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Review

Demonstrating efficacy of rural land management actions to improve water quality - How can we quantify what actions have been done?

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ABSTRACT

Despite several decades of encouraging land management actions to improve water quality on rural land, we are still struggling to accurately quantify what management actions have been implemented, where these actions have been used and the intensity of implementation. This is largely because standardised approaches to recording and reporting of land management actions have not been established, resulting in a lack of robust information that can be used to determine the effectiveness and longevity of these actions at a catchment or larger scale. Better information on the effectiveness of different land management actions will provide land managers with more certainty that their investments in land management actions will make a difference. We reviewed a total of 91 global publications and proceedings between 1989 and 2019 which assessed the complexities related to recording and reporting sustainable land use actions with a focus on freshwater ecosystems in rural areas in the developed world. We then summarised these complexities (i.e., temporal and spatial lag-effects, confidentiality issues, lack of data robustness) and mined the literature about methodologies on how actions can be measured, how to address the challenges with doing this and recommended a suite of indicators of land management actions that could be standardised and widely used to improve water quality. Our review of literature identified numerous sources describing land management actions, but little information on standardised indicators of location, scale and intensity of the most common actions. Some common actions are measured using a wide variety of incompatible approaches (e.g., riparian management is often indicated by length of fencing, width of vegetated buffer strips, proportion of the catchment with stock exclusion), whereas other indicators of land management action are at such a high level (e.g., costs) that they do not provide information on the actions used. The scale/intensity of land management efforts is often not reported spatially with information typically restricted to small scales such as single point location information, making it difficult, if not impossible to determine the scale of actions within a catchment relative to a given water quality monitoring site.

1. 1.Introduction

Globally, the long-lasting impacts of agricultural production on the rural environment are well recognised (Clark and Tilman, 2017; Food and Agriculture Organization of the United Nations, 2016; Molden, 2007; Steinfeld et al. 2006). The impacts on water quality are particularly prevalent, including elevated concentrations of diffuse pollutants such as nutrients (predominately N and P), sediment and faecal microbes from leaching and runoff (McDowell et al. 2003; Monaghan et al. 2005). In addition, rural stream habitats are often heavily physically modified and commonly degraded causing wide diel changes in pH, temperature and dissolved oxygen, as well as poor water clarity due to eroded fine sediment (Basher, 2013; Davies-Colley, 2013; Wilcock et al. 1999). At larger scales, in particular, the management of these diffuse pollutants is commonly referred to as a 'wicked problem' (Defries and Nagendra, 2017) as they originate from multiple sources, are influenced by multiple drivers and actors with contrasting values and spread across complex systems where possible solutions will vary from place to place (Gunningham and Sinclair, 2005; Kumar et al. 2019; Patterson et al. 2013). Delivering effective control of these pollution sources poses significant challenges, and despite decades of research how to best address this 'wicked problem', decision-makers worldwide have not been able to halt these profound impacts on our environment (Water/WWAP, 2015).

Numerous on-land management actions are being practiced globally

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to reduce the loss of contaminants from rural land, or to lessen their impact on their environments (Bernhardt and Palmer, 2011; Bernhardt et al. 2005; Palmer et al. 2005). However, testing of the effectiveness of agricultural on-land management actions is most commonly done at a small spatial scale (i.e., farm or reach scale), and there have been limited examples of quantifying the effectiveness at larger scales (i.e., (sub-) catchment scales). For land managers to be confident that their investment in mitigation actions will be returned, however, we need to find a way to measure our actions and report these at catchment scale. Failure to record and subsequently advise on the performance of mitigation actions is likely to lead to misallocation of resources and false expectations with regards to treatment speeds and expected positive outcomes (Daigneault et al. 2017b; Parliamentary Commissioner for the Environment, 2019). For example, in 2018, the New Zealand Ministry for the Environment conducted a survey asking environmental experts to rate the current state of availability of land management action data and what improvements are needed in New Zealand (Larned et al. 2018). They concluded that data on land management actions was generally unavailable at regional and national scales due to the lack of standardised procedures for data collection and classification. They highlighted the need for standard procedures for the collection and classification of this information and to develop a set of specific indicators that can be measured. Briefly, environmental indicators can be response-type indicators which describe the state of the environment and its impact on human beings, ecosystems and materials, as well as indicators of pressures on the environment (New Zealand Ministry for the Environment, 2007). Environmental indicators can also include action-type indicators which describe (re)actions of organisations or societies, such as sustainable land-use actions (Heink and Kowarik, 2010). Our review focusses on action-type indicators.

Without standardised recording methods, the effectiveness of land management actions is impossible to measure. This limits the ability to analyse project outcomes in terms of changes to water quality and ecosystem health and provide guidance for future projects (Bernhardt et al. 2007; Parliamentary Commissioner for the Environment, 2019; Robert et al. 2005). Over the last two decades, research has given us relevant insight on the kinds of land use actions that need to be implemented to address rural water quality degradation, especially in regions in temperate climates where water is not scarce. For example, the benefits of fencing and planting riparian margins to reduce the input of contaminants into waterways are well recognised (Bragina et al. 2017; Craig et al. 2008; Parkyn et al. 2003).

But we lack standardised approaches and techniques to robustly assess our actions by using relevant indicators. For example, Gilvear and Casas-Mulet (2008) assessed strategies for river restoration at a catchment scale for 127 projects throughout Scotland of which 48% anticipated monitoring, but only 32% had set up response indicators that measure the success or failure of a project. They concluded that despite the huge range of indicators used in their review (e.g., biological, physical, financial), Scotland lacks standardised approaches and techniques for recording and reporting on the outcomes of actions. Similar conclusions were found for the World Overview of Conservation Approaches and Technologies (WOCAT; www.wocat.net; accessed 09.09.2019) whose case studies offer an extensive collation of sustainable land use actions practiced with insight on the level of stakeholder and landowner participation, finances and impact analysis. However, their database does not provide any detailed recommendations on how to measure land management practices. WOCAT themselves recognised this gap and highlighted the need for development of mechanisms to measure and evaluate the effects of changes in land management projects (WOCAT, 2007).

