# A horizon scan for pastoral weed science – a New Zealand perspective.

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## Abstract

There have been horizon scans (strategic science reviews) recently for weed biology, but none that focus on weeds of pastures. Here we report on our process for writing the Pastoral Sector Weeds Research Strategy (2018-2028) for New Zealand and then follow-up with the focus of the current article, a horizon scan for pastoral weed science. Scientists and stakeholders involved in weeds and pasture systems participated in two workshops to determine which issues and opportunities are emerging as drivers of innovation for weed science and weed management. We identified 11 major issues and 46 subordinate ones, but the three most highly ranked major issues were: 1) anticipated reductions in our access to herbicides; 2) rethinking weed management under an ecosystem services paradigm; 3) responding to a regulatory push for farm system planning designed to address biosecurity risk, biodiversity, carbon budgets, contaminants, and nutrient run-off in addition to production value. The workshop participants were asked to rank the 3 major issues (and some subordinate ones) using the criteria: 1) is this a horizon (is the issue or question likely to become more important in 10-20 years?); 2) will it require stretchy science (is the question or issue currently not well addressed by the science community?); 3) is it transformative (will successful scientific research in this area lead to significant changes to weed management in pastures?). Most of the issues identified are shared in pastoral systems worldwide and involve reducing environmental footprint of farming while maintaining productivity.

Keywords: white-paper, invasive plants, agriculture, grazing

## 1. Introduction

### 1.1 Weeds and pastures in global food security

Weeds have important negative impacts on global food security. A global review of crop-protection for major staple crops shows that weed control potentially helps farmers avoid crop losses of 34%, which is higher than losses caused by insect pests (18%) and plant diseases (16%) (Oerke & Dehne, 2004; Oerke, 2006). The historical focus of the agricultural industry and science on weed management in arable cropping systems might reflect the calorific importance and profitability of cereals and root vegetables for people but belies the global area of land dedicated to livestock grazing (2 billion ha) which makes up ca. 50% of the global agricultural lands (Mottet *et al.*, 2017). Weeds of pastures do not get as much attention. For example, a search of article titles in two prominent weed science journals (Weed Research and Weed Science) for the word “pasture” reveals only 113 mentions versus “crop” which had 2035 mentions (accessed January 2021). Understanding weed ecology and impacts in pasture systems is challenging because pastures are often botanically diverse, species composition changes over time, grazing management impacts outcomes, and low abundances of weeds may be easily tolerated by farmers, plus measuring weed impacts on livestock production is difficult especially for species that are consumed (Klingman, 1956). For weeds that are rejected by grazing animals, the losses are more easily estimated. For example, *Ranunculus acris* is avoided by dairy cattle in New Zealand pastures so that the loss incurred in a pasture is proportional to the area occupied by the weed (Bourdôt *et al.*, 2019). Dairy pastures in the Tasman District of New Zealand typically have 24% of their area covered by the weed in May (late autumn). This equates to 24% annual loss in production or a potential increase in productivity of 24/(100-24) = 32%. Another example of an unpalatable weed is *Cirsium arvense*. This species occurs on almost all pastoral farms in New Zealand and covers, on average, 6% of the grazed area during its time of peak ground cover in January-February with sheep farms having the highest cover (12%) and beef farms the lowest (4%) (Bourdôt *et al.*, 2013). Overall, the area of land occupied by this weed coverage represents a present value loss of $700 million per year (Saunders *et al.*, 2017).

Because of the importance of pastures for its economy a New Zealand perspective on weed management in pastures is relevant. In New Zealand, pastures occupy 38% of the total land area, supporting mainly dairy, sheep, beef, and deer industries. In comparison, <0.5% of the land area is dedicated to arable and horticulture production (Moot *et al.*, 2009). New Zealand animal products contributed ca. $19 billion NZD to its gross domestic product in 2018 https://www.stats.govt.nz/), the bulk from exports which contribute significantly to the global food supply, e.g. New Zealand's dairy products account for 3% of the world production (https://www.dcanz.com/about-the-nz-dairy-industry/). New Zealand pastures are dominated by introduced grasses and forbes that provide year-round grazing. Systems with high rainfall and soil fertility rely heavily on ryegrass and white clover cultivars (*Lolium perenne*, *L. multiflorum, Triflolium repens*). They are the dominant sown pasture species and are most productive within a temperate mesic habitat. In areas that are less ideal for these preferred species, such as in the modified tussock grasslands that prevail throughout much of the New Zealand (South Island) hill country, other pasture species become more important. For example, in sites that are cooler, drier, warmer, or less fertile, *Dactylis glomerata*, *Bromus catharticus* and *Agrostis* spp. are important. Animal health, and high productivity is maintained by applying fertilizer (e.g., containing, nitrogen, phosphate), and soil deficiencies require farmers to add the trace element cobalt to fertilizers or to animal drenches (Moot *et al.*, 2009).

Estimates of the number of species considered to be weeds in New Zealand pastures varies from 187 (Bourdôt *et al.*, 2007; Saunders *et al.*, 2017) to 245 (Ghanizadeh & Harrington, 2019). Some of these species may have yet unrecognised value as sward components. For example, *Plantago lanceolata*, once considered a weed of pastures, is now sown in dairy pastures to mitigate nitrogen leaching (Cheng *et al.*, 2018). The estimated aggregate cost from pasture weeds, based on the 10 species for which useful data has been published and therefore a conservative estimate, is NZD [2014] 1.3 billion per year (Saunders *et al.*, 2017). The productivity loss component of this cost has been estimated at 86%, with 14% attributed to control costs (Bourdôt *et al.*, 2007). At a local scale, the range of impacts varies between species. For example *Cirsium vulgare* densities of 10,000 plants per hectare can reduce sheep liveweight gain by 20% and *Carduus nutans* at 1000 plants per hectare can reduce forage dry matter yield by 8% (Hartley, 1983; Thompson *et al.*, 1987). Similarly large variation between species in their impacts occurs at the national scale as illustrated by the losses that have been attributed to the 10 species for which data is available, in NZD [2014] millions/year: *Ulex europaeus* 72; *Cirsium arvense* 702; *Cytisus scoparius* 8, *Rubus fruticosus* 14; *Nassella neesiana* 0.013; *Nassella trichotoma* 27; *Rosa rubiginosa* 7; *Hieracium* spp. 6; *Setaria pumila* 258; *Ranunculus acris*; 210 (Thompson *et al.*, 1987; Bourdôt *et al.*, 2007). The true aggregate cost of pasture weeds, using the median annual cost for the assessed weeds in New Zealand ($20.5 million/year) could be as high as NZD [2014] 5 billion per year (20.5 x 245) if all 245 species affect pastoral production similarly, and do so independently of each other. Australia and New Zealand are known for relatively intense herbicide-based weed management efforts in pastures. This has resulted in multiple cases of herbicide resistance (*Carduus nutans, Carduus pycnocephalus, Ranunculus acris, Nassella neesiana*), more than in any of the other four countries with documented cases of herbicide resistance in pasture (Heap, 2021). In this context strategic research to support weed management in pastoral systems is needed.

