4][2]	y					y	y		y		

[*] The scale at which each knowledge gap is relevant

[**] **Numbers in superscript indicates which topic report described the knowledge gap; 'y' in the table indicate all the aspects of RA to which this knowledge gap is relevant.**

[1]Davidson et al. 2021; [2]Grelet et al. 2021c; [3]Schon et al. 2021a; [4]Gregorini et al. 2021; [5]Lister 2021; [6]Lavorel & Grelet 2021; [7]Donovan et al. 2021; [8]Letica 2021; [9]Grelet et al. 2021d; [10]Schon et al. 2021b; [11]Davidson et al. 2021; [12]Norton 2021; [13]Burns et al. (in prep.); [14]Conland et al. (in prep.).

3.2 Summary of methodological considerations discussed in other reports

This section summarises the methodological considerations discussed in the topic reports. These considerations and their relevance to investigating different aspects of RA examined are listed in Table 2. Collectively, different methodological considerations were discussed in the topic reports, with some considerations diving deep in detailed experimental designs whereas other considerations remained at very high level (research methods or type of research partnership), and this was unevenly discussed in the different topic reports. In addition, each topic report was constrained in scope to a single aspect of RA – determined by the type of outcomes sought to be quantified or understood. Should the experts have been tasked to examine suitable methodological approaches to address multiple aspects of RA simultaneously, the range of methodologies they discussed would have likely been broader. For this reason, Table 2 lists all methodological considerations discussed in these reports regardless of the aspect of RA they sought to address (unlike Table 1).

The methodological considerations are separated in three categories:

- The type of research methods considered: this is related to the type of investigation considered, including the format/structure of the object investigated, and the level of intervention on this object that has to be exerted by the research team as part of the investigation. For example, field/plot trials focus on a small proportion of the farm, and large-scale monitoring might investigate multiple farms across the country or entire sub-catchments outside of farmed areas (format/structure of the object). Similarly, field/plot trials require intervention/manipulation by the research team, whereas large-scale monitoring does not. Large-scale monitoring can be seen as a type of natural experiment. The differences between these types of research approaches are further explained in Appendices I–V.
- The type of experimental design considered addresses issues of spatial scale and temporal scale, as well as the level of intervention by the research team.
- The type of partnership considered to assemble the research team: this category of methodological consideration considers the level of co-innovation recommended to investigate different aspects of RA. This is further explained in the following section in this report, as well as in Appendix V.

Experimental designs relevant across all aspects of RA include treatment and system comparisons at various scales (herd, plot, farm, sub-catchment). These experimental designs are typically deployed as part of agricultural studies. Other types of experimental designs considered relevant are designs common in ecological and social studies. These include chronosequences where a set of sites (farms/fields/plots) are compared because they share similar attributes but differ in time since adaption of RA management. This design implement a theoretical substitution of space for time – see Appendix II). Also included are multi-year assessments across gradients/categories (longitudinal and cross-sectional studies). These experimental design, anchored in ecology and sociology, are relevant when the effect observed is known to require a long time to be detectable, cannot easily be mimicked via controlled experimentation, and/or when as broad a range of variation in conditions is needed to be captured to understand whether the effect observed is context-specific or universal (i.e. only occurring in a restricted set of conditions or occurring widely across multiple sets of conditions (e.g. multiple soil type, climate, population segments, social and cultural values of specific groups, influence of wider context, power dynamics, etc.).

To address most research gaps, multiple research methods will need to be combined, for example combining surveys, interviews, and the use of case studies (taken in its broad definition, i.e. including farmlet studies, commercial farms, etc.). Depending on the research gap being addressed and the context within which it is being addressed, some methods, for example interviews and case-studies, can support a Kaupapa Māori framework better than others.

There needs to be a common thread that weaves across these methodologies and tests the validity of knowledge in space and time. On the one hand, some of the research methods require 'control' and characterisation of the influencing factors that make them applicable to a narrow band of quantified parameters. On the other hand, modelling – and especially complex system modelling – is identified as a research method that could potentially weave all aspects of RA together. Modelling, of which scenario analysis is a part, is a vital research method to travel in time and space and address various long-term issues such as those pertaining to behaviour change, evolutionary trajectories, and resilience/adaptation to climate change.

Finally, all topic reports considered partnership and co-innovation with RA practitioners as relevant and, most often, critical. Depending on the knowledge gap examined, the extent to which the research ought to be co-designed or driven by researchers but implemented in collaboration with farmers/growers, varies.

Table 2. Summary of methodologies considered in the 'topic reports' examining particular aspects of RA

Type of methodology considered	Methodology
Research methods	Long-term experimental research / demonstration farms
	Short/medium/long-term case-studies (e.g., commercial farms, sub-catchments)
	Paddock / plot studies
	Lab-based experiments
	Modelling & scenario analyses
	Large-scale 'monitoring' (proximal & remote-sensing, in situ/in person assessments)
	Qualitative methods (e.g. interviews, focus groups, workshops)
	Surveys
	Literature & websites reviews / analyses
Partnership type	Co-design and co-implementation of research projects with RA practitioners
	Farmer-led/community research (which includes citizen science)
	Academic-driven research
	Research by proxy/collaboration (which includes citizen science)
Experimental design	Trials to test cause-effect hypotheses (lab/field-based)
	Comparison against benchmark data
	One-off or repeated assessment across gradients / segments / categories (e.g. longitudinal & cross-sectional studies and large surveys)
	Treatment comparisons at various scale (herd, plot, farm, sub-catchment)
	Pairwise comparisons (i.e. chronosequences, substituting space for time)
	Modelling studies (experimental designs may vary)

4 Specifics of RA research

4.1 Defining the purpose of RA research

The RA movement is now backed by global food corporates[4] and by an increasing number of global companies seeking to purchase carbon credits for their offsetting requirements[5] – none of which are waiting for absolute proof that RA can deliver on its claims. RA is also an innovation movement driven by farmers – with 'brands following, and consumers lagging behind' (Beef+Lamb NZ & NZ Winegrowers 2021). The role scientific institutions might play in this innovation is questionable at present (Cumming 2020).

So RA research currently can have multiple purposes:

1 Documenting and quantifying outcomes from RA, to test whether claimed benefits are true or false (RA research purpose #1 – claims testing)

2 Understanding the processes and mechanisms underpinning observed outcomes, if those conflict with our current understanding of the behaviour of agroecosystems and agricultural landscapes (RA research purpose #2 – processes and mechanisms)

3 Bringing more innovation into RA to support / optimise its adaptation to NZ and its adaptation to future environmental and trade conditions (RA research purpose #3 – optimising RA), thereby researching RA as one of the possible solutions to future-proofing NZ agriculture.

The 'RA think piece' project was primarily funded to highlight research pathways addressing the first purpose (claims testing). However, RA is already backed by many global companies (before having robust evidence of claimed benefits). Furthermore, there is increasingly intense and complex pressure placed on NZ agriculture to evolve or even transform (e.g. changes in regulations, social licence to farm, global trade trends, frequency, and intensity of adverse climatic events). Hence RA research should also contribute to meeting at least the third purpose, and strategically, the second purpose. The subsequent sections of this report provide a time-sensitive, high-level analysis of the specificities of RA (with focus on NZ) to subsequently propose possible research strategies that meet not only the first but also the second and third research purposes.

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[4] https://www.nestle.co.nz/csv/regeneration/regenerative-agriculture; https://www.edie.net/news/5/McCain-commits-to-regenerative-agriculture-across-all-farms-by-2030/; https://www.generalmills.com/en/Responsibility/Sustainability/Regenerative-agriculture

[5] https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/111921-totalenergies-to-generate-australian-carbon-credits-from-soil-carbon-sequestration; https://www.greenbiz.com/article/how-carbon-smart-farming-catalyzing-big-bucks-needed-transform-way-america-eats

4.2 RA as a continuum – implication for RA research

4.3 Testing RA claims – purpose #1

4.3.1 Testing RA claims where? And for how long?

Farms are agroecosystems that, by nature, are complex adaptive systems (CAS; Holland 2006; Levin et al. 2013). Each farm is unique, characterised by a unique set of social, cultural, economic, and biophysical attributes, including some highly changeable in space and time. Farms might share an exact same sub-set of attributes, but the sum total of each farm's attributes is unique. RA management is likely to re-enforce this 'uniqueness' because RA is more adaptive than many other managements commonly deployed as part of mainstream agriculture, particularly in sectors where the farming system has been simplified (lower diversity) and/or relies heavily on optimisation of inputs, to enable efficiency of scale at all levels of the supply and value chain. RA management also proactively seeks to deliver positive environmental outcomes (a step beyond avoiding negative environmental outcomes), i.e. RA management includes some elements of restoration ecology (Graham & Bartel 2017; Lacannes & Lundgren 2018; Case et al. 2020; Newton et al. 2021) that will be specific to the farm's context. With the uniqueness of each farm comes variability between farms – and, for the reason given above, this variability is likely to be even greater under RA management.