One example which attempted to quantify environmental benefits of conservation practices at national, regional and catchment scales is the Conservation Effects Assessment Project (CEAP; accessed 09.01.2020), initiated by the United States Department of Agriculture (USDA) in 2002 (Duriancik et al. 2008). Data for these analyses are provided from modelled estimates as well as farmer surveys and show estimations of sediment, nutrients and pesticides that reach waterways after conservation practices are implemented (Mausbach and Dedrick, 2004). Despite this comprehensive database on conservation practices, the need for the recording of '*real effectiveness of precision conservation approaches for improving water quality*' remains (Tomer et al. 2014). We consider this step critical and will discuss potential approaches for measuring land use actions below.

In this paper, we use the term land management <u>action</u> to refer to actions that are being practiced on land to reduce the loss or transfer of contaminants to waterways (e.g., fencing, stock exclusion, changes to fertiliser use, altered stock management practices), and the term <u>indicator</u> to describe the type, location and/or intensity of the action (e.g., area of riparian planting, kilometres of stream bank fenced, number of farms adopting sediment reduction practices). Overall, indicators need to quantify actions that occur at varying intensity and scale (OECD, 2003). For some actions, indicators may provide data that describes intensity and scale such as the length and width of riparian planting, while for other actions, such as grazing management, indicators may simply state whether something is happening (or not), but do not provide details on the scale or intensity (Heink and Kowarik, 2010).

Taking learning from a literature review, we 1) have summarised the complexities associated with recording sustainable land management actions, 2) have synthesised the most widely used sustainable land management actions, 3) propose potential concepts on how to best quantify management actions, and 4) prioritised action indicators.

2. Methods

We reviewed a total of 91 global publications and proceedings from 1989 to 2019 which assessed the complexities related to recording and reporting sustainable rural land use actions with a focus on freshwater ecosystems. We then summarised these complexities (i.e., temporal and spatial lag-effects, confidentiality issues, lack of data robustness) and mined the literature to assess how actions can be measured, how to address the challenges with doing this and recommended a suite of indicators of land management actions that could be standardised and widely used to improve water quality.

Our literature search was primarily based on peer-reviewed journals, however, many project descriptions that summarised progress on sustainable land-use actions were recorded in governmental, unitary authority and consultancy reports. Search engines used included Web of Science, Scopus, Science Direct, ProQuest Central, ResearchGate and Google Scholar. Many of the non-scientific reports were available online from relevant websites. Key words that were used in the search included "agricultural best management practice (BMP)" + "good management practice" + "management actions" + "sustainable land use" + "mitigation" + "intervention" + "restoration" + "water quality" + "environmental recording and reporting".

3. Results and discussion

3.1. Complexities of recording land management actions – why is it so difficult?

Projects seeking to improve land management practices often have multiple objectives and multiple land management actions are being used to reduce the loss of contaminants from land or lessen their impact in receiving environments (McDowell et al. 2009, 2018; Melland et al. 2018). However, the location, scale and intensity of most of these actions have not been robustly recorded and/or appropriately reported on, demonstrating just how complex the process of recording land management actions is. To fully comprehend the magnitude of this complexity, we will discuss some of the challenges that arise when it comes to recording and reporting these actions.

3.1.1. Costs associated with collecting robust data

A key issue associated with the lack of available information on the types, location and intensity of land management actions is the cost associated with collecting and recording this information. This is especially important at large scales. Often resources are devoted to the implementation of actions, resulting in few resources being available for monitoring. Although several countries and regions have land degradation maps, mapping of land management actions has been 'badly' neglected (WOCAT, 2007). Depending on property size and topography, and the number of waterways present on the property, accurate measurement of riparian fencing and planting, for example, can be labour-intensive and costly (New Zealand Ministry for Primary Industries, 2016). However, with the right degree of buy-in recording of useful information can be done at substantial scales. For example, New Zealand's Taranaki Regional Council have been collaborating with farmers to develop individual riparian management plans for their properties since 1992, assessing the extent of riparian vegetation, type of fence, and farm numbers with riparian management plans. All information is recorded on-site at a paddock scale on a portable electronic device and then uploaded into the Council's internal Geographic Information System. The programme has been widely adopted and 2587 (99.5%) Taranaki dairy farms now have riparian management plans in place, 12,200 km (85%) of waterways are mapped and fenced and 7700 km (70%) of streambank is protected with riparian vegetation. Until the completion of the project in 2026, the total anticipated cost (including planting, fencing and collaborative engagement with over 2500 plan holders) to the farming sector is set at €52 million (Bedford, 2017).

The high costs associated with assessing on-land management actions could be addressed with affordable and applicable remote sensing tools and standardised restoration sampling methodologies. The increasing need for robust remote sensing methods has led to the development of a variety of approaches that combine different methods based on project needs, such as satellite or Unmanned Aerial Vehicle (UAV) imagery, or Light Detection And Ranging (LiDAR) interpretation (e.g., Dufour et al. 2013; Jeong et al. 2016). The applications of LiDAR and UAV systems include topographic mapping, surface movement detection as well as environmental monitoring. Dufour et al. (2013), for example, looked at the applicability of 3D imagery to provide information for narrow riparian planting strips with high temporal resolution to allow detailed monitoring following restoration programmes. Their high-resolution 3D LiDAR imagery (4-points per m^2 density) and height accuracy ($\pm$0.1 m) allowed them to conduct accurate biophysical measurements of leaf area, above ground biomass and bank erosion. Having adequate sampling tools available is an important step towards standardised sampling methodologies and the recent advances in imagery technology and sampling application development should help the development of robust and repeatable sampling protocols.

3.1.2. Privacy and confidentiality

One of the biggest issues related to the recording of any land management work is the restricted sharing and accessibility of data. The data that has been collected during changes in land management often 'belongs' to the implementer or funder of the project who have the right to decide whether the data will be made publicly available. Unfortunately, data collated as part of specific projects is often not shared with third parties due to privacy agreements which leads to valuable information being inaccessible to the public. This, again, can lead to duplication of effort as any lessons learnt during the process are not shared with others. Privacy related issues can be addressed by only reporting information at a larger spatial scale so information specific to individual properties is not made public. However, spatial aggregation of data means that some specific detail will be lost in the process. Spatial aggregation of information until sufficient thresholds are reached is a common tool used to address data confidentiality issues in other data reporting systems, such as census data (Buron and Fontaine, 2018; StatsNew Zealand - Tatauranga Aotearoa, 2018).