Strategic reviews can elevate weed research beyond the basics, and identify emerging issues and opportunities (Fernandez-Quintanilla *et al.*, 2008; Ricciardi *et al.*, 2017; Neve *et al.*, 2018; Westwood *et al.*, 2018), but it is difficult to know how often these efforts actually spark transformative research efforts. This may be because weed science is necessarily an applied field that has been dominated by short term solutions and commercialization of products (e.g. herbicide use, efficacy and resistance) to solve current problems (Fernandez-Quintanilla *et al.*, 2008). A lot of weed science expertise is embedded in herbicide companies, and only partially visible to the public through product documentation or direct advice. Regionally, weed science and extension efforts are rightly driven by farmer concerns, address specific local issues, and information is often available in difficult-to-access 'grey' literature. Scientists' search for funding, and a 'publish or perish' model limit our ability as scientists to creatively solve the world's biggest problems (Paasche & Österblom, 2019). This may or may not tip the balance toward research that focuses on narrow applications relevant to farmers (Fernandez-Quintanilla *et al.*, 2008). Despite the importance of weeds in food production, basic knowledge about weed biology and ecology (e.g., seed biology, population dynamics) is often lacking, and there has been a repetitive focus on a few themes such as herbicidal control, seed germination, seed banks, and competitive interactions with crops. Nevertheless, strategically aligned research initiatives, formulated with key stakeholders have the potential to address current and future needs (Bourdôt *et al.*, 2018). We adapt and expand on the horizon scan approach (Sutherland & Woodroof, 2009; Ricciardi *et al.*, 2017; Neve *et al.*, 2018; Sutherland *et al.*, 2019) to identify emerging weed management issues and research opportunities that could reveal avenues of transformative investigation for pasture weeds research.

# Methods

## Pastoral Sector Weeds Strategy (2018-2028)

In November 2017 scientists from AgResearch Ltd., a crown research institute (CRI) in New Zealand organized a workshop to identify the key challenges that would underpin and inform a ten-year stakeholder-led weed research strategy for the pastoral sector (Bourdôt *et al.*, 2018). The weed management emerging issues (37 in total) identified during the workshop were ranked by the 12 scientists and 10 industry representatives participating in the workshop and subsequently grouped into 8 key science challenges. The details of the methods and participants are provided in the published Pastoral Sector Weeds Research Strategy (2018 - 2028) (Bourdôt *et al.*, 2018). Here we present the key challenges since they provided the starting point for our horizon scan.

## Pastoral weed science horizon scan

We adopted a horizon scan approach to identify potential collaborators locally and internationally. Doing transformative research and developing weed management approaches that address emerging issues is a shared aspiration for weed scientists, corporate leaders, policy makers, government agencies, industry groups, land managers, and funding agencies. Future foresighting, roadmapping, and science whitepapers can help create robust investment cases. Timely identification of transformative research is key and horizon scans are emerging as a way forward (Sutherland & Woodroof, 2009; BMAC, 2015; Ricciardi *et al.*, 2017; Neve *et al.*, 2018; Sutherland *et al.*, 2019). Horizon-scans are future-focused, and they:

- are medium to long term 10-20 years,
- focus on threats and opportunities not well recognized in a field,
- raise awareness and provide momentum for innovation,
- inform policy,
- help set research agendas, and
- stimulate action that addresses plausible threats.

They generally identify opportunities and threats that need to be addressed but may or may not involve a process for expert ranking and scoring of questions (Sutherland *et al.*, 2011). As a first step, following publication of the strategy (Bourdôt *et al.*, 2018), in 2019 two independently facilitated expert elicitation workshops were held, one at Ruakura (29/11/2019) and the other at Lincoln (12/12/2019) in New Zealand. The meeting involved 9-13 people and breakout groups of 3-5 people. Participants were introduced to the concept of horizon scans outlined in the bulleted list above. Each group wrote down their **issues** and **questions** under **key themes** on post-it notes and poster paper (previously identified by workshop leaders) during 20 minutes, then carried out peer review on the other groups' ideas. The key themes used to prompt workshop participants were: 1) low-input future (fertilizer, herbicides, pesticides); 2) agriculture and global change (climate, water quality, soil, biosecurity); 3) fit for purpose plants and animals; 4) robotics/tech/big data, remote sensing; 5) omics (genomics, proteomics, metabolomics, microbiomics, gene manipulation and gene-silencing techniques); 6) Mātauranga Māori. **Ideas** were documented before synthesizing them into **major issues** and **subordinate questions** which were shared with 3 participants who checked that the synthesis reflected the intent of the workshop. We envisage that the subordinate questions could each form the basis for a research proposal. Each of 5 randomly chosen issues were ranked on three criteria by dragging them into rank order on the app screen: 1) is this a horizon (is the issue or question likely to become more important in 10-20 years?); 2) will it require stretchy science (is the question or issue currently not well addressed by the science community?); 3) is it transformative (will successful efforts in this area lead to significant changes to weed management in pastures?).

The issues were ranked by the 23 experts from taking part in the workshops via a shiny app (developed by AgResearch), first by viewing and scoring the Maori knowledge issues (see Table 1) and 5 of the 10 randomly ordered major issues, and then by scoring subordinate questions for their 3 most highly ranked key themes. If a respondent did not rank an issue no value was assigned. Data about participants demographics and expertise in the weed science field were collected, as well as a prompt to participants to optionally provide information about potential global collaborators for the different issues and questions presented. Ranks for major issues were converted to scores by subtracting the rank from the number of items ranked+1 (in this way the lowest ranked item scored a 1 and the highest a 6), then scores were weighted to visualize criteria importance by taking the square of the mean score and multiplying it by the proportion of respondents that ranked the issue in top 3 (see Table1, Supplementary_Data_S1, Fig. 2). Finally, the importance of different key issues by was visualized using a Sankey plot from the networkD3 package (Allaire *et al.*, 2017)

# Results and Discussion

Pastoral Sector Weeds Research Strategy (2018-2028)

The AgResearch pastoral sector weeds research strategy (Bourdôt et al., 2018) briefly reviews the weeds research capacity in AgResearch Ltd. and in New Zealand, as well as pastoral weeds research internationally. The challenges (target research areas) in the strategy, shown here in Fig. 1, are: improved internal biosecurity; increased suite of non-chemical control options (alternatives to herbicides); herbicide resistance evolution understood and controlled; weed population biology informs and disrupts weed management; weed control economics informs and disrupts weed management; best practice pastoral weed management adopted by farmers; effective riparian weed management (Bourdôt et al., 2018).

Pastoral weed science horizon scan

Here we discuss the issues and opportunities that should be addressed in pastoral weed research. The issues, and some of their specific subordinate issues provide opportunities for innovative research solutions. We examine the importance of each issue in the context of: 1) is it a **horizon** (an emerging or growing problem); 2) will work on the issue **stretch** current knowledge and create new research opportunities; 3) is there potential for research on the issue to transform weed **management**?

### Major issues selected and ranked

A summary of the final ranks for the major issues is provided in Table 1, and for the major and sub-issues, the ranks are provided in Supplemental data S1. Fig. 2 shows the relative importance of the issues described in terms of a short summary phrase that captures the issue concept (the full descriptions are provided in Table 1), but rank averages were converted to weights (see methods). From an original list of 11 items, the high priority issues by weighted scores were: 1st) reduced access to herbicides, 2nd) ecosystem services, 3rd) farm system changes 4th) lower chemical inputs, and 5th) internal and border biosecurity (Table 1; Fig. 2). Starting at the lowest ranked issues we have 11th) Big data, automation, and technology, 10th) Indigenous knowledge, 9th) water quality 8th) climate change, 7th) fit for purpose plants and animals and 6th) weed, animal and soil microbiomes.