Furthermore, as discussed extensively by Grelet et al. (2021b) and Merfield (2021) (and many references therein), RA is not defined solely by practices, but also by principles (Lang 2021) and mindset (Seymour 2021). Hence testing RA claims should primarily be carried out on commercial RA farms, to account for the complex and adaptive nature of the management, including practices, principles, and mindset. The study will also need to include multiple farms to account for between-farm variability. Complementary insight can be gathered from trials undertaken in experimental research farms, in collaboration with experienced RA practitioners to mimic RA management as closely as possible – or to test effects of particular sets of RA practices and/or principles, acknowledging that the results obtained might not be representative of full system transition to RA management and are unlikely to unravel impact created from adopting a 'RA mindset'.

Ideally, studies would include, among others, farms that have been successfully transitioned to RA for many years, to be able to detect any impact that RA might have on farm outcomes that are slow to change (e.g. soil carbon stocks; Schipper et al. 2017). Hence studies focussed on testing RA claims would target farm systems and landscapes that have been under RA management for as long as possible, compared when relevant to farm systems that operate under current best practice (depending on the research gap investigated). Other options include sets of farms representing a chronosequence of transition to RA (see Appendix II), or newly transitioned farms/landscapes studied over multiple years.

However, one key point of consideration in selecting study sites is that 'there is no hard and fast distinction between mainstream and RA systems and practices. There is instead a continuum of practices with significant overlap between mainstream and RA, with some RA-specific practices and some practices commonly employed in current farming systems being inconsistent with RA principles' (Grelet et al. 2021b). This continuum and absence of clear boundaries between RA and current farming management makes selection criteria for study sites challenging. Fenster et al. (2021a, 2021b), when assessing the impact of RA on financial and environmental outcomes in almond orchards, have opted for a scoring system based on a combination of principles and practices. Almond orchards were classified as 'regenerative' or 'conventional' based on an aggregated score quantifying the 'stacking' of multiple regenerative practices/principles into a single operation. The study found that the more regenerative practices/principles were adopted and implemented as part of the overall farm system management, the greater the performance. A similar scoring system could be developed and adapted to NZ farming systems.

Cross-sectional and/or longitudinal studies would enable the testing of RA claims across a range of biophysical contexts among farms displaying a similar aggregated score (adapted from Fenster et al. 2021), or across farms displaying a range of aggregated score but occurring on similar biophysical contexts. These types of studies can examine the relationship between key sought-after outcomes and a range of management simultaneously, including RA management, or a gradient of managements along the RA-mainstream continuum. In doing so, linkages between different sets of principles/practices and on-farm outcomes can be tested and the range of principles/practices yielded the most desirable outcomes be identified. This type of approach would require a large N-number of study sites, but could be implement in partnership with regional councils, catchment groups – collaborating with entities that are connected with or connect together large network of landowners, including industry levy bodies, catchment groups, NZ institutes of technologies and polytechnics, agricultural consultants, extension practitioners and agricultural consultants.

Modelling would here be essential to build theoretical trajectories (in time and/or space) of the farms outcomes being investigated, using datasets acquired from study sites to parameterise the models.

4.3.2 Examining the concepts of 'scientific evidence'

Testing RA claims means acquiring scientific evidence for or against the validity of these claims. It means acquiring data on the behaviour of RA agroecosystems. The concept of 'science' and 'evidence' must here be scrutinised carefully. RA farmers have their own perspectives on what constitutes 'evidence' and what can be taken as valid 'data' to make informed decision on-farm. Consequently, recognising the position of RA farmers as co-investigators in research about farming practices and impacts revives old arguments. In the late 20th century, postmodernists were investigating the social construction of systems, including knowledge systems and science. Proponents of science described the way in which scientific knowledge is produced and verified as a demonstration of its unique status outside social, political or cultural forces. Knowledge could be divided into 'scientific knowledge', which can be supported with evidence and verified or falsified, and all other knowledge. The debate over the status of scientific knowledge has origins in unresolved philosophical discussions about the nature of knowledge as well as causation. It is an echo of earlier debates from the period of the Enlightenment, as well as ancient Greek philosophy. Thus, arguments over what constitutes knowledge or evidence about RA are linked with fundamental arguments about epistemology. The approach in this work has been intentionally broad, recognising the practitioner origins of much of RA and both its practices & principles, and the bicultural context for science in Aotearoa New Zealand.

To further explain the significance of these unresolved debates about the nature of knowledge and causation, Figure 1 schematises the proposed feedback loop between prior belief/worldview and how data (or evidence) are translated into knowledge – to then inform decision making, and worldview upgrade. The diagram emphasizes what happens on farm, but could equally be applicable to other systems. The diagram shows how data (or evidence) are interpreted within a pre-existing worldview, sets of principles, and sets of values. These, in turn, will be influenced by the specific context and will influence the decision-making process. The combination of all these factors will result in certain practices that then lead to context-specific outcomes. These outcomes will be assessed (qualitatively or quantitatively), and the data (or evidence) gained from this assessment will be interpreted and translated into 'new' knowledge. The observations (data collected), and the interpretation and translation of data into knowledge will be influenced by what questions one chooses to ask, and what worldview frames one's thinking. A Bayesian feedback loop[6] is then created, whereby 'new' information and resulting knowledge is used to update one's worldview (similar to incorporation of expert knowledge in causal probabilistic models such as Bayesian networks; Constantinou et al. 2016). However, the level/extent and likelihood of the updating depends on the strength of pre-existing data, worldview, and values. This Bayesian feed-back loop applies to all worldviews, whether based on culture (e.g. indigenous worldview), profession (farmers/researchers/retailers), or scientific disciplines in which different researchers most often operate.

A common refrain when a non-orthodox approach to agriculture is being adopted by farmers is to ask, Where is the scientific evidence? (e.g. Hickford 2020, and other articles therein). This call for further 'scientific evidence' expressed by many scientists, and the dismissal of farmers' observations and farm performance results (anecdotal data) are symptomatic of the hierarchy of evidence institutionalised in the western agricultural, education & health systems.[7] This hierarchy of evidence also has the perverse effect of relegating traditional and indigenous knowledge to the position of lowest quality, leading to it being most commonly excluded from science-based policies (Milbank et al. 2021) despite its increasing recognition as valuable evidence by high profile Intergovernmental Science-Policy Platforms, e.g. Intergovernmental Panels on Biodiversity and Ecosystem Services (IPBES) & Climate Change (IPCC) (Pörtner et al. 2021).

> "It is the belief in objectivity and universality that enables Western scientists to hold their own knowledge system above others, often in a non-critical way".[8]

This is a systemic issue that needs to be at least acknowledged, if not addressed, by all NZ scientists, if Te Tiriti o Waitangi is to be successfully and genuinely embedded across NZ

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[6] https://towardsdatascience.com/a-step-by-step-guide-in-designing-knowledge-driven-models-using-bayesian-theorem-7433f6fd64be

[7] https://www.cebm.ox.ac.uk/resources/levels-of-evidence/oxford-centre-for-evidence-based-medicine-levels-of-evidence-march-2009

[8] http://www.maramatanga.co.nz/sites/default/files/CB_TePutahitanga_A4_2021_inner_Digital_final.pdf

research, science, and innovation (RSI) systems, as promoted by MBIE in its recent green paper.[9] It is reasonable to propose that, for this exact reason, NZ can show international leadership in building the evidence for RA systems by drawing on multiple knowledge systems, including quantitative and qualitative sciences, a whole-of-systems perspective from RA practitioners, and, in the appropriate time and context, Te Ao Māori.

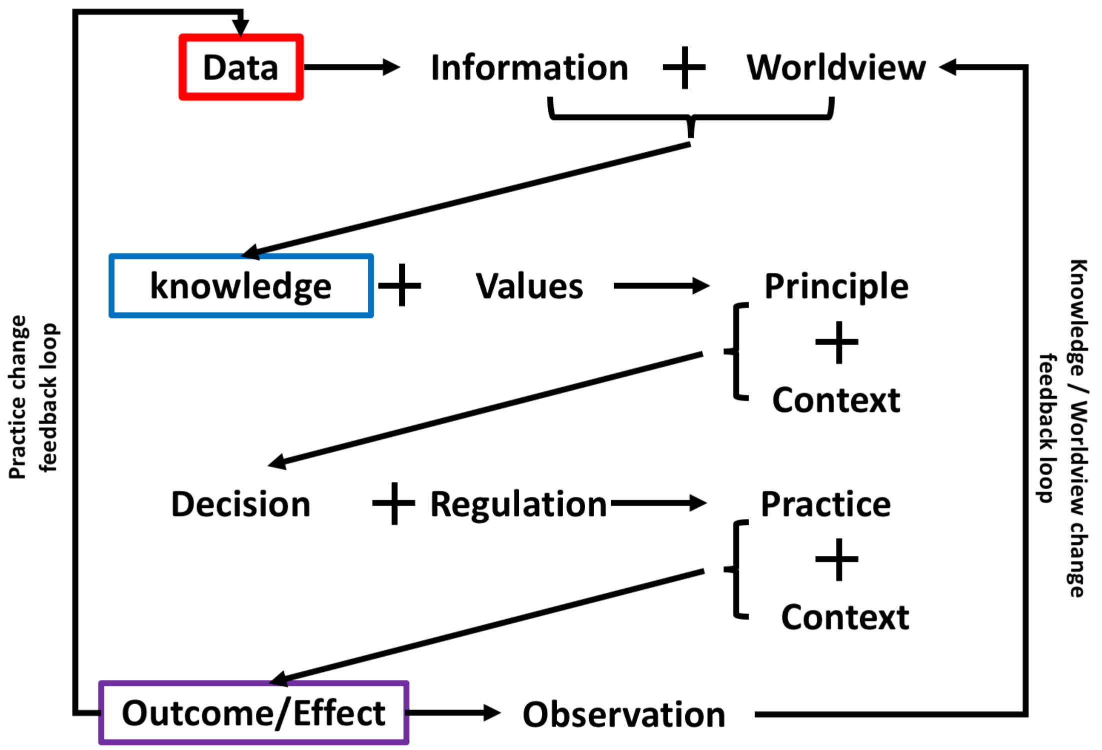

Figure 1. Proposed schematic of the feedback loop between data, information, knowledge/worldview, decision-making and practice/action.