3.1.3. Lack of standardisation of recording methods

At present, we lack consistent ways to measure and quantify land management actions. This contrasts with the more common use of indicators associated with marketed goods and services in the economy. Goods and services are generally easy to define and monitor, so reporting of economic data is generally more comprehensive. For example, farm financial information describes how many different products and their exact amount are produced on the farm in a given year (e.g., number of livestock/kg of meat sold; how many ha of land planted in corn, etc.) and the amounts of inputs used (e.g., fuel used, kg of fertiliser bought, labour provided, etc.). However, because land management actions are typically not traded in markets, there has not been the same type of systematic effort spent to standardise the recording of these actions. Our review also showed that even if the effectiveness of land management actions were recorded, there are large inconsistencies in how this is done (e.g., ranging from paper records to digital recording and aerial coverage) and the level of quality assurance employed by the people/agencies recording the data (e.g., data collection by agencies with substantial data experience such as local government agencies through to individual property owners) (Parliamentary Commissioner for the Environment, 2019). Data collected by property owners is an example of citizen science which has become increasingly popular worldwide since the mid-1990s (Gordienko, 2013). The robustness and validity of such data, however, can be questionable due to limitations such as lack of adequate training in research and use of appropriate monitoring protocols. This uncertainty can lead to limitations in the suitability of data for different purposes.

3.1.4. Variability of data quality due to multiple spatial scales

In addition to the issue of multiple data providers, the scale at which sustainable land use actions are being recorded is equally important when assessing the effectiveness of land management efforts. The European Water Framework Directive (WFD) treats the river catchment as one interconnected system and describes it as an 'optimal management unit' to implement management (European Commission, 2012). However, land management and restoration projects worldwide are commonly implemented at reach-scale in the form of small and isolated projects. Land degradation happens at all scales - from farm to catchment scale - and any restoration planning should be done at spatial scales equivalent to the area where damage has occurred. But catchment-scale projects on land management are often not an option, due to, for example, high costs, difficulties in obtaining legal mandates or the large amount of effort required to coordinate land managers. Project managers typically narrow down their implementation area to targeted sections within a catchment instead of entire catchments or ecosystems (Doehring et al. 2019; Louhi et al. 2011; Parkyn et al. 2003). These sections only represent a fraction of the catchment and are biased towards the lower parts that are often densely populated and most intensively farmed. Spatial scales also commonly differ for data collection within a specific project, depending on who collects the data. For example, sustainable land use data recorded at a farm scale by individual landowners may be very different to sustainable land use data recorded on a regional or national scale conducted by sector groups or government agencies. These inconsistencies in scale for the recording of management actions are likely to lead to inconsistencies in the reporting of the outcomes and highlight the need for standards on how to record sustainable land management data.

3.1.5. Lag effect of management actions

For sustainable land management practices to be effective, we not only have to ask ourselves "At what scale do we need to apply management actions?", but also "How long will it take before we see any improvements in water quality?". Many sustainable land management efforts have reported little or no improvements in water quality even after extensive implementation of Best Management Practices (BMP) (Bond and Lake, 2003; Palmer et al. 2005; Roni et al. 2008), partly

Table 1
Most common land management strategies reported by management class/type. Modified from McDowell et al. (2018).

Land Management class/Type	Management strategy
Riparian for streams/rivers/wetlands	Fencing
	Stock exclusion
	Vegetated buffer strips/planting
	Riparian management plan
	Construction of artificial and natural seepage wetlands
Grazing & Crop management	Restricted grazing (of winter forage crops)
	Off-pasture animal confinement/controlled grazing
	Change animal type
	Supplementary feeding with low-N feeds/reduction of protein intake
	Minimum tillage and direct drilling of seed
	Cover crop after harvesting
	Stubble mulching
	Contour cultivation
	Grazing & Crop management plan
Nutrients & Contaminants	Restricted grazing (of winter forage crops)
	Off-pasture animal confinement/controlled grazing
	Bridging stock stream access
	Sediment traps/retention ponds/bunds/wetlands
	Change animal type
	Precision application of fertiliser
	Denitrification beds
	Diuretic supplementation (increased salt intake)
	Supplementary feeding with low-N feeds/reduction of protein intake
	Tile drain amendments
	Low water-soluble P fertiliser
	Nitrification inhibitors
	Nutrient & contaminant management plan
Soil conservation & Erosion control (incl. Critical source run-off)	Sediment traps/retention ponds/bunds/wetlands
	Restricted grazing (of winter forage crops)
	Off-pasture animal confinement/controlled grazing
	Afforestation/windbreaks
	Bridging stock stream access
	Tile drain amendments
	Contour drains/benched headlands/slopes
	Contour cultivation
	Cover crop after harvesting
	Minimum tillage/direct drilling of seed
	Silt fence/trap
	Stubble mulching
	Wheel track dyking/ripping
	Wind break crop
	Preventing fence-line pacing (deer)
	Alternative wallowing (deer)
	Application aluminium sulphate to forage cropland/to pasture
	Red mud (bauxite) to land
	Soil conservation plan/Erosion management plan
	Critical source run-off management plan
Water use	Precision irrigation
	Refurbishing and widening flood irrigation bays
	Dams and water recycling
	Water use management plan
Effluent management	Greater effluent pond storage and deferred irrigation
	Low rate application to land
	Enhanced pond system
	Effluent management plan
Generic to all farming practices	Establishment of Farm Environment Plans (FEP)
	Establishment of Good Management Practices (GMP)
	Participation