### Major issues ranked under the horizon, stretch and management criteria

Ranks differed depending on the criteria, and our weighting of the ranks emphasizes the relative contribution under the three criteria (Fig. 2). If we take the "horizon" criteria we identified as important, there is a growing trend toward **lower chemical inputs** as farmers seek to address sustainability and social-license challenges (Rowarth *et al.*, 2020; Clothier *et al.*, 2021). This is expected to drive far-reaching changes in farm and weed management. This is related to another highly ranked horizon issue, namely the recent **reductions in the number of herbicide** active ingredients that are available for farmers to use, as regulators in many regulatory jurisdictions have removed some effective broad-spectrum herbicides that have actual or perceived problems with their safe use. Meanwhile, there has been a simultaneous slow-down in the development of new herbicides and modes-of-action because of the prohibitive costs of bring new products to market (Phillips, 2020). Effective widely used low-risk herbicides are currently under review by regulators (e.g., glyphosate) in New Zealand and elsewhere. Some say there is a growing regulatory emphasis on *hazards* (potential to harm at any use level) as opposed to *risk* under normal use conditions i.e., the potential to harm given actual recommended rates and use conditions (Duke, 2012; Phillips, 2020). When we look at the ranks given for "stretchy science" the **ecosystem services** concept, and **microbiomes** were ranked highly. Ecosystem services research provides rich opportunities for understanding the role (services and disservices) of weeds in pasture systems (Harrington *et al.*, 2006; Dale & Polasky, 2007; Vilà *et al.*, 2010; Blaix *et al.*, 2018), potentially shifting farmer attitudes toward some weeds as it has for chicory and plantain formerly (Dodd *et al.*, 2017; Cheng *et al.*, 2018). While for microbiomes research, its potential was framed in terms of understanding or altering allelopathic interactions, plant palatability, and plant ecology, which in turn could be applied to weed management (Masteling *et al.*, 2019; Dahiya *et al.*, 2020). Finally, participants believed that research addressing the **reduced availability of herbicides**, and **ecosystem services** could transform weed management practices.

**Table 1.** For the major issues raised in the horizon scan workshops we show mean ranks provided by the workshop participants, ordered by the mean rank. Survey participants were randomly assigned 5 major issues to rank (in brackets we put the times an issue was ranked in top 3 vs the number of times seen by respondent) also expressed as percent of times an issue was in the top 3.

| **Question** | **N** |
|---|---|
| There is **reduced availability of chemical weed control** options due to environmental and consumer health concerns which lead to the removal of active ingredients from the market and a lack of new alternatives which are costly to develop. | 16 |
| **Farm system changes** are increasingly required to encourage better management of multiple values, biosecurity risk, biodiversity, carbon, and nutrient run-off and production value. These plans result in spatial and temporal farm system changes that will alter weed ecology and weed management. | 9 |
| A better understanding of **ecosystem services**/disservices could lead to changes in farmer perceptions and weed management. For example, perceptions of weediness have changed over time (e.g., chicory and plantain were once regarded as weeds but now planted in pasture). | 9 |
| There is pressure to use **lower chemical inputs** (herbicides, pesticides and fertilizers) due to concerns about their perceived impacts to the environment and human health. This will alter pasture weed species composition, abundance and management. | 15 |
| The effectiveness of **biosecurity at the border, and internally** (between farms and regions) is increasingly important as economic/population growth, and international immigration (e.g., climate refugees) increases connectivity domestically and internationally. | 11 |
| We do not understand how weed (leaf, root), animal and soil **microbiomes** interact to potentially alter allelopathy, plant palatability, plant ecology and the effectiveness of weed management measures. Knowledge and technology development in this space could lead to improved outcomes. | 7 |
| Human mediated change in greenhouse gases is leading to **climate change** and sea level rise altering weed/crop ecology. Greenhouse gas emission regulations and downstream changes to farm practices will also change weed ecology and management. | 14 |
| **Water quality** concerns are driving farm system changes related to nutrient run-off and agrichemical use that will impact weed ecology and management. | 16 |
| Selection and design of **fit for purpose plants** and animals will alter farm systems. Animals and forages are optimized for weed management outcomes, minimized environmental impact, increased consumer confidence and maximised product value. | 12 |
| Efforts to improve outcomes for indigenous people (Maori) increasingly call on us to engage with indigenous people/clients/scientists, and to incorporate **indigenous knowledge systems** and values into farming and science endeavors. | 20 |
| **Big data, automation, and technology** will become increasingly important for weed science and management. | 9 |

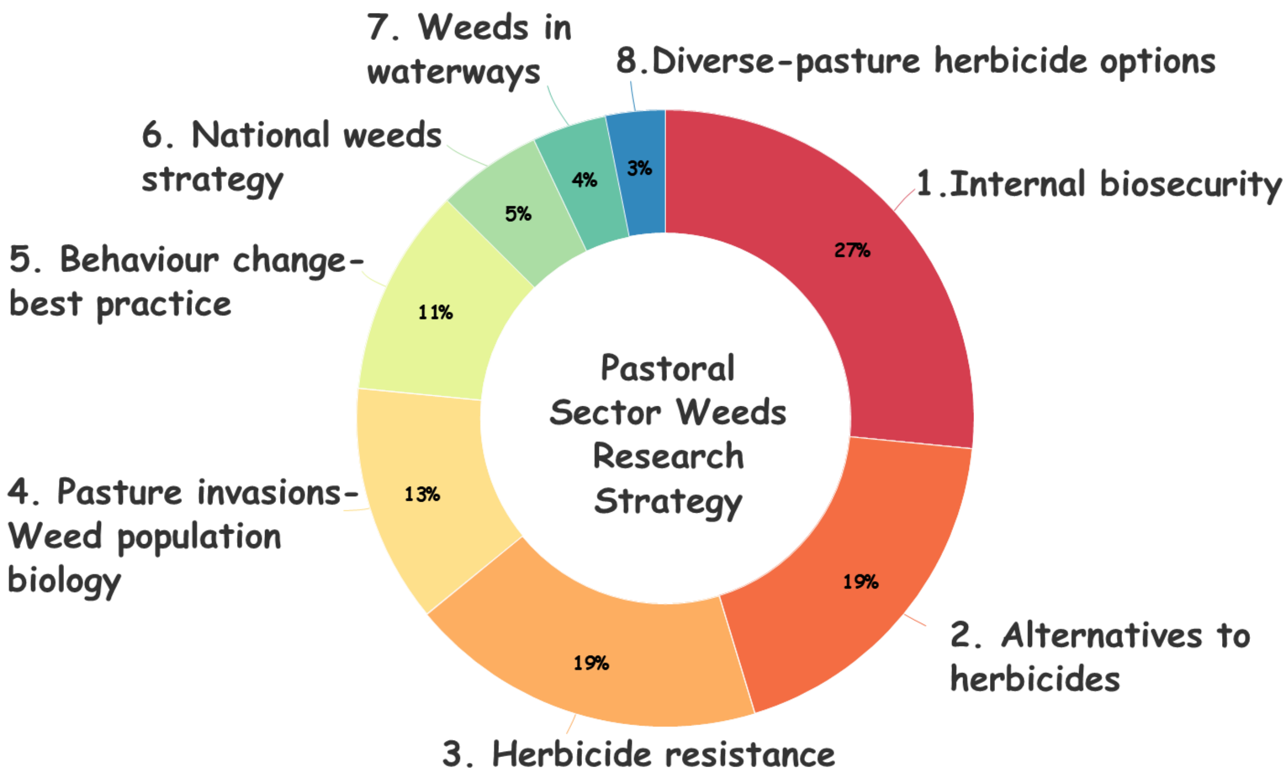


**Fig. 1.** The weed management Target Research Areas (challenges) in the Pastoral Sector Weeds Research Strategy as defined by a stakeholder workshop made up of pastoral sector industry representatives and scientists in New Zealand (Bourdôt *et al.*, 2018). The segment size is determined by the sum of the votes given by the workshop participants to each of the challenges (segments) constituent issues and given here as a % of the total. Diagram modified from Bourdôt *et al.,* (2018).