The possible gains from adopting a much more inclusive definition of 'scientific evidence' are apparent in Table 1, which highlights knowledge gaps pertaining with insufficient calibration of metrics used by RA practitioners in the NZ context, due to their usage being driven either by the replacement of other more standard metrics (e.g. particular soil tests) or by the need to have access to a simple, fast, and low-cost on-farm tool to monitor pasture and crop 'health' (e.g. visual assessments). It is also apparent in Table 2, where farmer-led/community research & research by proxy/collaboration is proposed as one of the recommended types of research partnership, which would include farmers' observations in scientific datasets, and include RA practitioners as scientific thinkers at every phase of research. This type of research partnership builds on transdisciplinary research and the growing field of citizen science.

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[9] https://www.mbie.govt.nz/dmsdocument/17637-future-pathways-green-paper

4.3.3 Farmers as non-professional scientists

Citizen science (CS) is growing rapidly across the world. While there is no generally accepted definition (Heigl et al. 2019), citizen scientists can range from members of the public with no scientific experience at all who may join in activities such as a BioBlitz[10] or annual garden bird surveys, through to amateur (as in non-professional, not unskilled) scientists who may have very considerable expertise but are not paid for work they undertake (Gura 2013). The benefits of citizen science are two-fold: first, advancing research by improving the scientific community's capacity, and second, increasing the public's understanding of, and engagement with, science (Hand 2010).

Within agriculture, farmers and growers could be viewed as citizen scientists. However, unlike citizen scientists from the general public, who have no or limited scientific expertise, farmers and growers are, by definition, are experts in farming and growing. Particularly in NZ, many have a degree-level education in agriculture and many years, or even decades, of practical experience. They therefore have a science-based education in agriculture and continue to receive and use science-based information throughout their careers. In addition, they gain many tens of thousands of hours of practical experience, and often become astute observers of their farm systems and changes that occur when management practices or other influences change, such as the climate (Nuthall 2016). Farmers and growers therefore accumulate vast amounts of both observational and experiential knowledge about farming. Furthermore, their financial wealth, their livelihood, and their well-being depend on the decisions they make based on their interpretation of the observations they make. The view expressed by Hickford (2020) and others in the same volume undervalues farmers' and growers' ability to observe, experiment, and deduce knowledge from their management of farmland.

This is not to say that farmers observations can always be considered infallible. Like other data (or evidence), those observations are interpreted within the context of the farmer's pre-existing worldview and associated pre-existing body of evidence (including prior experimental observations, see Fig. 1). Moreover, when these observations are reported in isolation as 'anecdotal data', by nature these observations are not recorded in a standardize manner. Hence comparability between 'anecdotal data' across time, space and individuals is often challenging. In recent years, the use of citizen science in ecological and agricultural research has become more prevalent (Mourad et al. 2020, Dickinson et al. 2010), further supported by advances in digital technologies, crowdsourcing methodologies, and citizen science theories (van de Gevel & van Etten 2020; Graham & Smith 2021). Digital technologies, social media and crowdsourcing enable scaling, such that (i) data capture can be made more cheaply and in a standardized manner allowing comparability and (ii) the number of citizen participants can increase to large N-numbers. This yield large datasets to which the 'Wisdom of the Crowds' principle (Surowiecki 2005) can be applied. This principle asserts that a large group of independent participants with diverse worldviews can yield highly accurate aggregated results, even if the accuracy of each individual observation is low. A study used modelling of empirical data to test the accuracy of farmer-generated data using digital technologies and a crowd-sourcing approach, for tricot-style trials (i.e. trials to

[10] wikipedia.org/wiki/BioBlitz

assess various aspects of varietal performance in cropping systems). The study found that N-numbers <200 would be sufficient to produce meaningful results for this type of data (Steinke et al. 2017). This approach could also be used to monitor on-farm environmental data – these data would meet the need of researchers and provide unvaluable data assets to landowners/farmers. By acquiring such datasets, landowners/managers can test the potential of their farm to secure or access environmental credits, or assist in footprinting.

RA research, at its heart, must embrace the systemic change to NZ's science and agricultural systems, that are being called for. This cannot be done without bringing together the current evidence from farmer experience, scientific understanding and mātauranga Māori understanding, which can learn from each other to develop new insights and breakthroughs in ways that each audience finds credible. The methodologies and technologies to do so are becoming more accessible. It is this production of credible, relevant, and legitimate knowledge (after Cash et al. 2003), produced in a way that engages, connects, and respects the multiple worldviews held by farmers, practitioners, industry, tangata whenua, iwi, government, and scientists across Aotearoa New Zealand, that will be key to understanding the impact of RA on NZ's landscapes.

4.4 Processes and mechanisms – purpose #2

The investigation of processes and mechanisms that pertain to basic or fundamental research, can be seen, on the surface, as being of interest only to researchers/scientists within academia. In whatever way fundamental research is critical for medium- to long-term knowledge and technology gains (Petit 2004), in the short term, fundamental research is also critical to develop or parameterise models, and for appraising the transferability of observations from one specific context to another (e.g. different soil types, climate, innovation adoption archetypes, etc.), all of which are key to meet purpose #3.

The investigation of processes and mechanisms underpins the deciphering of cause–effect relationships: what practice/intervention will cause which effect, to which extent, and under which circumstances? And for which reason?

This type of research tests causal hypotheses and is at the core of academia. Relevant study designs and methods almost always involve a degree of manipulation by the researchers, to control for confounding factors and identify the source of the effect observed. Typically field, plot, glass-house trials, and any lab-based experiment are used to test causal hypotheses and decipher mechanisms / processes (see Appendices VI and VII).

4.5 Lessons from overseas from RA research to meet purposes #1 and #2

Research into Livestock-based RA has already delivered results for overseas scientists (LaCanne & Lundgren 2018; Teague & Kreuter 2020). Importantly, these overseas researchers have highlighted the tension between the desire to design research experiments that control meticulously for certain variables and the desire to adapt in real time to the needs of the living systems that constitute one's farm and one's primary business. When this tension is resolved entirely in favour of the scientific preference, optimal results are not achieved (Briske et al. 2008; Teague et al. 2013; Teague 2015). For example, experienced RA practitioners, such as US ranchers implementing adaptive multi-paddock (AMP) grazing, have extremely valuable insight into their systems and may realise, mid-experiment, that a variable must change to allow for optimal outcomes. Experiments need to be designed to accommodate this sort of agile response, or there is a risk of prioritising knowledge that is irrelevant to the real world.

This highlights the need to conduct some baselining research on real farms, in partnership with the farmers, rather than research stations, so that all the nuances of how farming is actually undertaken, including unplanned changes that are required to respond to or mitigate unforeseen or non-predictable problems, are included (Teague & Kreuter 2020). Selecting which farmers and farms to work with therefore becomes a critical part of the research. It is considered vital to consider farmers' performance in the selection criteria. Depending on the number of farms included in the study, and on the focus of the study, it might be advisable to select top performers (e.g. when the study aims to quantify the maximum rate of carbon accrual in soil due to holistic management) or a range of farmers representative of a range of performance (e.g. when studying transition pathways, leviers, and barriers to adoption). However, hobby or lifestyle farmers should be excluded from studies for most questions asked, because the scale at which they farm and the constraints they are under for decision-making as part of the farm management are not representative of the majority of farmers contributing a particular ag sector.

For example, because the Agricultural Research Group on Sustainability (ARGOS) project[11] comparing organic, low-input, and intensive farming systems in NZ contained a larger number of lifestyle and retiring farmers in the organic dairy farm group who had much lower performance than the best organic dairy farmers, project results were widely questioned (Jon Manhire, pers. comm.). Defining and identifying the 'best' farmers therefore becomes a key issue, and has the potential to be subjective and therefore biased. One approach could be to use financial performance, but that may not be aligned with the best regenerative practices (i.e. the farming approach could still be exploitative). An approach by Teague used soil surveys to identify those ranches with the highest soil carbon levels as a proxy for overall soil health and which had also achieved superior economic outcomes (Richard Teague, pers. comm.).

Having identified farmers, as discussed in the section 'Farmers as non-professional scientists', the farmers should be partners in designing the experiments, including the treatments and interventions to ensure they are both relevant to real-world farming and are valid ways of improving or modifying the farm system (Teague & Kreuter 2020).