because monitoring programmes are often designed to run over short to medium time frames (i.e., 5–10 years) which are too short to demonstrate any water quality or ecosystem health improvements. One of the key components adding to the complexity of measuring outcomes of sustainable land use practices is the lag in time before a response to actions can be seen (Meals et al. 2010; Viaud et al. 2004). Although water quality monitoring post-mitigation may be well designed and implemented, envisaged improvements may not occur as quickly as hoped and cannot be clearly linked to specific land management efforts. Lag times depend on many variables taking place at various dimensions and are therefore difficult to predict. For example, Meals et al. (2010) listed examples of lag times in response to environmental impact or treatment which ranged from $<$1 year (for faecal bacteria waste management) to over 50 years (for sediment erosion control at a catchment scale). Puckett (2002) studied transfer times of nutrients through riparian buffer zones to streams and found lag times of 5 up to 200 years due to the residence time in the groundwater within the catchment area. Various other studies have investigated the effects of lag time on restoration outcomes (i.e., Boesch et al. 2001; Hamilton, 2012; Louhi et al. 2011; Wilcock et al. 2013; Wohl et al. 2015), highlighting the complexity of this issue and the subsequent difficulties for demonstrating the effectiveness of management efforts. To detect any shifts in water quality, we suggest that environmental monitoring programmes need to span over at least ten years to provide sufficient statistical power to detect trends given high natural variability in some water quality parameters (e.g., water temperature and nitrate concentrations). In addition, the time taken for actions to be implemented and long-term shifts, such as climatic cycles, market forces or slow rate of adoption need to be recognised (Bernhardt and Palmer, 2011; Kondolf and Micheli, 1995; Wilcock et al. 2013).

3.2. Common land management actions and how to report them

Our review found that very few land management initiatives focussed on a single land management action. Instead, most included a combination of actions at both, small and larger scales tailored to suit the physical conditions (soil, climate and slope), farming types, and the community within a catchment. This large tapestry of land management actions makes it challenging to design, measure and report the combinations of actions at the catchment scale. Environmental status is usually assessed at large, water body scale (e.g. lake ecosystems), rather than the scale at which actions are typically implemented (e.g., reach-scale), meaning that evidence is increasingly required on the scope for combined or integrated diffuse agricultural pollution control actions to help achieve policy targets (Bouraoui and Grizzetti, 2014). We found that the dominant recorder and reporter of land management actions worldwide are central government agencies, regional or local government agencies, industry groups, indigenous groups (such as Māori in New Zealand), community and farmer groups, and not-for-profit organisations, due to their role in co-ordinating and funding land management actions on individual, or across multiple, properties. We identified the following key management classes to be universal: riparian (including wetlands), grazing and crop management, nutrients and contaminants, soil conservation/erosion control/critical source run-off, water use, effluent and management strategies generic to all farming practices (Table 1).

3.2.1. Recording and reporting land management actions by effectiveness

The concept of grouping (also commonly called clustering/bundling) of land management actions enables comparisons of effort between situations without needing to describe detail of every individual action. Depending on the management outcomes desired, many kinds of grouping are being applied. For example, a commonly applied grouping of management actions is based on cost, as managers generally know the funding received and costs associated with certain projects (Daigneault and Elliot, 2017a; Matheson et al. 2018; Vibart et al. 2015).

Grouping management actions by effectiveness, however, is one of the most prevalent strategies applied for land management because it can be meaningfully linked to outcomes. By doing so, multiple sectors can be covered by a single system, because each sector follows a consistent and rigorous assessment process, allowing their effectiveness at reducing a given contaminant to be compared at the end. For example, management actions categorised as ‘good’ for the forestry sector are likely to be different from management strategies categorised as ‘good’ for horticulture, however, by applying an overarching categorical system each sector's score can be assessed for relative effectiveness and used to report on an area of land which contributes to an overall measurable score for a region or catchment. McDowell et al. (2018), for example, systematically evaluated and scored management actions based on their effectiveness (%), relative cost ($/ha/yr) and response rate (fast, moderate, slow) to reduce on-land agricultural contaminants such as nitrogen, phosphorus, sediment and *E. coli.* The actions that scored highest were the most suitable for reducing a given contaminant in any situation. For example, stream fencing is a highly effective action for phosphorus mitigation associated with low costs and a fast response rate, however, for mitigation of sediment contamination, stream fencing is less effective, although still low in costs and with fast response rates.

Another concept of grouping land management actions by effectiveness is done through Farm Environment Plans (FEPs) which are typically used by the agricultural and horticultural sectors in New Zealand and Australia (Federated Farmers, 2018; Manderson, 2018). FEPs provide a useful basis for reporting and are likely to provide an existing data source that can be used to report indicators. In New Zealand, FEPs are emerging as a tool for land managers to record progress on actions to address water quality and have been proposed as part of latest freshwater management strategies by central government (Federated Farmers, 2018; NZ Ministry for the Environment, 2019). FEP's can be driven by regulation, such as resource management plans or resource consent requirements, or by industry quality assurance schemes such as the Environment Management System (EMS) or Cleaner Production (CP) approaches (Cheremisinoff and Bendavid-Val, 2001; El-Haggar, 2007; New Zealand Gap, 2019). These plans often use three to four levels of action. For example, Irrigation New Zealand (2019) grouped actions in their FEP based on ‘acceptability of practices’ from ‘poor’ to ‘premium’, meaning that if a required outcome such as the design and installation of new irrigation infrastructure is ‘poor’, then there were no design or installation checks done by the landowner and the action is categorised as ‘generally inadequate’. If the outcome was ‘basic’, then the system has been designed with ‘site specific knowledge of the soil, climate and crop needs’ and the action is categorised as ‘potentially adequate for small blocks with low application depth’. A ‘good’ outcome means that ‘all new irrigation infrastructure has been installed in accordance with Installation Code of Practice’ and the action is categorised as a ‘minimum for most spray irrigators’. Finally, the ‘premium’ outcome requires the landowner to use ‘comprehensive evaluation and decision-making processes’ which are ‘required to ensure [that the] design can achieve effective and efficient use of water’. This process is followed for a range of management objectives, including irrigation system design and installation, irrigation management, nutrient and soil management, effluent management, etc. (Irrigation New Zealand, 2019).

Based on the growing popularity of FEPs as tools for environmental recording and reporting worldwide, but also for the purposes of reporting at national scales, we consider the grouping of management actions by effectiveness the most applicable way of grouping. For the purpose of this review, we will adopt the ranking system used by Irrigation New Zealand (i.e., poor, basic, good, premium) as indicators of measuring management actions. We have used this strategy and applied it as an indicator in Table 2 to quantify the implications of management plans for a range of land management classes.