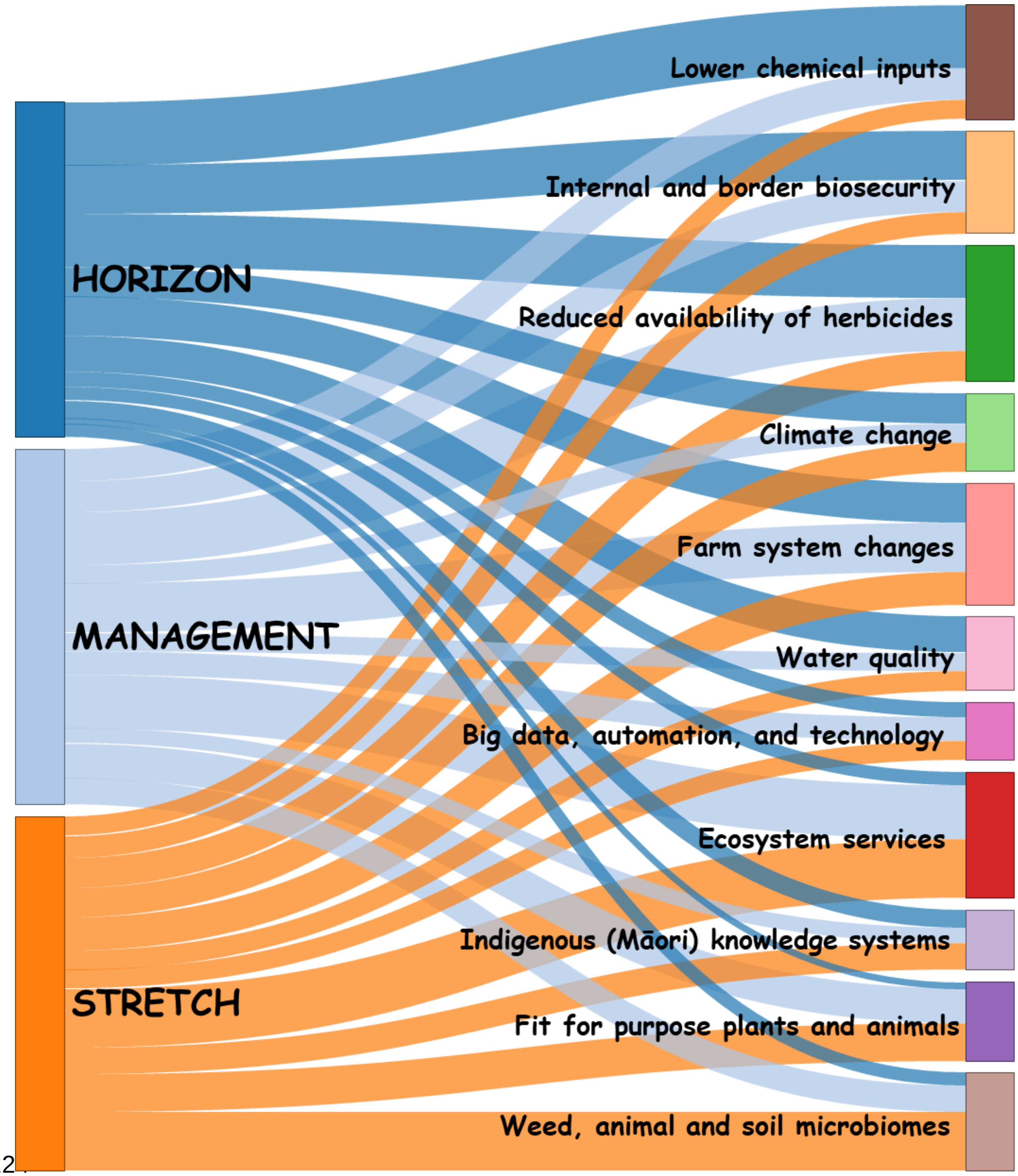


**Figure 2. Major issues** (RH boxes) have their node boxes and link widths scaled by the sum of their weights=$(\text{mean}(\text{weight}))^2$×proportion of recipients that ranked the item in the top 3, across the **three ranking criteria** (LH boxes). Ranks were provided by 22 weed experts under each of the three criteria.

## Subordinate issues for the highly ranked major issues

The top three major issues for the combined ranks, plus highly ranked issues under the criteria for "science stretch" and "management transformation" highlight four issues for which we will describe the subordinate issues in rank order. They are 1st) reduced access to herbicides, 2nd) ecosystem services, 3rd) farm system changes. We have additionally reviewed the issue of improved outcomes for Maori.

## Improved outcomes for Maori

Issue: Efforts to improve outcomes for indigenous people (Maori) increasingly call on us to engage with indigenous people/clients/scientists, and to incorporate indigenous knowledge systems and values into farming and science endeavors.
We note there was limited Maori participation in the workshop and the preparation of this paper. Future research should provide for greater contribution from Maori communities and researchers. The key responses from the workshop participants were:

1. Incorporating Maori world views could fundamentally change weed and farm management decisions.
2. Best practices must be identified to ensure effective engagement between the science community and Maori.
3. We must understand which weed management issues matter more to Maori.
4. We must improve Maori science capacity and employment rates in our research institutions.

As Harmsworth and Awatere (2013) explain, Māori view themselves as a part of ecosystems and recognize a reciprocal interdependent relationship between caring for the land (manaaki whenua) and caring for the people (manaaki tāngata). Rivers, land, flora and fauna are considered to share a connection, lineage or genealogy (whakapapa) with Māori people and the connections, and ecosystem health or condition can additionally be explained in terms of a shared life-force (mauri). As such, for many Māori stewardship of the environment is akin to caring for family. They also have in place a system of practical rules, customs and laws (ritenga) to convey proper management of people and natural resources. Māori own a lot of land in sheep and beef, and have significant financial investments in the dairy industry (Kingi, 2013), as such they have interests in weed control. Concern about weeds is inherently cultural, value driven and practical, clearly a meaningful dialogue with Māori could lead to meaningful innovation of science or management practices. However, meaningful long-term engagement between government funding bodies, scientists and Māori has often been elusive, and best practices for collaboration and engagement are needed. Hiring, mentoring, and sustaining Māori cultural experts, scientists, and technicians is one way to help meaningful long-term engagement. (McAllister, *et al.*, 2019; McAllister *et al.*, 2020b). A set of best practices should be followed for engagement with Māori in New Zealand, including for weed research. Research should involve respectful, early engagement and co-development of projects with Māori, from project inception and to implementation, and on through to the realization of research impacts. This engagement should incorporate Mātauranga Māori which is an indigenous knowledge system that integrates Māori philosophical thought, worldview, and practice, and seek to maintain the mana (prestige, authority, dignity, charisma, and spiritual power) and active roles of collaborators, landowners, educators, scientists, iwi (Māori tribes and people) and hapū (sub-tribes), particularly those that are mana whenua / people with authority over the land where any of the research is carried out (McAllister *et al.*, 2020a).