It is also critical to select farms that have been under regenerative management for at least 5 years, ideally more, so that the farm system has had sufficient time to change from the previous management system (Teague & Kreuter 2020). As part of this, it is also important that farm management practices be consistent with clearly defined criteria for determining which sets of practices are taken to be associated with RA management, and which set are

[11] www.argos.org.nz

taken to be associated with other, contrasted managements. Given there is no universal definition of RA, these criteria have to be chosen and clearly stated for each study.

Adequate training in systems research among agricultural researchers is also an issue, as systems research methods and design are very different from the typical randomised control trials that most agricultural scientists have been trained in and commonly use (Van Der Ploeg et al. 2006).

In summary, the kind of research recommended by US researchers in livestock-based RA is also transdisciplinary and draws on multiple knowledge systems:

> conducting research with innovative land managers on real operations, applying adaptive treatments, and combining detailed field experimentation with embedded, small scale, reductionist experiments in the context of the management options being studied, and simulation modelling approaches. (Teague & Kreuter 2020)

4.6 Optimising RA – purpose #3

4.6.1 Understanding innovation processes and structures within RA

RA can be seen as a movement of complex, interweaved agricultural, environmental, and social innovation. Within NZ agri-food system, there are processes and structures already either driving or hindering RA innovation – which will act as barriers or levers of change for further innovation/optimisation/adaptation of RA to NZ. These processes and structures are complex, cross-sectoral, occur at multiple scales and are evolving through time. In NZ, Australia, North America and parts of Europe, the source of innovation within RA seems strongly embedded in grassroot farming communities (Montgomery 2017; Brown 2018; Masters 2019) and the dominant diffusion and adoption pathways also appear largely contained within farming communities, driven by farmers, and with little involvement from academia or other corporate agricultural research providers.[12] When/if RA becomes more widely implemented, sources of innovation as well as diffusion & adoption pathways will likely change. In fact, concerns are already expressed about the potential for 'greenwashing' and the shift from grass-root driven adoption to adoption driven by pressure exerted from processors and various actors along the value chain.[13]

A more systematic assessment of innovation processes and structures within RA is essential to support further innovation/adaptation, and could also promote bidirectional transfer of innovation between RA and other farming approaches. The Agricultural Innovation Systems (AIS) framework has been used for such type of systematic assessment. For example, using AIS thinking, deep-seated structural issues in NZ research institutions were identified, that negatively affect agricultural innovation because of (i) competitive science in silos, (ii) laissez

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[12] https://understandingag.com; https://www.quorumsense.org.nz; https://regenerationcanada.org/

[13] https://www.nationalobserver.com/2021/06/18/news/food-giants-regenerative-farming-eco-friendly-fancy-greenwashing; https://modernfarmer.com/2021/07/what-is-greenwashing/; https://sustainablefoodnews.com/the-greenwashing-of-regenerative-agriculture/

faire innovation, and (iii) science-centred innovation (Turner et al. 2016, 2017). Noteworthy is the fact that these issues where highlighted again in the MBIE 2021 green paper.[14] However, where the source of innovation is separate from public or private research professionals, and when alternative forms of agriculture compete with the dominant industrial agriculture paradigm or with each other, AIS thinking might be unable to account for competing normative directions in the innovation – diffusion – adoption pathways (e.g. (Douthwaithe & Hoffecker 2017; Pigford et al. 2018). Hence AIS thinking might not fully cater for the systematic assessment of innovation in alternative agricultural systems such as agroecology, regenerative agriculture, and others, that do not operate within the realm of industrial agriculture (Pigford et al. 2018). Instead, alternative frameworks, evolved from AIS, are currently being explored, such as Innovation Ecosystem Thinking (IES, Pigford et al. 2018) (which places greater emphasis on environmental outcomes than AIS) and mission-oriented agricultural innovation systems (MAIS, Klerkx & Begemann 2020) (which allows reflection on directionality of innovation and on ex-novation). The concept of mission-orientated innovation is also being applied at policy level (Mazzucato 2018), to tackle complex challenges related to sustainability by promoting investment-led sustainable growth. These frameworks might be more relevant for a systematic assessment of RA innovation, because they can better account for drivers of innovation emerging at multiple levels (grassroot/corporate, farm/brands, localised/international, institutional/social & green entrepreneurial, conventional/green finance, food & fibre value chains/environmental credits).

Another point of consideration is that the interest in RA is not restricted to food &fibre production, and extends to RA being considered as a strategy for landscape restoration/management. Other frameworks might be used to further understand interactions between the various actors involved in the RA innovation pathways, and nature itself. Included in these frameworks are Coupled Human and Nature Systems (Ferraro et al. 2019) and Socio-ecological systems (Levin et al. 2012).

4.6.2 Empowering further innovation within RA or via RA

Working with complex, systemic problems requires different approaches to research (Duncan et al. 2018). Such problems are challenging for many researchers because the research is not always structured by the knowledge gap to be filled, but by the task of solving real-world problems (Fernandez 2016). Research that acknowledges an intent to create change (Mitchell et al. 2015) requires researchers to shift from being producers of knowledge to being active contributors to a social process of tackling real-world problems (Pohl & Hirsch Hadorn 2008). Furthermore, complex systemic problems, such as food systems or climate change, are not neutral objects of inquiry (Popa et al. 2015), and the values of the individuals, institutions, and industry partners involved influence how such topics are researched (see Fig. 1).

Transdisciplinary research (TDR) is a research approach aiming 'at the solution or transition of societal problems' while addressing related scientific problems (Lang et al. 2012; Polk

[14] https://www.mbie.govt.nz/dmsdocument/17637-future-pathways-green-paper

2014). TDR braids together multiple knowledge streams (Lang et al. 2012), including indigenous/local knowledge, multiple scientific disciplines, collaborative adaptive management, and recent forms of citizen science (Knapp et al. 2019). TDR is systems focused, embeds integration and learning, relies on adaptation, and builds implementation pathways into the research itself (Newig et al. 2007; Pohl & Hirsch Hadorn 2008; Jahn et al. 2012; Bammer 2013; Polk 2014; van Kerkhoff 2014; Mitchell et al. 2015; Bennich et al. 2020).

A variety of transdisciplinary research and innovation structures have emerged in the last 15 years, including Knowledge and Innovation Communities (KICs) of the European Union,[15] Living labs (Mulvenna et al. 2010; Reay et al. 2019; Leminen et al. 2020; Massey University 2021a, 2021b; and Real-World Labs). Knowledge and Innovation Communities create 'a favourable environment for creative thought and innovation to flourish, allowing innovative products and services to be developed in every area imaginable, new companies to be started or accelerated; and a new generation of entrepreneurs to be trained'.[16] The KICs are thriving to meet some of the research & innovation needs of the European Green Deal.[17] Living labs are open innovation networks, which are growing in popularity, are dynamic in their creation, expansion, termination, and recurrence, allowing a timely response to stakeholders' needs. They are characterised by their level of openness and transparency within the living lab network. Many Living labs deploy some version of citizen science. Real-world laboratories (RwLs) are newer than Living labs, and have been created as incubators of societal innovation within solution-oriented sustainability research (Bergmann et al. 2021). RwLs are deeply anchored in transdisciplinary research structures. After few years of experimentation using RwLs for social change and sustainability innovation, the efficacy of 14 RwLs were examined (Bergmann et al. 2021). Successful RwLs (1) find the right balance between scientific and societal aims, (2) address the practitioners needs and restrictions, (3) make use of the experimentation concept, (4) actively communicate, (5) develop a 'collaboration culture', (6) are attached to concrete sites, (7) create lasting impact and transferability, (8) plan for sufficient time and financial means, (9) have high adaptability, (10) embrace research-based learning, and (11) recognize dependency on external actors. Schneidewind et al. (2018) further emphasized the importance of RwLs' structural properties, including (i) explicit interpretative schemes, (ii) legitimatory rules, and (iii) allocative and (iv) authoritative resources. We note (i) and (ii) are related to concepts schematized in Figure 1. RwLs can be set up as intended long-lasting structures that foster innovation and social change. We posit that the structures of both living Labs and RwLs could effectively power up innovation research and social change relevant not only to RA, but also to the enhancement of nature-based contributions both to climate change adaptation and to changing markets requirements.

[15] https://www.eitfood.eu/

[16] https://eit.europa.eu/what-are-eit-knowledge-and-innovation-communities-kics

[17] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

5 Proposed Research strategies relevant to RA in NZ

Section 3 summarised knowledge gaps identified by multiple groups of experts. They were asked to restrict their thinking to what happens within the farmgate whenever possible. Knowledge gaps in aspects of RA such as RA influence on biodiversity, freshwater health, access to markets, or farmers' well-being extend well outside the farmgate. The examination of these research gaps collectively highlighted that the purpose of RA research was threefold: 1) testing its claimed benefits, 2) deciphering processes and mechanisms (i.e. understanding how RA works), and 3) optimising RA for NZ context now and in the future. Section 3 also highlighted that a breadth of methodological approaches, drawn from agricultural, ecological, and social research, would be required to fill these research gaps.

Section 4 highlighted the need to undertake research inclusively with multiple knowledge systems and segments of society, which requires broadening the definition of what constitutes 'data'. Section 4 also highlighted the need to examine existing processes and structures that are enabling or hindering innovation within RA, when seeking to further promote innovation within or via RA.