3.3. Reporting of land management indicators to measure common actions

The importance of long-term monitoring of land management actions has been recognised for some time. We argue, however, that one of the biggest impediments to demonstrating whether changes to land management have been effective, is the lack of robust and repeatable indicators of the types and intensity of these actions at appropriate scales (i.e., catchment versus reach-scales). As such, we are unable to answer ‘simple’ questions like ‘what percent of the riparian length in a catchment is planted?‘, or ‘on what percentage of grazed land are low N-feeds used for supplementary feeding?‘.

Without robust indicators, we cannot confidently say whether certain actions can be related to water quality or ecological responses (Parliamentary Commissioner for the Environment, 2019; Rubin et al. 2017; Woolsey et al. 2007). Our review focussed on literature sources describing projects which aimed to improve water quality based on land management actions and the indicators used to measure their location and extent. We found that land management indicators suitable for reporting generally followed global Tier 1 statistics classifications. For these, indicators need to be clear, relevant, authoritative and trustworthy, provide long-term continuity and enable international comparability (IAEG - SDG, 2019; OECD, 2017). Statistics NZ, for example, have developed ten principles which guide the production of Tier 1 statistics. These include criteria such as relevance, integrity, quality,

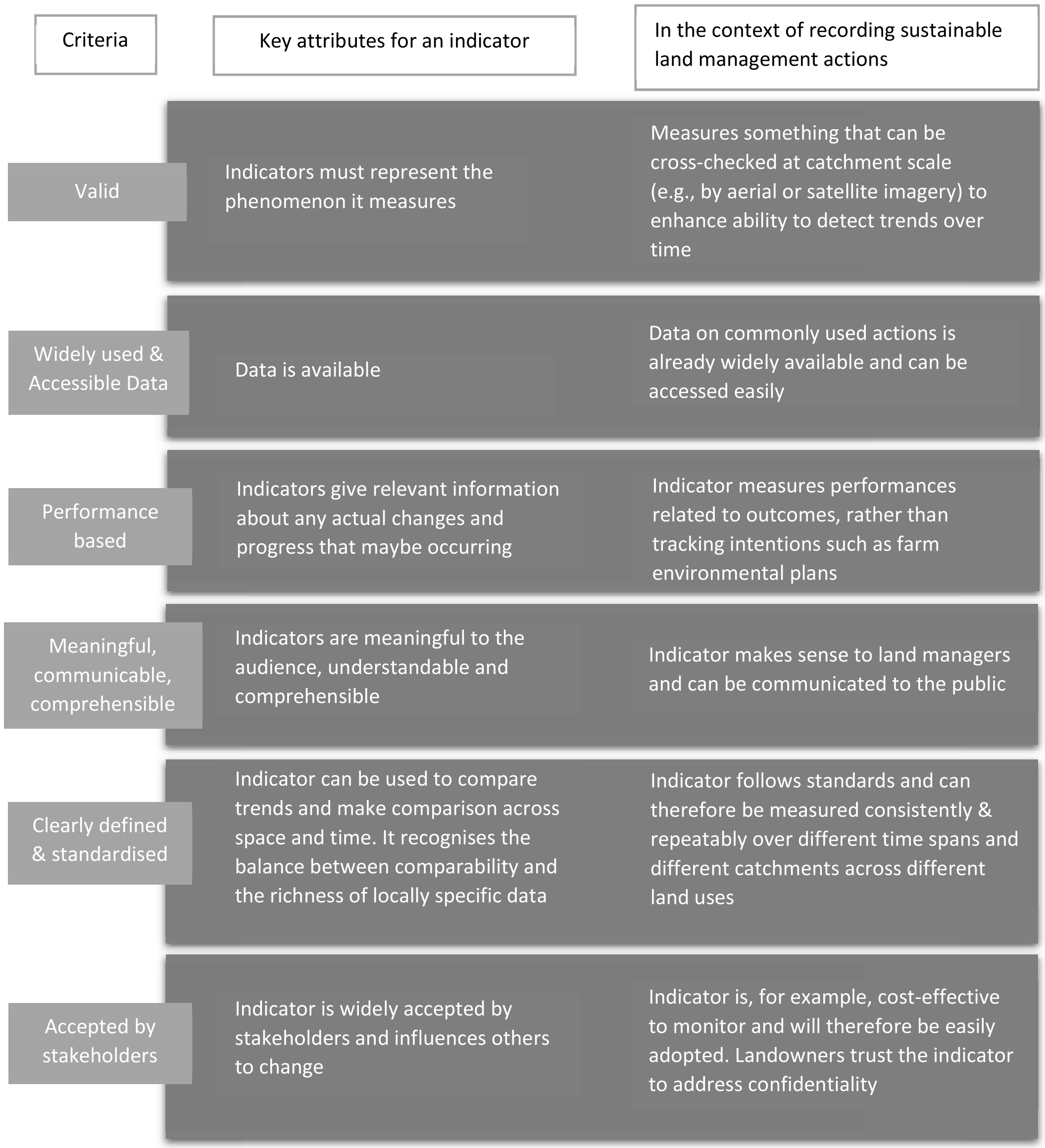

Fig. 1. Recommended criteria for indicators of management actions to improve water quality and their associated attributes (synthesised from commonly applied criteria for indicator development).

coherence, confidentiality, efficiency or accessibility (Statistics NZ, 2018). Another classification was proposed by Pricewaterhouse PwC (2017) who recommended key criteria for fit for purpose indicators for the 'Our Land and Water National Science Challenge' in New Zealand. Briefly, the Challenge aims to facilitate changes in land use practices to improve both, the value derived from agriculture and the environmental effects of agriculture (Our Land and Water - Toitu¯ te Whenua, 2019). We combined and adjusted these global Tier 1 criteria classifications to support the assessment of the sustainable land action indicators identified in this review (Fig. 1). We are also anticipating applying these in the development of a New Zealand wide register of management actions with the aim of providing information to land managers to ultimately improve water quality (Table 2).