## Reduced availability of herbicides

Issue: There is reduced availability of chemical weed control options due to environmental and consumer health concerns which lead to the regulatory removal of active ingredients from the market and a lack of new alternatives which are costly to develop.

Subordinate issues (in rank order):

1. We need to understand the viability of alternative weed control measures if important herbicides are banned.
2. Reduced availability of herbicides available will result in more cases of herbicide resistance.
3. New chemical herbicides can be developed with benign breakdown products.
4. Reduced availability of herbicides will impact our ability to respond to biosecurity incursions.

Weed control efforts in New Zealand often involve the use of herbicides, with about 158 million NZD being spent annually (Buddenhagen *et al.*, 2019). Some commonly used herbicides are under review, (e.g., glyphosate, 2,4-D), or their use has recently been strictly limited (e.g., paraquat; EPA NZ, 2021). Given the reliance on herbicides, their effectiveness in improving productivity, or helping respond to new weed incursions, the potential removal of key products came up as the highest priority issue for pasture weed management. Workshop participants thought we should use viable alternatives as full or partial replacements to herbicides, if they are effective, but more work is needed to understand alternative strategies. Some alternatives deserve to have continued scrutiny and testing, such as classical and inundative biocontrols (Bourdôt *et al.*, 2007, 2018; Bourdôt & Cripps, 2018; Ghanizadeh & Harrington, 2019), deferred grazing (Tozer *et al.*, 2020, 2021), or regenerative agricultural practices. There was a hope that new herbicides with benign breakdown products could be developed in future, perhaps using innovative genetic approaches (Duke *et al.*, 2019) or naturally occurring chemicals involved in plant defense.

## Ecosystem services

Issue: A better understanding of ecosystem services/disservices could lead to changes in farmer perceptions and the way they do weed management. For example, perceptions of weediness has changed over time (e.g. chicory and plantain were once regarded as a weeds but are now planted in pasture).

1. Weeds provide ecosystem services/disservices.
2. Weeds are potentially valuable as forage.
3. Weeds impact animal health/microbiomes.
4. Society values grasslands with weeds, and wildflowers - can farmers receive benefits if they manage for these values?

As discussed briefly under issues ranked highly for the “horizon” criteria, weeds are not merely a disservice to production, but also provide ecosystem services. Research is needed that addresses the ecosystem services/disservices of weeds in pasture systems, with previous economic assessments focusing mostly on costs/disservices (Saunders *et al.*, 2017). Not long-ago farmers in New Zealand regarded *Chicorum intybus* and *Plantago lanceolata* as undesirable weeds in ryegrass and clover pastures but these are now valued as late summer fodders that may reduce excreted nitrogen concentrations and downstream leaching (Dodd *et al.*, 2017). Many weedy plants can provide livestock nutrition, but there is poor understanding of practical value in the field as fodder, or as an enhancer of microbiome health, versus negative impact on overall pasture production. The benefits of weeds can vary e.g., as a pollen and nectar resource, soil biology, act as carbon sinks, decrease nutrient leaching, or they may bed value for aesthetic and cultural reasons, as non-native wildflowers often are. It is unclear to what extent farmers could be compensated for these other values.

Expertise in the areas of green economics, carbon budgeting, soil biology, and ecosystem services paradigms can be quite specialized, and useful collaborations with weed and plant ecologists is needed.

## Farm system changes

Issue: Farm system changes are increasingly required to encourage better management of multiple values, biosecurity risk, biodiversity, carbon and nutrient run-off, and production value. These are documented in farm plans result in spatial and temporal farm system changes that will alter weed ecology and weed management.

1. We need to understand how to incentivize “public good” farm management.
2. The barriers to adopting best practice need to be understood.
3. Certification schemes that emphasize good practices for weed management and biodiversity protection could create market incentives.
4. Grazing regimes (stocking rate, timing and frequency of grazing) impact weed abundance and farm profits.
5. Emphasizing pasture persistence over productivity alters farmer behaviour and weed impacts, and economic and environmental outcomes.

In New Zealand farm environment plans are increasingly required by local governments to promote good practice and are designed help farmers to mitigate farm impacts on water use, water quality, contaminants, effluent, biodiversity, biosecurity and green-house gas emissions. Understanding what influences farmers to adopt best practices and innovate is key. We need to demonstrate the extent that the recommended best practices achieve the stated goals. Such work requires the interdisciplinary efforts of educators, farmers, marketers, and scientists with expertise in specialized chemical, biological, economic and social fields. The hope is that such efforts can capture value chain opportunities beyond the farm gate.

## Social license

The issue of social license and consumer perceptions was repeatedly raised during the workshops, under multiple contexts (Appendix 1. Table 1). Social license is a cross-cutting issue for societal change, and the pursuit of scientific and technical innovation, including in pastoral farming systems (Edwards & Trafford, 2016; Camara *et al.*, 2018; Norton *et al.*, 2020). Research into different aspects of social license, and addressing societal needs generally needs to be built into every project. Society may be reluctant to adopt unfamiliar but excellent innovative solutions, or scientists may inappropriately push some solutions. Any search for solutions to problems and issues that are on the horizon requires new ways of doing business and depends ultimately on innovation adoption by people. A key research area is to understand the barriers to adoption of innovations or established best practice (Supplemental Data S1). However, social license is required for the business-as-usual approach too, and some of the major issues that need to be addressed are a direct consequence of reduced social capital as farm activities impact shared resources, often centered around the use of chemical inputs (fertilizer and pesticides), irrigation, high stocking densities, effluent, contaminants, and biodiversity. Some concerns around contaminants may reflect our increasingly sensitive tools to detect minute amounts of any given chemical in the environment. Many of these societal concerns are being reflected in the development and enforcement of policies, rules and regulations directed at farmer behavior.

Issues we identified are clearly linked via a concern about farm impacts on the environment, including the availability of chemical weed control (herbicides), farm system changes, lower chemical inputs, water quality concerns, climate change and the incorporation of Mātauranga Māori. Participants believed there are societal shifts in expectations for the pastoral farming sector generally. These include the adoption of sustainability and animal welfare measures which can be market driven (Lyons & Lawrence, 2017), or come from government agencies through regulation and policy (Kaye-Blake *et al.*, 2019), subsidies (Gołębiewska & Pajewski, 2018; Pajewski *et al.*, 2020) and taxation shifts (Barrett & Makale, 2019). A mix of intrinsic and extrinsic motivations like these are expected to drive farmer efforts to reduce their environmental footprint. Work under one issue is likely to address some concerns under other issues we identified.