Taking all the above into consideration, this section describes, at high level, a proposed research strategy for testing RA claims about resilience, deciphering mechanisms and processes that would underpin increased resilience, and using this body of knowledge and the transformative power of RA to increase the resilience of NZ farming systems and agricultural landscapes now and for future climate and trade conditions. This proposed strategy is based on two plausible assumptions:

- NZ farming systems will increasingly be challenged with extreme climatic events
- Access to export markets will require quantitative and/or qualitative proof of the magnitude and direction of impact of food & fibre production on the environment and society.

This proposed research strategy is schematised in Figure 2. The strategy deploys a combination of research methods and study designs. It is organised in multiple interconnected research steps increasing in complexity with time and as new knowledge is gained. First, the impacts of RA, relevant to resilience, are quantified. A range of RA adoption (RA 'score') is embedded in the study designs. Second, trials are used to test causality. Third, Real World Labs, set up at the start of the programme, ramp up their activities based on data acquired in step 1 and 2. RwLs objectives are: (i) examine barriers and levers of innovation relevant to RA and its adoption, and (ii) optimise RA practices & principles for increased resilience at farm and landscape scale. Various modelling methodologies are used to interpret, predict, and test transferability of observations with space and time. Research is co-designed and co-implemented with landowners/managers – who are also partners in the RwLs. Blockchain technology to upscale and accelerate Data Flow (transfer between groups/projects, across scale and time) is explored as part of the research objectives, and so is multidomain footprinting at both farm and landscape scale. Agile start-up companies, as well as government-funded entities (e.g. research councils) are integral parts of the research teams so as to build and foster connection with value chains and regulatory bodies.

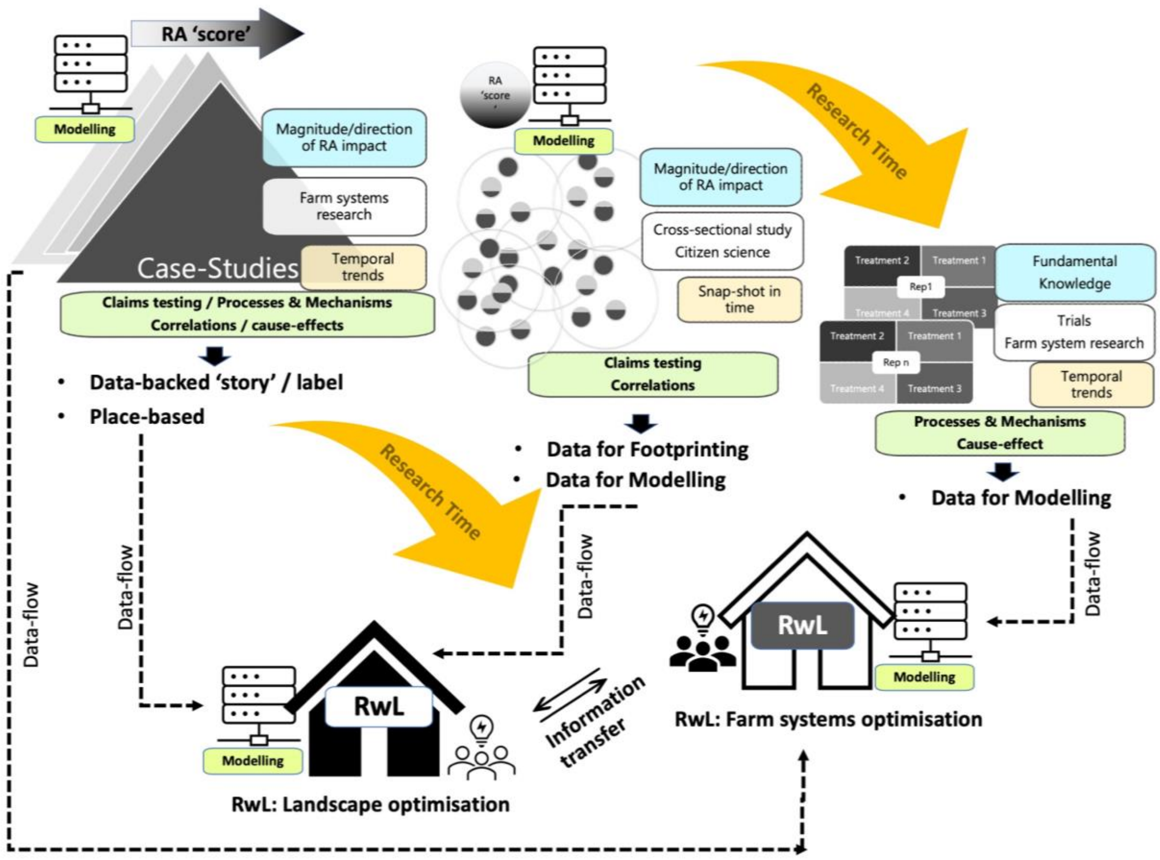

Figure 2. Proposed multi-year multiscale research strategy to optimise landscape for *resilience* via RA.

6 Acknowledgements

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[18] https://ourlandandwater.nz/incentives-for-change/regenerative-agriculture-regen-ag/

7 Glossary

Acronym	Meaning
AIS	Agricultural Innovation Systems
MAIS	Mission-oriented Agricultural Innovation Systems
IES	Innovation Ecosystem Thinking
CHNS	Coupled Human and Nature Systems
SES	Socio-Ecological Systems
CAS	Complex Adaptive Systems
RwLs	Real World Laboratories
KICs	Knowledge and Innovation Communities (EU)
MBIE	Ministry of Business Innovation and Employment
RA	Regenerative Agriculture
NZ	New Zealand

Appendix I: Natural experiments versus intervention research

Gwen-Aëlle Grelet (Manaaki Whenua – Landcare Research)

Natural experiments are used to study living systems without intervention, such that the systems are neither controlled nor manipulated by researchers. The only control exercised by the researcher(s) is solely through site or patient selection (Diamond 1983). They are considered experiments because a population can be divided into exposed and unexposed groups, allowing for comparison (Craig et al. 2012). This type of experimental approach is becoming more prominent in many fields of science dealing with living organisms or living systems, when complexity is an inherent part of the system studied, when manipulations are unethical or unaffordable (e.g. in community ecology to understand species abundances and distributions; Diamond 1983), in public health matters (Crane et al. 2020), or to assess the impact of policies on society (Craig et al. 2017). However, compared with randomised controlled trails, there are a considerable number of pitfalls both in 'designing' the experiment and particularly in the statistical analysis that, unless effectively addressed, render the results suspect, or worse, completely invalid (Sekhon & Titiunik 2012; Craig et al. 2017).

Within agriculture there are different natural experimental designs. Pairwise comparisons are based on two groups that are as similar as possible except for the practice of interest (e.g. regenerative farmers and non-regenerative farmers); whereas long-term farm monitoring uses repeated measurements over time, often called chronological measurements or chronosequences (Walker et al. 2010), which are often used before and after a change of management system (see Appendix II). The two approaches are also hybridised in a range of ways (e.g. pairs of farms are selected, with some undergoing a change of management system).

Longitudinal/cross-sectional studies are also a type of natural experiments, such as, for example, the ongoing NZ soil carbon monitoring program.[19]

[19] https://www.nzagrc.org.nz/domestic/soil-carbon-research-programme/monitoring-soil-carbon/

Appendix II: Pairwise comparisons and chronosequences

Charles Merfield (BHU), Gwen- Aëlle Grelet (Manaaki Whenua – Landcare Research)

Pairwise comparisons compare two similar but contrasting farm management systems (e.g. organic vs non-organic farms) (Shadbolt et al. 2009), inversion tillage vs no-till (Olson et al. 2014), or irrigated vs unirrigated pastures (Schipper et al. 2019). Occasionally more than two management systems are compared (e.g. organic, low-input, and intensive), but the complexity of the analysis increases considerably with additional farm types. The farms are paired to be as similar as possible, to reduce confounding factors (e.g. soil type, topography, climate, size, etc.), except for the different management systems (Charnet & Beaver 1988). This often means they are neighbouring farms or a close distance to each other.

Typically, the comparisons are made at a single point in time. The paired sites are chosen to share similar attributes, e.g. same soil type, land use, topography. This is equivalent to characterising a 'chronosequence', whereby space is substituted for time (Sparling et al. 2014; Mudge et al. 2017). For example, with this approach, soil carbon stocks are quantified at adjacent sites (generally on commercial farms) that have been under different land uses or management regimes for multiple years (usually more than 5 years). The average difference in carbon stocks between the different treatments is assumed to be due to differences in management, and rates of divergence between treatments can be calculated if the time since management changed is known. However, measurements can be repeated (Olesen et al. 2016), which is where the pairwise approach blends into long-term on-farm monitoring. The trade-off between a single time-point and multiple time-points (long-term monitoring) is that, with the single time-points, a (much) larger sample of farms is required to achieve sufficient statistical power (Charnet & Beaver 1988). This is the key trade-off between pairwise comparisons and long-term, on-farm monitoring of contrasting farm systems: number of farms vs duration. More farms are required for a single or a few sample dates, while fewer farms are needed where they are monitored over longer durations. The result is that the number of data points for each system required to achieve sufficient statistical power is often similar.