It is important to consider that when developing indicators, we are aware of the differences between indicators used for recording actions and how we report on these. For example, while land managers might record an indicator measuring the length of stream fenced on their farm, the adequate reporting indicator could be the percentage of streams fenced within a catchment. This difference, albeit subtle, needs to be in the back of our minds when developing indicators for sustainable land management actions, as the reported outcome may be quite different from the initially recorded action. Otherwise, there could be misrepresentation of the land use actions conducted at large scales.

Table 2 summarises land management indicators based on the grouping of land management actions synthesised in Table 1 and the adoption and reporting criteria listed in Fig. 1. Each indicator has been scored against the six criteria described in Fig. 1 (i.e., valid, widely used/accessible data, performance based, meaningful/communicable/comprehensible, clearly defined/standardised, accepted by stakeholders) based on expert opinion. For this, each indicator was given a score from one to five for each criterion, enabling us to distinguish between more appropriate (i.e., higher scores) or less appropriate indicators (i.e., lower scores; Table 2). We believe it is important to highlight the subjectivity of the scoring process applied for indicators in Table 2. Each indicator might be given a different score, depending on local circumstances. We, thus, recommend that each indicator should be re-tested and re-scored by land managers at scales and land uses relevant to their situation (e.g., local catchment scale for dairy land use).

4. Conclusions and recommendations

The value of recording and reporting actions is well-recognised, and while information is being recorded, it is not done consistently. Hence, standardised recording and reporting of land management actions is a critical gap in international efforts to improve freshwater ecosystem health (WOCAT, 2007). Our review has shown that although monitoring of land management actions has increased over the past decade, documenting them has not been given sufficient priority, despite the billions of dollars spent annually on implementation (e.g., Australian Government and Queensland Government, 2016).

The key challenges associated with recording and reporting of sustainable land use actions are 1) costs associated with collecting robust data, 2) privacy and confidentiality, 3) lack of standardised recording methods, 3) variability of data quality due to multiple spatial scales, and 4) lag effects of management actions on water quality outcomes.

Given these challenges, there is value in a coordinated effort across multiple catchments and collaboration among parties who collect and/or report data. However, our review of international initiatives and literature neither found a reporting system that incorporated data on land management actions from multiple sources across catchment-scales, nor clear recommendations on potential indicators and measuring techniques for those actions. To fill these gaps, we recommend:

a) The grouping of land management actions by effectiveness and reporting them as seven overarching 'land management classes': 1) riparian (streams, rivers, wetlands), 2) grazing and crop management, 3) nutrients and contaminants, 4) soil conservation and erosion control, 5) water uses, 6) effluent management, and 7) generic to all farm practices;
b) The adoption of the following six indicator criteria: 1) validity, 2) widely used and accessible, 3) performance-based, 4) meaningful, communicable and comprehensible, 5) clearly defined and standardised, and 6) accepted by stakeholders;
c) Using Farm Environmental Plans as a recording platform of land management practices (recognising that some information on actions is also available from communities, government or specific funding agencies);
d) The recording of land management actions based on the highest scoring indicators (see Table 2 for detailed information).

Land managers have recognised the need to develop practical tools and guidelines for the design of cost-effective land management actions and acknowledge the importance of detailed pre- and post-recording of these actions and feedback techniques, such as the 'Plan – Do – Check – Act' cycle, setting SMART project objectives and BACI monitoring. While these systems are useful tools, most do not provide guidance on how to systematically record sustainable land use actions. However, without data on the extent and intensity of implementation of actions and changes in land management, managers and implementors are unable to confidently link improvements in catchment water quality to a specific management action which makes them unable to determine the effectiveness of their investment at catchment-scales. In addition, adoption strategies of proposed practices need to be developed early in the planning process to ensure that land management actions are successfully used. If land management recommendations are to influence practice, then the success of these will depend on gaining landowner confidence and addressing concerns about confidentiality.

Investment in sustainable land practice is extensive but without consistent recording and reporting there is a lost opportunity to better understand the links between actions and freshwater outcomes. We therefore believe that a register recording sustainable land use actions using the indicators identified in this review as a starting point will be a useful first step to help demonstrate the scale and type of actions needed to improve water quality. This will prove a necessary contribution to the aim of improving the health of our global freshwater ecosystems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2020.110475.

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Table 2/Appendix. Common land management actions and their proposed indicators to quantify the location, extent, and intensity of each land management class/type. The order of the content has not been ranked and actions and indicators are listed arbitrarily.

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Riparian for streams/ rivers/ wetlands	Fencing	Length of fencing (including virtual fencing) installed per landowner/ farm, # of wetlands/ springheads fenced	25	- GIS mapping - Digital aerial photography (e.g., satellite/ plane/ drone imagery) - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Community group reporting - Project reports for funded projects including those by catchment collectives	(Doehring *et al.* 2019; Hicks *et al.* 2001; Manderson 2018; McDowell 2008; Muirhead 2016; Wilcock *et al.* 2013)
		% of streams/ wetlands fenced	26		
		Quality/ permanence of fencing (e.g., electric vs. 5-wire)	18		
	Stock exclusion	% of streams/ wetlands with effective stock exclusion	26		
	Vegetated buffer strips/ planting	Length/ width/ area of riparian planting per landowner/ farm/ wetland	27		(Graham *et al.* 2018; Hicks *et al.* 2001; Manderson 2018; NZ National Riparian Database)
		% of bank length planted	25		
		# of seedlings planted	21		
	Riparian management plan	Area/ # of properties with riparian plans prepared and implemented	24		(Dairy Environment Leadership Group (DELG) 2015; Graham *et al.* 2018; Manderson 2018; Manderson *et al.* 2007; Taranaki Regional Council 2019; Waikato River Authority 2018; Whakaora Te Waihora 2017)
		# of people employed in restoration initiatives	16		
		% of land with active riparian management plans	24		
		Area/ % of land falling into/ # of landowners implementing 'poor/basic/good/premium' riparian/wetland management practices as set out in farm plans	25		
	Construction of artificial & natural seepage wetlands	Area/ # of artificial and natural seepage wetlands established	20		(Headley *et al.* 2008; Mitsch 1995)