Workshop participants believed the widespread use of social media may disproportionately amplify some critics, with sound science getting no more traction than disproven lines of reasoning because of widespread distrust of the scientific process and government authority. Nevertheless, they believed farmers will try to cater to the changing attitudes of consumers. Many of the solutions to these issues raise special concerns. Even the relatively inanimate technologies like the use of robotic weeders, automatic weed detection, distributed applications decision and information systems create issues around privacy, safety, and control (farmer-led versus contracting out specialized services). Biocontrol comes with widely understood and manageable risks (e.g., potential non-target impacts) and a suite of perceived risks and ethical considerations. Development of genetically modified organisms is widely viewed by the public as risky. These doubts are not helped by difficulties in interpretation of multiple lines of scientific evidence, and distrust of experts, scientists and regulatory bodies. Improving evidence-based decision making needs to involve transparent public processes, regulators, social scientists, and communication experts. We think the agricultural sector (and scientists working in the field) are working within an expanded ethical framework. We need to be guided by the goal of objectivity, even if it is hard to obtain, but know that we balance our research in a space between what is objective and subjective, value free and value laden, neutral and advocatory (Rykiel, 2001).

## Acknowledgements

The following people participated in the workshops: Nigel Bell, Mike Dodd, Han Eerens, Hossein Ghanizadeh, Andrew Griffiths, Tai Harmer, Kerry Harrington, Peter Heenan, Phil Hulme, Trevor James, John Kean, Shona Lamoureaux, Joe Neal, Irena Obadovic, Sofia Orre-Gordon, Helen Percy, Rebecca Redmond, M. Phil Rolston, Lee Tane, Sue Zydenbos. Mark Hurst, Maxine Bryant, Lee Tane and Tamara Mutu provided helpful comments on the manuscript.

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# Appendix 1: Workshop ideas recorded by participants.

## Lower input future

What are the costs/benefits of weed control in a low input system?

**Consumer perceptions**

Consumer concerns about pesticide use (impacts to human health) is a driver.

What does contamination mean given our great ability to detect low levels of any chemical?

How can we prove that a farm system is using low inputs?

Science literacy, sound bites and societal fragmentation (social media) and declining public trust of scientists and government agencies.

How do we define “lower input”? Should we use “lower impact”?

**Targeted application of herbicides**

Blanket application of chemical control methods results in higher inputs.

What technologies do we need in low input farming system?

**Changing rural communities**

Fewer people are living in rural landscapes. Less utilization, less control capacity available, increasing reliance on contractors.

**Reduced availability of chemical control options**

Viability of alternative control measures if chemicals are banned.

What alternatives to chemical control are there, other than biocontrol (predation or herbivory) or competitive exclusion?

What chemical herbicides can be developed with benign breakdown products?

What can we do to understand and influence below ground competitive interactions?

What insights can be provided by examining the relative impacts of:

Farm system enterprise (overall),

the weed,

the control of said weeds (e.g. lifecycle analysis).

How does biocontrol agent (insect) microbiome relate to their effectiveness?

How would reduced availability of control options impact internal biosecurity?

A lower input future will lead us to accept more weeds, but at what cost?

Cost benefit analyses are needed to examine changing scenarios in labour and other inputs.

Tech improvements needed to enable effective lower input systems- using a limited suite of tools to better effect.

**Water quality**

What are the costs/benefits/trade-offs of riparian plantings?

What are the impacts of weed control efforts on nutrients, water quality, carbon, biodiversity and erosion?

Enterprise impact assessment vs weed impact assessment.

**National Policy Statement for Freshwater and the Zero Carbon Bill**

Large proportions (70%) of sheep and beef farms would need to be planted in forest to meet stated emissions and water quality 56 standards (check references).

**Multiple land-uses, and farm system changes**

Farm system changes in grazing intensity, livestock interactions with weeds and competitive species.

Diverse land uses creates more boundaries that may provide more weed niches.

The role of intensification as a form of land-sparing needs to be understood.

Weed problems and control options may shift with a move away from livestock.

**Farm systems ***

Farm system decisions emphasizing pasture persistence over productivity may lead to more resistant pastures (with concomitant ecosystem service benefits).

What are the unintended consequences of lower input systems, e.g. less herbicide leads to more cultivation?

How do grazing regimes impact weed abundances?

Holistic approaches to farm systems – mix of species balancing non-production factors.

What is the impact of lower stocking rates or novel grazing animals on weed/animal interaction?

How can low-input management be monetized to increase product value?

**Weed utility**

Viewing weeds as alternative forages in low input systems (they may be more competitive).

Turning weeds into opportunities, redefining weed roles in the landscape.

Weeds as tools for heavy metal capture/accumulation.

What opportunities do weed provide to deliver a range of ecosystem services?

Can use weeds to create high value products?

Are there beneficial properties in weeds?

**Fertilizer reductions ***

Integrated systems for capture and use of excess inputs are needed.

Recapture of nutrients from water bodies using microbes and plants to support a circular economy.

Utilizing and improving species that perform under lower inputs – nitrogen fixing species, and better NUE in forage plants.

Weed control becomes more important under low input systems. A related assumption is that weeds are more efficient at using available resources.

Changes are expected in weed spectra under lower soil fertility.

Lower pesticide inputs increase the need for integrated weed management utilizing natural enemies.

Reduced use of fertilizers could lead to lower pasture production, weed abundance increases, and declines in the competitive ability of desirable species.

**Animals ***

“Peak cow” and overstocking is a recognized problem. Less animals may lead to (opportunity) fewer weed problems and better pasture persistence.

## Agriculture and Global Change

Greenhouse gas taxes, what would they do to our systems?

Growing population increases require increasing food production – so inputs may need to increase?

Is high-input production with a small footprint possible?

Changing land-use, temperature, $CO_2$ and nutrient deposition impacts the “weedscape”. *

What will pastoral agriculture look like in the next 50 years?

Increase reliance on legumes for Nitrogen – to avoid N run-off, weed control options need that protect clover.

Forestry increases likely (billion trees etc) but many forestry species are “weedy” how will the proposed changes look?

How does $CO_2$ enrichment and temperature affect herbicide/biocontrol effectiveness? *

The need for reduced fossil fuel use will lead to reduced N and P application – how will this impact weed composition and competitiveness? *

Increases in extreme weather events raise pasture perturbations making weeds the “new normal”.

*

Pasture plants and weeds will be selected for increased environmental plasticity rather than productive biomass. Increased drought frequency will select for altered species composition e.g. drought resistant grasses like *Paspalum, Pennisetum, Bromus.* *

What is the relative importance of phenotypic/genotypic plasticity in the response of weeds to climate change?

How durable are biocontrol systems under climate change?

What types of extreme events will favour weeds over pasture species?

What are the direct impacts of climate change (increased CO2, temperature etc) on weed management (e.g. seed bank longevity, timing, and herbicide effectiveness)?

**Diversified land use ***

Future pastoral landscape may be more diversified and include other non-pastoral enterprises.

Drive for more resilient species rich pastures may lead to lower weed ingress.

Do we know the relationship between diversity and invasability in pastures?

Climate refugees, and population increases could lead to increases in invasive species.

Will future multifunctional landscapes be resilient to weed invasion?

**Biodiversity links ***

Bush remnants and riparian zones are managed for nutrient run-off and native biodiversity values weeds are ubiquitous to those areas and pasture – some impacts to internal biosecurity are expected.