While pairwise comparisons are at a point in time, the selected farms need to have been consistently running their respective systems for sufficient duration that the new systems have caused enough changes to be detectable, or better, to be representative of what those farm systems can achieve (Charnet & Beaver 1988). Many biophysical aspects of farms can change quite slowly (e.g. biodiversity or soil health; Kibblewhite et al. 2008), depending on what is being measured farms need to have been running the management system for at least 5 years, with around 10 years being preferable. However, for management systems that produce a quick change (e.g. the effect of changing from twice to once-a-day milking on farm profit), 1 year may be sufficient. The number of years the farms have been running their current systems can also be used in the analysis to bring a temporal dimension where only a single measurement in time or a few time-point measurements are made.

Measurements in pairwise comparisons can look at quite focused areas (e.g. soil biology or farm profit), or measure multiple aspects of the farm system (Greer et al. 2008; Magbanua et al. 2010). The latter clearly requires considerably more resources, but with enough farms in the comparisons internal linkages can be elucidated (e.g. tillage intensity with soil health).

Pairwise comparisons are suited to researching both specific parts of the farm system and the farm system as a whole. When used for whole-system study, they are inherently trans-/multi-/interdisciplinary.

Pairwise comparisons are of particular value for studying RA, because of the urgency with which the climate and other environmental emergencies (e.g. biodiversity loss) need to be addressed. There is not the luxury of the decadal time-spans required for long-term monitoring, and there are already hundreds of farmers in Aotearoa New Zealand who have been practising RA for sufficient periods of time to allow rigorous comparisons with equivalent non-RA systems.

Appendix III: Long-term monitoring

Charles Merfield (BHU)

Long-term monitoring is a common research method used in ecological science: repeated chronological measurements (Havstad & Herrick 2003; Likens & Lindenmayer 2018). It can also be applied to individual farms, or more typically to a number of sufficiently similar farms (e.g. dairy farms, or arable farms), which are monitored over a period of time of at least 1 year (i.e. a full annual farming cycle), or more commonly multiple years (e.g. 5–10; Bhullar & Riar 2020). This may be done with no changes being made to the farm systems, or, more commonly, when a significant, system-level change is made (e.g. conversion to organic agriculture), with several years under the original farming system and then several years under the new farming system (Bhullar & Riar 2020). This can be expanded such that some farms remain unchanged, and others undergo the system change, so the difference between the two sets of farms can be compared in parallel. This approach is similar to the pairwise comparison at a point in time approach, and indeed the greatest analytical power is gained when long-term on-farm monitoring is undertaken with multiple paired farms. Long-term, on-farm monitoring is a whole-of-farm/system approach and is inherently trans-/multi-/interdisciplinary, as typically many aspects of the farm will be measured at the same time (e.g. soils, crop and livestock yields, through financial performance) and can include sociological aspects such as farmer and farm family health and well-being (Brew et al. 2016).

Beyond the selection of the farms, the researchers typically do not control any further aspects of the systems, rather, the farmers or growers continue to farm as if no research was occurring. This means that long-term on-farm monitoring captures the full complexity and messiness of real-world farming, which has the benefit of capturing what really happens on real farms, but the resulting data are inherently highly variable, and strong inferences cannot be made linking management/farming actions and on-farm outcomes (Thierfelder et al. 2015). Therefore, only correlations can be made, but these are strengthened by the number of farms participating. Long-term, on-farm monitoring is therefore well suited to tracking the changes that happen as farmers or growers convert from their current systems into regenerative systems. A minimum of 3 years pre-conversion data is required to give a reasonable baseline measurement, but 5 years would be superior, considering the often-large, year-to-year climatic variation found in Aotearoa New Zealand. A minimum of 5 years is required to monitor the effects of conversion, but, as many biophysical systems, particularly soil parameters (e.g. soil organic matter), can take many decades to reach a new equilibriums after a significant management system change, 10 years is considered a better timeline.

Appendix IV: Longitudinal/cross-sectional studies

Gwen-Aëlle Grelet (Manaaki Whenua – Landcare Research), Charles Merfield (BHU)

Cross-sectional studies is an observational research approach that collects data on from the study population or sub-population (e.g. farms, animals, plants, people) at a specific point in time. They are typically undertaken to estimate the prevalence of the outcome of interest for a given population, e.g. how many farmers are using diverse species cover crops (Kesmodel 2018). They are commonly used in medical, social and economic research. Typically, the approach is often descriptive, e.g. a survey. Cross-sectional studies can also be repeated over time on a different subset of study objects representative of the same population, and are considered pseudolongitudinal studies (Levin 2006).

In comparison, true longitudinal studies involves repeated observations of the same variables (e.g. people, farms, soil health) over short or long periods of time on the same representative of the study population or sub-population (same animals, same fields, same farms, etc.). They seek to establish correlations between variables so do not necessarily collect information on intervention/practice (Whelan & Savva 2013). Longitudinal study design is commonly deployed in farm system research to monitor a set of farms. The design could also be applied to track through time consumer food choices of a group of millennials in NZ compared with a group of similarly sized millennials in Europe.

Data for both study designs are usually aggregated prior to interpreting patterns. In both types of studies, associations of interest can be established, but not causal relationships (Levin 2006; Cataldo et al. 2019). Hence these types of study design can test relational hypotheses but not causal hypotheses.

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Appendix V: Farm-system research

Ina Pinxterhuis (DairyNZ), Robyn Dynes (AgResearch), Racheal Bryant (Lincoln University)

Background

Farm systems research combines a range of approaches to investigate and develop systems and management, and is well suited for questions asked about RA. This section summarises what farm systems research is and how it can be implemented.

An introduction to farm systems research

Farm systems can be defined as 'decision-making units comprising farm household, cropping and livestock systems that transform land, capital, and labour into products for consumption and sale' (Fresco & Westphal 1988). Fresco and Westphal (1988) provide a useful diagram (Fig. 3) that shows where farm systems sit in the hierarchy of agriculture. However, in research we often must prioritise one level.

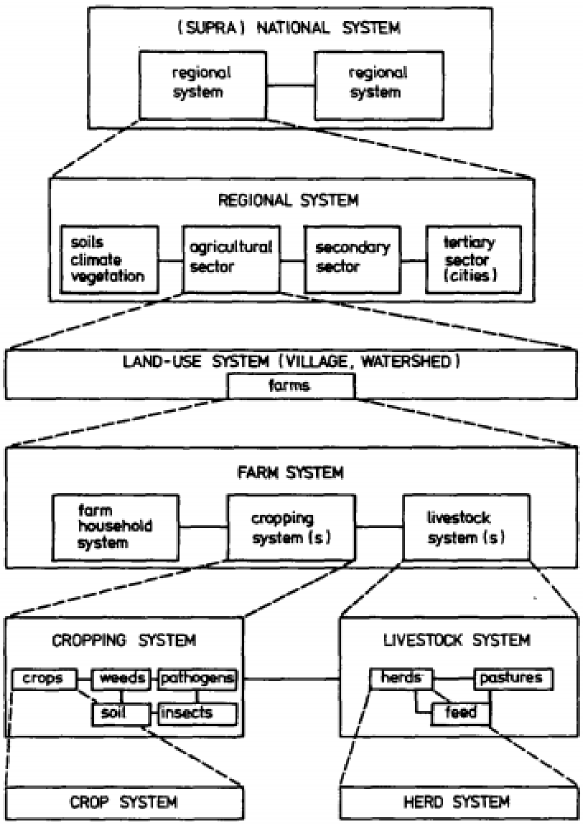

Figure 3. Position of the 'farm system' in the system hierarchy of agriculture (source: Fresco & Westphal 1988).

Farm systems research and development is therefore rooted in systems thinking, aiming to understand the contributions of the sub-systems individually and together, with their complex interactions and emergent properties, and involves the impact the higher-level systems have on the farm system. This makes farm systems research by definition interdisciplinary and holistic (Darnhofer et al. 2012; Stevens et al. 2016).

The term 'farm system' concerns a farm unit; the term 'farming system' is used where it involves more farms of similar land use, a sector, usually in a particular region (FAO 1997). However, 'farm system research' and 'farming system research' are often used interchangeably. Here, we use 'farm system research', limiting the research to the farm unit, with its biophysical, economic, and social aspects, determined and influenced by the subsystems within the farm and the higher-level systems the farm is part of (**Error! Reference source not found.**).

Characteristics of farm systems research

The context of the farm business is integral to farm systems research: its multiple stakeholders and their values and goals (which can be conflicting) and the presence of uncontrolled and confounding circumstances that affect outcomes and the ability to be sustained (e.g. the biophysical context, weather, and market conditions). This means the research needs to have sufficient spatial scale and duration to be relevant to a farm business (Barlow et al. 2002), and also needs to be participatory/transdisciplinary (i.e. involving the stakeholders; Darnhofer et al. 2012).

These characteristics make farm systems research distinctly different from component research, and this must be addressed in the design and management of farm systems research programmes Because of the ever-changing context and complex interactions, flexibility is key in farm systems research (Darnhofer et al. 2012), and reflexivity is needed to ensure connectedness and adaptability, with conscious choices for programme and project design, activities, and interventions.

Components of farm systems research

The management of farm systems research requires clear reporting lines and responsibility, a project team, and a steering group (or industry advisory group), plus a communication and extension plan. Also, structures may be deployed to facilitate the active participation of stakeholders in the project management, or sector representatives and farmers may be members of the project team.