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Grazing & Crop management	Restricted grazing (of winter forage crops)	Area/ % of land retired during winter grazing	21	- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives - ABCD (Advanced, Best, Conventional, Dated) banding for grazing practices - GIS mapping - Digital aerial photography (e.g., satellite/ plane/ drone imagery)	(Christensen *et al.* 2012; de Klein *et al.* 2011; Fleming 2003; Godwin *et al.* 2003; Hicks *et al.* 2001; Hoogendoorn *et al.* 2011; Irrigation New Zealand 2019; Ledgard *et al.* 2006; Lynch *et al.* 2018; McDowell *et al.* 2009b; Monaghan *et al.* 2008; Wheeler 2016)
		# of stock unit grazing days (SUGD)	26		
	Off-pasture animal confinement/ controlled grazing	Area of stand-off areas	22		(Christensen *et al.* 2012; Collins *et al.* 2013; de Klein *et al.* 2011; Hoogendoorn *et al.* 2011; State of Queensland 2018)
		Time per year spent on stand-off	21		
		Area/ # of properties adopting strategic grazing management (e.g., duration-controlled grazing)	22		
	Change animal type	# of stock units per animal type	23		(Haynes *et al.* 1993; Hoogendoorn *et al.* 2011)
	Supplementary feeding with low-N feeds/ reduction of protein intake	% of reduction of protein concentration in feed by improving the match between the protein quality fed and that required by the animal	12	- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives	(Barber 2014; Basher 2013; Basher *et al.* 2016; Basher *et al.* 1997; Beukes *et al.* 2012; Clark *et al.* 2007; Rotz 2004)
	Minimum tillage/ direct drilling of seed	Area of land where minimum tillage and direct drilling of seeds has been implemented	24		
	Cover crop after harvesting	Area of land planted in cover crops	22		
	Stubble mulching	Area of land in stubble/ mulched	21		
	Contour cultivation	% of cultivated land that has used contour cultivation	18		
		Size of bank height/ channel depth	8		
	Grazing & Crop management plan	# of properties with grazing & crop management plans prepared	22		(Australian Government & Queensland Government 2016; CEAP 2015; Gooday *et al.* 2015; Gourley *et al.* 2012; State of Queensland 2018; Zhang *et al.* 2012; Zhang *et al.* 2014)
		% of farm with established soil maps	20		
		Area/ % of land falling into/ # of landowners implementing 'poor/basic/good/premium' grazing and crop management practices as set out in farm plans	25		

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Nutrients & Contaminants	Restricted grazing (of winter forage crops)	As for Grazing & Crop management		- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives - GIS mapping - Digital aerial photography (e.g., satellite/ plane/ drone imagery)	As for Grazing & Crop management
	Off-pasture animal confinement/ controlled grazing	As for Grazing & Crop management			As for Grazing & Crop management
	Bridging stock stream access	# of stream crossings avoided via culverts or bridges	27		(Davies-Colley *et al.* 2004) (Dairy Environment Leadership Group (DELG) 2015)
	Sediment traps/ retention ponds/ bunds/ wetlands	# of sediment traps/ retention ponds/ detainment bunds/ wetlands in place/ constructed	21		(Bryant *et al.* 2007; Clarke *et al.* 2013; de Klein *et al.* 2011; Hicks 1995; Ledgard *et al.* 2006)
		% of drainage area filtered by sediment traps/ retention ponds/ bunds/ wetlands	21		
		Size of bank height/ channel depth	8		
		Storage capacity to contributing catchment ratio (e.g., at least 120 m^3: 1 ha)	22		
		Retention time of traps/ ponds/ bunds/ wetlands	20		
	Change animal type	As for Grazing & Crop management			As for Grazing & Crop management
	Diuretic supplementation (increased salt intake)	# of properties using diuretic supplementation	17		(BoP Regional Council *et al.* 2018; Burns *et al.* 2002; Hively *et al.* 2009; James *et al.* 2007; Ledgard *et al.* 2007; Manderson 2018; Muirhead 2016)
	Precision application	Area/ # of properties using nutrient management systems/ nutrient budgeting tools	25	- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives	(Collins *et al.* 2013; Godwin *et al.* 2003; Hedley *et al.* 2010)
	Denitrification beds	Area/ #/ capacity of denitrification bed	19		(Barkle 2006; Schipper *et al.* 2010)
	Supplementary feeding with low-N feeds/ reduction of protein intake	As for Grazing & Crop management			As for Grazing & Crop management
	Tile drain amendments	Proportion of tile drains that have had P-sorbing materials (e.g., Ca, Al, Fe) used for backfilling	14		(McDowell *et al.* 2008; State of Queensland 2018)
	Low water-soluble P fertiliser	% of land fertilised with low water-soluble P fertiliser	19		(McDowell *et al.* 2003)
	Nitrification inhibitors	Area of land with nitrification inhibitors applied	18		(Clough *et al.* 2011; Cookson *et al.* 2002; Di *et al.* 2002; Monaghan *et al.* 2009)
	Nutrient & contaminant management plan	# of properties with nutrient management plans prepared	22		(Australian Government & Queensland Government 2016; CEAP 2015; Gooday *et al.* 2015; Gourley *et al.* 2012; State of Queensland 2018; Zhang *et al.* 2012; Zhang *et al.* 2014)
		Area/ % of land falling into/ # of landowner implementing 'poor/basic/good/premium' nutrient & contaminant management practices as set out in farm plans	25		