Farm Environment Plans encourage better management of biodiversity values, carbon and nutrient run-off, and production value.

Formerly viewed as a weed manuka is valued for its nectar.

What native species could become weedy due to climate change or systems change?

Mātauranga Maori – valuing indigenous biodiversity, Taonga species, forest remnants.

How do we best manage two-way movement between natural and pasture systems?

How do we maximize biodiversity outcomes through farm management plans, market drivers and mātauranga Maori?

**Farm management to avoid weeds under changing environmental stressors**

How do we manage pastures to tolerate droughts/floods and therefore avoid weeds?

How to extend the life of pastures?

**Incipient invaders**

Context: Sleeper weeds can be new problem species or known species can become more impactful (as their range increases, or under global change).

Sleeper weeds what are they? Predicting traits –to aid identification of future problems?

How to stop new species becoming weed problems?

Can we compare NZ with overseas pasture to predict species invasions and shifts in composition under climate change?

Does comparison of weeds and their management at different latitudes within NZ tell us what to expect under climate change?

**Ecosystem Services**

Context: Weeds as part of multi-trophic interactions e.g. parisitoids and pollinators

Weeds provide ecosystem services – need to replace services if you remove the weeds.

Weeds can act as primary or secondary hosts of pests and diseases.

Questions: How do you measure, and balance ecosystem services provided by weeds?

What opportunities do weeds provide to deliver and range of ecosystem services (e.g. forage, heavy metal accumulators)

Quality of weeds as nectar sources, pollen, to feed into cost accounting.

Economics. What is the fodder value of weeds?

What is the quality of weeds as food for ruminants?

How will the net “cost” of a weed change when its contribution to ecosystem services (e.g. carbon sequestration, NO emission reduction etc.) are considered?

**Social and economic perspectives/ Consumer demand***

What are the incentives for “public good” land management?

Future consumer driven demand for greenhouse gas accounting is expected – this may impact stocking rates and biodiversity – with concomitant (poorly understood) shifts in weed abundance.

Product value could be enhanced under certification schemes that emphasize good practices for weed management and biodiversity protection. How much are consumers actually willing to pay?

**Social Licence**

What publicly acceptable weed control tools are there?

How to address or mitigate public concerns about weed control techniques? e.g. glyphosate hysteria.

Consumers of our high-value agricultural products may be more accepting of weeds than of weed control tools (e.g. herbicides) – and end consumers may have a growing influence.

### Alternative value of weeds

What aesthetic values will tourists/public place on grassland ecosystems?

Are some colourful weeds acceptable “wildflowers”?

How do we capture the value wildflowers etc. in pasture?

Current weeds may be future crops.

Systems approach to defining the “net” cost of a weed in a pastoral system – benefits need to be accounted for too. *

Pasture carbon sequestration are slightly weedy systems better? *

Government policy around biodiversity and carbon sequestering will drive land use changes. Under these policy initiatives what is the interaction between pasture weeds, forests, and soil sequestration? *

Current weeds may be tomorrow’s valued crop.

Will some current pasture species become “bad” while some existing weeds become “good”?

### Riparian conservation efforts increasing

Creation of edge environments to protect water quality, creates weed habitat – need better weed control in riparian zones, to support clean but flowing waters.

Riparian wed management includes more than water weeds – indigenous biodiversity *

Salination effects on weeds and plants due to rising sea levels.

## Fit for purpose plants and animals

### Consumer driven change

Context: Increasing emphasis on plant-based diets.

Still a strong emphasis on high-protein diets.

Horticulture plus pasture.

Land based production systems that provide an attractive backdrop for tourism.

Consumer perceptions of “naturalness” in pasture.

Changing landscape uses and multifunctional farms – effects of invasive species e.g. *Pinus spp*.

What can we do to address public perception around contaminants (given that we can detect extremely low levels of any given chemical)?

**Social license**

Weed management interventions with minimal biological impact.

Use of digital approaches (automated weed control) – less human intervention could have unknown effects on weeds.

What is the public/user perception of multifunctional landscapes (biodiversity and weeds)?

Who are future consumers and are weed or weed management important to them?

When does a weed have a cultural value?

**Shifting species composition, managing genetic resources.**

A narrow spectrum of plants and animals are favoured in pastures now.

Changing demographics leads to new species introductions and shifts human mediated spread of species already in NZ.

Genetic technologies could have unexpected consequences e.g. on biodiversity.

What GMO/genetic technology should NZ allow?

Weed species could be repository of desirable crop genetics.

GE/Gene silencing technologies a potential opportunity.

What plants/species will form the basis of pasture-based systems in the future?

What plant traits are we looking for and how do we get them?

What are some of the known and unknown consequences of invasive weed species (incl. GMO on dynamics)?

**Species need to be best suited to changing climatic conditions.**

More nutrient and water efficient plants needed.

Pasture species adaptable to changing climates.

What is the impact of weeds on soil health and nutrient supply?

**The relationship between weeds and animal and/or human health is poorly understood.**

The impact of weeds on animal health both positive and negative.

The impact of weeds on human health directly or via animals.

What are the (e.g. metabolic) compounds (beneficial or not) that move between plants and animals and vice versa?

How do we harness the nutritional or medicinal benefits of weeds?

**Endophyte and microbiome manipulation ***

Weed microbiomes (leaf and root) could have important interactions related to weediness, allelopathy and the effectiveness of weed control measures.

**Opportunities in the breeding and GE space ***

Increased use of legumes improved under strong selection (interacts with low input future).

Selection has focused on productivity of individual species but a focus breeding for optimal multi-species assemblages and inter-specific competitive ability could alter outcomes.

Super pasture plants become super weeds.

Selecting varieties for other roles than productivity (e.g. erosion control, or nutrient uptake).

Breeding for reduced N and P, or tolerance to stressors.

Nitrogen fixing grasses are only 10 years away.

Societal demands and consumer attitudes will influence what can and should be done with breeding and GE.

How can microbiome/endophyte biology help us to improve weed management?

How does the plant microbiome interact with biotic/abiotic control tools?

Can we breed plants for a low input future (less fertilizer and increased disease/pest tolerance)?

Are epigenetic traits useful as a breeding tool?

**Viewing weeds as useful ***

A changing mindset, and a better understanding of the role of weeds as valuable fodder, or key components of pasture systems.

What can we do to weeds to make them more palatable?

Do weeds provide important ecosystem services?

How do weeds improve meat/milk flavour?

**Animal interactions with weeds ***

Animal saliva as a transmitter of desired microbiome.

Improving animal tolerance to toxic plants.

New livestock options, different systems to direct weed management.

How can vertebrate livestock/invertebrates be used to improve weed management outcomes?

## Omics, GE, gene silencing, Microbiomes

How realistic are the proposals for genetic genomic “silver bullet” tools for future weed management?

Can we predict when epigenetics will impact weed evolution (e.g. in apomictic, clonal and selfing weeds)?

Using genomic tools to develop specific herbicide “safeners” to allow crop to metabolize herbicide and not be harmed?

Can we use genomic tools to assess the seed bank for herbicide efficacy and future weed threats?

Would the NZ pasture industry support a pasture weed genome database?

How does the plant microbiome facilitate or prevent weed invasion and can endophytes themselves be invasive?

Will the social license barriers to use genomics be less for weed management than for crop improvement?