Farm systems research is often a combination of study methods so that sub-questions can be appropriately addressed (e.g. at different spatial scales, such as paddock, farm, landscape, community), and at the appropriate time within a programme of work so that results can be combined and evaluated in a meaningful way to inform the next steps. Examples of study methods are:

- modelling
- targeted component research
- systems experiments
- on-farm experimentation
- partner farms
- case-studies

- survey and scientific data analysis
- system design
- social research
- economic research and evaluation
- demonstration
- adoptability assessment
- impact evaluation studies.

Study methods, their benefits and limitations, and published examples:

Table 3 provides the benefits, limitations, and short descriptions of examples of these methods.

Table 3. Farm system research study methods, their benefits and limitations, and published examples

Method	Benefits	Limitations	Examples
Modelling	• A large variety of models exist, so can tackle many different questions • Scenarios can be explored and compared • Boundaries can be examined • Data from modelling can be used to inform power analysis • Low cost • Generates scenarios, which can be used to engage the wider community in discussion	• Currently unknown factors are not in the models (e.g. complexity in multi-species swards and their interaction with grazing rules). • Emergent properties and unintended consequences may not be identified.	• Using computer models to combine component research results to develop and evaluate future dairy farm scenarios (Pastoral 21 – Beukes et al. 2011) • Life cycle analysis to assess the environmental effects of cross-sectoral systems (Van Selm et al. 2021).
Targeted component research	• Better understanding of mechanisms • Controlled environment	• Results can be different on farm, with interaction between variables.	• Field trials to understand effect of defoliation strategies on pasture yield (Lestienne et al. 2011)
Systems experiments (farmlet trials)	• Able to assess if system, or new technologies, can be transferred and sustained in practice • Emergent properties identified Unintended consequences evident	• Limited number of comparisons possible • High financial investment and running cost	• Farmlet trials to investigate a range of novel practices on sheep, beef and dairy systems (Clark 2013) • Pastoral 21 farmlets to implement and compare outcomes of earlier modelled dairy farm system scenarios that reduce nitrate leaching (Chapman et al. 2020)

Method	Benefits	Limitations	Examples
On-farm experimentation	• Scale and regional distribution • Centred in rural community – more opportunity for learning and improving adoption	• Limited treatment comparisons • Less control of environment and management • Access for management • Risks from farming practices compromising management • Data loss	• A white clover introduction trial on a hill country station to determine effects on yield and quality (Dodd et al. 2020)
Partner farms, co-development	• Improved practicality of new practices • Improved acceptance of practice and results – if you can still see the effects at farm scale, you are onto something	• Limited capacity to influence management • No control	• Farmers participating in a research programme to provide feedback on practicality and to test practices on farm (Pinxterhuis & Edwards 2018)
Case studies	• Large number can be undertaken • Relevant for individual farmers	• Unable to control management/'treatments' • Difficult to generalise results, which are context-specific	• Implementation of Lotus on a hill country farm (Stevens et al. 2020)
Survey & scientific data analysis	• Large data sets for better understanding of variability • Meta-analysis possible to extract core principles	• Cause and effect difficult to identify	• Determining the extent of fodder beet use on dairy farms and how farmers use it (Edwards et al. 2020
System design	• Can combine range of needs if conducted as participatory design • Improved understanding of future scenarios to examine further (e.g. through modelling)	• Can be highly theoretical, with limited implementation	• Co-design of future dairy farm systems that deliver on wide range of stakeholder needs (Romera et al. 2020)
Social research	• Acknowledges the influence of the human factor • Improved understanding of the human factor	• Results may be highly context specific. • Context and results can be isolated from economic impacts.	• Using interviews to understand farmers' motivations to voluntarily implement practices with lower environmental impact (Knook et al. 2020) • Facilitating and evaluating experiential learning to reduce disease in crop (Tafesse et al. 2020)

Method	Benefits	Limitations	Examples
Economic research & evaluation	• Able to scale up from field and farm to region and country • Able to assess impact of range of prices/costs	• Context and results are often isolated from social impacts • Results may not consider all the environmental impacts	• Economic evaluation of the implementation of plantain at national scale (Doole et al. 2021)
Demonstration	• Sufficient scale to be plausible	• Lack of control • No clear determination of cause and effect	• Implementation of the Pastoral 21 low-input system at scale. The P21 farmlet results gave the LUDF management board confidence to implement the low-input system, and they adjusted it to their needs (Pellow 2017)
Adoptability assessment	• Provides a reality check for likely uptake • Can inform investment decisions	• Difficult for adoption models to span a wide range of community cultures	• *A priori* and *ex ante* evaluation of adoption of new practices (Pannell et al. 2006)
Impact evaluation studies	• Can be used to feed back into adoption assessment	• Temporal scale means it can be a long time into systems research before answers are attained	• Evaluating farm system impacts of different dairy cow wintering systems using farm data (Pinxterhuis et al. 2016) • Using computer models to assess trade-offs between economics, production, and environmental impact of dairy farm systems (Doole & Romera 2015)

An example of a farm systems research programme

Farm systems research is used to co-design future farm systems and/or test practices that deliver optimal social, economic, and environmental services. For the purpose of this example we obtained a range of RA-related research questions collected during this project (Gwen Grelet, pers. comm.).

We selected one question to provide an example of what a logical framework for the planning and development of a farm systems research programme might look like (see Table 4). This is obviously a simplified version and may make farm systems research look easy. In reality, a farm systems research programme needs to facilitate on-going exchange between the stakeholders/end-users and researchers, and amongst researchers, and be agile to respond to emerging results and questions. This requires ongoing monitoring of the processes in the projects ('reflexive monitoring', Rijswijk et al. 2015). New Zealand examples of how this was implemented and responded to are given in Casey et al. (2015) and Pinxterhuis et al. (2018).

To start with, a logic framework would be developed by the project team and stakeholders/end-users to: (1) clearly identify the underlying questions and assumptions; (2) develop a common objective for the research; (3) agree on outcomes and outputs; and (4) identify the various activities that will answer the questions and deliver the outcomes and outputs. This will include activities at farmlet or farm scale to verify if causes and effects of different input and practices as found in other types of experiments still hold and which other effects on aspects of the farm system emerge.

We also do not pretend that the example is a complete research package for the question posed. However, it illustrates how many of the methods listed in Table 3 are relevant and can be used to good effect when combined. Also, a specific question can lead to additional questions and activities, e.g. to evaluate further effects of the system in question, to support the co-development of practices for optimal implementation and to improve the adoption of these on farm.

> *Example question: "What is the impact of diverse perennial pasture mixes combined with regenerative grazing practices on water capture, retention and use efficiency and potential for lowering or eliminating irrigation needs?"*

Table 4. An example of a simplified logical framework for a farm systems research programme

Objective	Output	Activity (type of activity)
To evaluate the impact of diverse perennial pasture mixes combined with regenerative grazing practices on water capture, retention and use efficiency and potential for lowering or eliminating irrigation needs	Matrix of pasture plant species and suitability to the range of environmental conditions across NZ	Develop representative soil x aspect x slope x climate cohorts for pastoral systems in NZ (GIS mapping)
		Define desired characteristics of pasture production, e.g. yield, feed value, water use, ground cover, soil organic matter (workshop with end-users; literature review)
		List pasture plant species relevant to NZ's current climate conditions and anticipated conditions in the next 50 years due to climate change (literature review; survey)
		Develop outcome matrix of pasture species x environmental cohorts (modelling with mechanistic models)
		Develop online pasture species selection tool (adoptability assessment, co-development)
	Definition of regenerative grazing practices	Identify grazing practices in use by farmers who identify themselves as regenerative; identify expected/desired system outcomes (broader than water use efficiency) (workshops with farmers and rural professionals)
		Monitor pasture management, pasture composition and resulting outcomes on selected farms across NZ (case studies; on-farm experimentation; economic evaluation; farm system modelling)
		Agree on selected grazing practices for further investigation (workshop; survey)
	Report on environmental and economic impact of regenerative grazing practices of diverse perennial pastures compared with standard perennial ryegrass/white clover pasture	Assess interactions between grazing management, irrigation/soil moisture and pasture composition on key pasture characteristics and outcomes (field experiments; economic evaluation)
		Co-develop management x pasture composition options 'that work' (field experiments; co-development)
		Assess farm system implications of selected irrigation and grazing management x pasture composition (farm system modelling; farmlet trials)
	Successful implementation and management of diverse perennial pastures on X farms	Support on-going interactions between stakeholders and project team to tap into participants' knowledge (on-farm experience, local knowledge, formal scientific knowledge) and for monitoring and evaluation of progress to enable rapid variations to the project's activities for maximum outcome (project management; stakeholder management; reflexive monitoring and evaluation; communication and extension)
		Develop guidelines for regenerative pasture management for selected regions (adoptability assessment; co-development)
		Support and demonstrate good practice (on-farm experimentation; demonstration farm; partner farms)

Appendix VI: Field plot and on-farm trials, including long-term trials

Charles Merfield (BHU)

> *"Excellent agricultural science only happens in the field"*
> Prof. Derrick Moot, Lincoln University, pers. comm.