**Problems ***

Limits of gene drives in polyploid weeds?

Weeds in the seed bank – how can genetic technologies address this?

Risk of breeding invasive pasture species that are problems in other ecosystems.

Is the NZ weed problem too specific to attract multinational investment in “omic” solutions?

GE/or selected HR resistant crops will create new HR resistant weeds.

Govt regulations limit opportunities, but so does consumer concern about GMO.

**Solution focus ***

Impact of epigenetics on weediness.

RNAi for weed control or herbicide resistance management.

Using omics for selective weed control by herbicides (creating new products)

Weed seed ID (and HR ID in seed for sowing).

Real time quick tests for HR.

Understanding the adaptation of weeds to non-herbicidal weed control methods.

A guide to the biological and weed management questions that can be answered using different “omics” methods.

**Social and scientific constraints ***

Most biological traits are polygenic – an issue for creation of “single gene silver bullets” and for VIG, RNAi, CRISPR etc.

Weeds are generally non-model organisms and there are no genomes available for them.

Difficult to understand the impacts of minor genes at the early stages of herbicide resistance evolution.

Cost effective microbiome/epigenome/metabalome analysis

**Microbiomes**

Below ground interactions between species is poorly understood.

Ecosystem communication e.g. volatiles are there opportunities

Do we have ways to collect and manipulate multiple microbial species?

Microbes as biocontrols.

Endophytes – deep understanding needed to find opportunities.

Are there invasive endophytes that could impact weed congeners or make them more invasive.

It can be difficult to target and culture useful taxa in complex microbiome communities.

**Utility of weeds and genetic elements in weeds.**

Useful compounds could be produced by weeds e.g. sunscreen, insecticides, allelopathic.

What strategies can we employ to better understand and harvest useful components from weeds or their associated organisms?

Weed functional roles and traits

Moving from gene/protein observations to understanding at macro scales.

Understanding allelopathic interactions between crop and weed species (both directions) using omics.

**Social license**

Public/Maori acceptance of different genetic manipulation technologies e.g. GE, gene silencing, CRISPR.

Intellectual property issues around GE.

Addressing unintended consequences.

Cultural ownership of species including exotics.

Sound-bite-based knowledge and short attention spans.

What is a robust screening protocol for identifying potentially adverse impacts of GE organisms?

How do we enable an informed public, and support decision-making?

Social media impact to public perception about science and omics.

Social license around GE/Gene editing.

**Omics technology development and adoption**

Should we be doing technology development in NZ?

At what point do current technologies become cost effective?

Is there a prioritization framework for technology adoption?

Weed seed identification in seed lots.

**Genetic engineering**

Creating sterile weeds, pollen swamping techniques, terminator genes.

## Robotics/technology/big data/remote sensing

What questions could phylogenetics and big data answer?

Can legacy data be used for contemporary issues?

Do we have platforms and pipelines suitable for multiple data sources?

Can the agriculture sector keep up with new technologies?

How do we integrate “weed management practice” with new technologies?

How can technology answer science questions with practical solutions instead of technology solutions looking for a problem?

What are the barriers to technology adoption?

**Fenceless farms**

Could animals be guided to weedy areas?

**Internal biosecurity**

Contractors play a big role in an efficient agricultural sector, and in the spread/spread-mitigation.

Risk-pathway analysis is needed to examine field, farm, and regional risk – real-time data potentially useful.

Omics data relies on big data platforms – that should be transitioned to public use datasets.

**Computer/phone technologies**

What is the role that apps can play in detection and management of weeds?

Are there any useful research tools that can be converted to apps?

What is the role of citizen science in pasture weed management?

What is the potential of phones as distributed information systems, data gathering, and decision support tools?

**Technology Adoption**

What factors influence technology/protocol/best practice adoption (e.g. herbicide wipers)?

What are the economics behind technology/protocol/best practice adoption?

Will the public accept active remote management systems?

How can you make technology affordable for low value pastures?

Farmers may become increasingly dependent on consultants to allow them to take advantage of new technology.

Concerns about employment under automation.

Data ownership and privacy for data driven by technology.

Traditional farming versus technocracy. How does farmer age and education interact with tech adoption?

**Robots**

There is a need for robots that can remotely ID and remove weeds from pasture. Can we create a weed Roomba?

How do we improve remote sensing tools?

Is there adequate infrastructure (e.g. rural internet access)?

Big data platforms and computing are expensive and have short half-lives…

Tools for managing weeds, virtual farming and drones.

**Scaling-up experiments to farm level /Remote sensing**

Landscape scale evaluation of pasture health, persistence and interactions with farm system.

Creating visualization tool for farm management choices.

Improving representativeness of experiments via remote sensing, drones and algorithmic observations.

Distributed sensor systems for farm management and experimental work at scale.

Can sensors be developed to better understand multi-trophic biotic and abiotic interactions above and below ground?

Can we improve research for larger spatial and temporal scales to whole farm or larger scale (e.g. catchments) by using drone imaging/algorithms/management regimes?

Is technology development the kind of research we should do, or should we guide others, build relationships and interact with technology companies?

## Mātauranga Maori

**Perceptions of weeds**

Examining native species as weeds (Tutu, Matakoura, Manuka and Kanuka)

Weed whakapapa

Why is the weed present vs how to kill it?

Are weeds topmost of Maori concerns given all other challenges faced by rural Maori?

Changed or different perceptions of weeds.

**Engagement with Maori**

Few CRI’s have Maori engagement strategies.

Lack of risk assessments.

Engagement with Maori infrequent, despite possible areas of common ground.

Engagement protocols and processes.

Lack of understanding of Mātauranga Maori.

**Weed management**

Use of Mātauranga Maori to manage weeds in pastoral systems.

What are Maori concerns over use of exotic biological control organisms?

**Value chain economics**

Economic perspectives could provide insights into Maori perspectives and values.

Valuing non-financial outcomes.

Use of Mātauranga Maori in pastoral systems could have impacts on product value.

Farming under a non-productionist paradigm (is that a thing)?

Incentivizing the inclusion of native biodiversity in farms systems.

**Maori Science Capacity**

Maori science capacity is needed in society and institutions.

Mātauranga Maori experts are rare.

There is poor knowledge in science organizations about Maori partnership opportunities to improve weed management.

Assume that Maori representatives in organizations know community needs for weed management.

**Te Ao Maori**

Opportunities are available for pursuing long term scientific investigations on community owned land.

Much Maori land is both marginal and spatially fragmented creating special challenges for weed management.

What are the social implications of weed management in rural maori communities?

**Governance and consultation**

What are the existing government initiatives that support Maori involvement in science?

Who should be involved? Understanding this is a nationwide problem.

MBIE 5-year funding not sufficient to build long term relationships.

What responsibilities do scientists have under the treaty?

There are problems with coordinating collective ownership and arriving at a consensus.

Questions:

How does weed management look in farms managed under a Te Ao as opposed to conventional practices?

How does the NZ science community best practice look?

How do we take a cultural and contextual perspectives into account when defining weeds?

How do we redesign government funding initiatives to capture Maori needs?

How do we improve Maori science capacity using institutional and indigenous community knowledge?

How can we effectively engage with Maori to discuss issues with weed science?

Social license?

What are the opportunities for added value by accessing Mātauranga Maori and farming under Te Ao Maori?