Field plot trials have been a mainstay of agricultural science since its inception (Russell 1966). They have many advantages, but the two key advantages are that from a scientific and statistical perspective they are methodologically 'robust' and 'complete', in that each treatment/variable is fully and independently controlled, randomised, and replicated, so strong causality (e.g. rather than correlation) can be established. Also, because they are undertaken 'in the field' (as opposed to a glasshouse pot experiment, for example), they are generally a reasonable approximation of 'real-world' farming and therefore the results can be directly applicable to comparable commercial production systems (Clewer & Scarisbrick 2013).

As the name implies, they are implemented by dividing an area of land (field) into 'plots', which receive different treatments. Plots vary in size from a square metre to hundreds or even thousands of square metres, to match the spatial effects of treatments, land availability, equipment, use of animals, etc. Typically, one to three factors (treatment type, e.g. crop cultivar, fertiliser rate and pesticide type) can be tested in one trial, because, depending on the number of variables for each factor (e.g. number of crop cultivars, different fertiliser rates), the number of individual plots becomes so many that the trial becomes impractical/unmanageable.

Small plot trials at experimental research stations, on-farm trials, and long-term trials all nearly always use the same randomised, replicated field plot experimental design (i.e. they are variations on the same theme) (Clewer & Scarisbrick 2013). The key differences are the scale: tens of square-metre plots on research stations, hundreds of square metres on-farm, and for long-term trials the difference is the duration – a long-term trial is a minimum of 5 years, although 10 years is more realistic, and multiple decades often provide the most valuable data. Even century-long trials exist, such as the Rothamsted (2006) long-term experiments that have been running since 1844[20] (Moss et al. 2004). The value of long-term trials is that agriculture is an ecological system, and many ecological systems (for example, and especially soil ecosystems) respond very slowly to changes in management practices, taking decades to reach a new equilibrium, so long-term study is required to elucidate such slow effects (Havstad & Herrick 2003; Likens & Lindenmayer 2018).

The difference between small-scale/research station trials and on-farm trials is primarily related to issues of practicality and post-experimental 'extension' (i.e. informing farmers and growers of the outcome of the research and getting them to implement the results in their own farming systems). Typically, a research centre field plot trial will have many more

[20] www.rothamsted.ac.uk/long-term-experiments

variables per factor and more factors than farm trials (e.g. over 100 plots on station but 10 plots on farm). Station plots are therefore smaller due to the number of plots, but also due to the equipment used (e.g. hand sprayers vs tractor sprayer).

Research station trials often take a large number of measurements, often repeatedly, which may require complex, expensive equipment, with the aim of achieving a deeper understanding of the mechanisms at work, while farm trials typically measure only a small number of key metrics (e.g. yield, disease levels, weed populations), which can be undertaken using existing equipment (e.g. yield monitors in headers/combine harvesters, using visual assessments, or quadrat samples). Research station trials, therefore, yield considerably more and richer data but at significantly greater expense. On-farm trials typically produce (very) limited data, but they are the key parameters farmers and growers want to know to determine the main farm outcomes of yield, costs, and profit; and, if well designed, they will require little extra work/cost for the producer beyond what was required were the trial not taking place. The cost:benefit ratio is therefore often quite similar for each.

In the spirit of Prof. Moot's argument that 'excellent agricultural science only happens in the field', unless the output of agricultural science is taken up and implemented by farmers and growers, then that science has been a waste of resources. Many decades of the science of agricultural extension have shown that farmers and growers are significantly more likely to take up and implement science when it is undertaken on a real farm, under real farming conditions, rather than at a research station, university, etc. Therefore, the most important benefit of on-farm trials is often that the rate of uptake and implementation by farmers is much greater than for research centre trials. Often it is worth repeating successful research centre trials on-farm, just for the extension outcomes.

While there are many advantages for randomised and replicated field plot trials, they also have multiple limitations. At the agronomic level, the key limitation is that only a few factors and treatment variables can be tested at one time, and for each factor having more than about five variables often becomes unwieldy and impractical. However, in real-world agriculture, farmers and growers are often manipulating many tens – even hundreds – of factors at a time, and are subjected to many uncontrolled variables, such as the weather. Farmers and growers can still be sceptical of the applicability of such tightly constrained experiments to their inherently unconstrained farming systems.

Field plot trials are a textbook example of reductionist science, as in the vein of physics: the system is taken apart, its simplest components are analysed, and, on the basis that the whole is the sum of the parts, the functioning of the whole is assumed from the parts. Unlike in physics, however, complex systems such as agriculture and ecology are rarely the sum of their parts; for example, there are often major internal interactions, such as symbiosis, and the number of parts are so great, that the whole is much greater than the sum of the parts. Field plot trials are therefore incapable of studying whole farming systems, or even systems with more than 10 variables.

Therefore, within RA, the best role of field plot trials – whether on-farm, at a research station, short or long-term – is considered to answer specific and straightforward agronomic questions/hypotheses, such as:

- Does mixing humic acid with foliar nitrogen fertiliser increase nitrogen use efficiency (NUE) / allow me to apply less nitrogen?
- Does biological pesticide X control fungal disease Y on crop Z?
- Will a half rate of glyphosate still kill weeds X, Y, and Z, effectively?

Field plot trials, especially long-term trials, can be, and are, used to answer broader and more complex questions; for example, what is the impact on soil organic matter (soil carbon) and soil structure, of no-till, min-till, and full-tillage. However, because the treatments are no longer a single simple component (not fully reductionist), and cause and effect are separated by often long and interacting chains, the strong inference/clear causal linkages of fully reductionist plot trials are considerably weakened. This means the generalisation of the results can be questioned (e.g. using the tillage example above, the results may be different on a sandy soil cv. a silt or clay soil). This is the point where field-plot trials reach their limit, and alternatives such as pairwise comparative studies of real farms, and long-term on-farm monitoring (ecological longitudinal studies) start to provide more valuable results.

Field plot trials are scale limited. While there are field plot trials that cover many tens of hectares of land, it is the individual plot size, and the need for physical separation with its neighbouring plots to prevent treatments in next-door plots interfering with each other, that means that only small-scale effects can be studied. For example, control of a pest or disease through a microbiological pesticide that is sprayed onto the crop is highly amenable to field plot study, but not the control of an insect pest by conservation biological control, through provision of floral resources around a field margin (i.e. field and landscape-scale effects are not amenable to field plot trials). Field plot trials clearly only study agronomic factors: they cannot study the wider farm system (i.e. sociology).

In conclusion, field plot trials, whether on a research station, on-farm, short-term or long-term, have a clear role in addressing specific and tightly defined questions/hypotheses within and about RA.

Appendix VII: Controlled-environment research methodologies

Charles Merfield (BHU)

Controlled-environment research is where various aspects of the environment (e.g. temperature, light, soil, atmospheric gasses) are manipulated and/or controlled. These vary considerably, from laboratory bench-based experiments, microcosms, and controlled environment rooms, where the entire environment is artificially controlled; through protected structures such as glasshouses for plants where temperature and water may be controlled, but not light and humidity, mesocosms and sheds/barns for containing animals; to outside areas with limited control (e.g. plants grown in pots or in lysimeters). The types of research conducted are even more varied than the environments (e.g. from completely artificial, such as culturing microorganisms in Petri dishes, to plants growing in field-like conditions in lysimeters).

Such research may be considered agricultural only due to the purpose for which it is being undertaken (i.e. to achieve an agricultural outcome, such as a biopesticide), otherwise the same type of research could also be 'pure' science (e.g. understanding why particular microorganism species make effective biopesticides).

There are many reasons for using controlled-environment experiments: most obvious is the need to control some or all aspects of the environment; for example as part of the methods, such as varying the amount of light radiation, or prosaic reasons, such as growing plants when it is too cold/dark outside. Other reasons include cost (e.g. a glasshouse pot experiment is typically much cheaper than a field plot experiment), speed (i.e. experiments can be completed quickly, testing and refining hypotheses), and creating a progression of results from simple-artificial conditions, (e.g. Petri dish), through glasshouse pot trials, before moving to full field trials (*in vitro* to *in vivo*). The level of environmental control, experimental design, and purposes are therefore limitless.

There are therefore limited generalisations that can be made about controlled-environment experiments, the key being that they are almost always designed to prove causality. Indeed, often a key reason for controlling the experimental environment is to allow its manipulation, or to keep it constant to determine its causal role in the experimental outcome. In most cases, the results of the experiments cannot be directly implemented or used by farmers and growers. More typically, they inform the research process that has the end goal of affecting agriculture.

The RA research questions that could be addressed through controlled-environment experiments are therefore also very broad. Some examples include:

- Do RA soils have greater capacity to detoxify glyphosate?
- Does coating seed with a Johnson-su compost extract accelerate germination and increase plant growth?
- Does RA promote soil methanotrophy and, if so, how much methane can be consumed by soils?
- Do synthetic fertilisers inhibit carbon transfer from roots to mycorrhizae as root exudates?

- Does RA increase soil microbiological activity?
- What is the impact of insecticides, fungicides, and herbicides on the nutrient-mobilising capacity of soil microbes?

In conclusion, controlled-environment experiments are exceptionally diverse and beyond simple classification, and while they are not representative of real farming practices, and most of their results cannot be used on the farm, they have an important role to play in answering many questions about, and for, regenerative agriculture.

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