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Soil conservation & Erosion control (incl. critical source run-off)	Sediment traps/ retention ponds/ bunds/ wetlands	As for Nutrients & Contaminants		- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives and regional council hill country erosion programmes (e.g., SLUI (NZ)) - GIS mapping; digital aerial photography (e.g., satellite/ plane/ drone imagery) - Digital change detection analysis of land cover using satellite imagery	(Barber 2014; Basher *et al.* 2016; Bidelspach *et al.* 2004; Bryant *et al.* 2007; Clarke *et al.* 2013; Cooper *et al.* 2018; Hicks *et al.* 2001; Hicks 1995; Hudson 2002; Manderson 2018)
	Restricted grazing (of winter forage crops)	As for Grazing & Crop management			As for Grazing & Crop management; (Basher *et al.* 2016)
	Off-pasture animal confinement/ controlled grazing	As for Grazing & Crop management			
	Afforestation/ windbreaks	Area of afforestation/ planting established for soil conservation	26		(Barber 2014; Basher *et al.* 2016; Hicks *et al.* 2001; Hicks 1995; Lyon *et al.* 1998; Manderson 2018; Ross *et al.* 2000; Rwanga *et al.* 2017)
		# of soil conservation poles planted	24		
		% of land with afforestation	25		
		Area of shelterbelt	21		
	Bridging stock stream access	As for Nutrients & Contaminants			As for nutrients
	Tile drain amendments	As for Nutrients & Contaminants			As for nutrients
	Contour drains/ benched headlands/ slopes	% of cultivated land that has used contour drains/ benched headlands/ slopes	17		(Barber 2014; Basher 2013; Basher *et al.* 2002; Basher *et al.* 2016; Bryant *et al.* 2007)
		Area/ # of headlands benched and/ or constructed	15		
		Surface runoff volume	13		
		Size of bank height/ channel depth	8		
		Length of contour drains put in place	17		
	Contour cultivation	As for Grazing & Crop management			(Barber 2014; Basher *et al.* 2016; Bryant *et al.* 2007)
	Cover crop after harvesting	As for Grazing & Crop management			(Barber 2014; Basher *et al.* 2016)
	Minimum tillage/ direct drilling of seed	As for Grazing & Crop management			(Barber 2014; Basher *et al.* 1997; Hicks *et al.* 2001)
	Silt fence/ trap	Area/ %/ slope of cultivated land that has silt fence/ trap installed	19		(Barber 2014; Basher *et al.* 2016; Bryant *et al.* 2007)
		Length of silt fence established	18		
	Stubble mulching	As for Grazing & Crop management			(Basher 2013; Basher *et al.* 2016)
	Wheel track dyking/ ripping	Length/ % of wheel tracks modified to minimise run-off	18		(Barber 2014; Basher *et al.* 2016)
	Wind break crop	Area of land planted in wind break crops	23		(Basher 2013; Basher *et al.* 2016; McDowell *et al.* 2008; Ross *et al.* 2000)
	Preventing fence-line pacing (deer)	% of fence lines planted with trees	15		(McDowell *et al.* 2006)
	Alternative wallowing (deer)	# of artificial wallows created	19		(McDowell 2009)
		Distance of wallows to waterway	18		

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Soil conservation & Erosion control (incl. critical source run-off) (Cont'd)	Application aluminium sulphate to forage cropland/ to pasture	Area/ % of land where alum has been applied	17	- Information entered into decision support tools such as Farmscoper (UK), Separate (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Project reports for funded projects including those by catchment collectives and regional council hill country erosion programmes (e.g., SLUI (NZ)) - GIS mapping; digital aerial photography (e.g., satellite/ plane/ drone imagery) - Digital change detection analysis of land cover using satellite imagery	(McDowell 2015; McDowell *et al.* 2009a; McDowell *et al.* 2014)
	Red mud (bauxite) to land	Area/ % of land where bauxite has been applied	17		(Summers *et al.* 1993; Vlahos *et al.* 1989)
	Soil conservation plan/ Erosion management plan	# of properties with soil conservation plans prepared and implemented	26		(Barber 2014; Basher *et al.* 2016; Cooper *et al.* 2018; Gooday *et al.* 2015; Hicks 1995; Manderson 2018; Zhang *et al.* 2012; Zhang *et al.* 2014)
		Area/ % of farm with established soil maps	21		
		Area/ % of land falling into/ # of landowners implementing 'poor/basic/good/premium' soil conservation/ erosion management practices as set out in farm plans	25		
	Critical source run-off management plan	Area/ % of land/ # of properties that have implemented farm environment plan recommendations for critical source areas	27		(Gooday *et al.* 2015; Lynch *et al.* 2018; Manderson *et al.* 2007; Zhang *et al.* 2012; Zhang *et al.* 2014)
		Length/ % of farm track designed, located and surfaced to minimise run-off	21		
		Area/ % of land falling into/ # of landowners implementing 'poor/basic/good/premium' critical source run-off management practises as set out in farm plans	25		
Water use	Precision irrigation	# of soil moisture sensors and automated irrigators installed	22	- Information entered into decision support tools such as Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Water meter records (e.g., resource consent information)	(Barlow *et al.* 2005; CEAP 2015; Central Plains Water Ltd 2018; Hedley *et al.* 2010; Houlbrooke *et al.* 2008; Irrigation New Zealand 2019; OECD 2010)
		#/ % of farms using Variable/ Uniform Rate Irrigation (VRI/URI) systems in a catchment	17		
	Refurbishing and widening flood irrigation bays	# of irrigation bays that have been re-contoured to prevent outwash	15		
	Dams and water recycling	# of dams/ water recycling practices per property	25		
	Water use management plan	Area/ % of irrigated land managed with soil moisture data	28		
		Area/ % of land falling into/ # of landowners using 'poor/basic/good/premium' water use management practice	25		

Land Management class/ Type	Management strategy	Potential indicators of action	Score (out of 30)	Potential methodology	Source (covering management strategies and/ or indicators and/ or methodologies)
Effluent management	Greater effluent pond storage and deferred irrigation	Area of effluent pond in proportion to managed land	17	- Information entered into decision support tools such as effluent spreading calculators, Farmscoper (UK), Overseer (NZ) - Acquisition of farm data through farm business surveys - Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Resource consent information	(DairyNZ 2015; Houlbrooke *et al.* 2004; Houlbrooke *et al.* 2008; Manderson 2018)
	Low rate application to land	Amount/ % of effluent applied with low rate application	22		
		# of low-rate sprinklers	20		
	Enhanced pond system	# of upgraded/ enhanced effluent systems in place (e.g., Covered Anaerobic Ponds or High Rate Algal Ponds)	23		(Craggs *et al.* 2014; Stuart 2015)
	Effluent management plan	# of animal units where waste is managed according to waste management guidelines	15		(Dairy Environment Leadership Group (DELG) 2015; Gooday *et al.* 2015; Zhang *et al.* 2012)
		Area/ % of land falling into/ # of landowners implementing 'poor/basic/good/premium' effluent management practices as set out in farm plans	25		
Generic to all farming practices	Establishment of Farm Environment Plans (FEP)	Area/ # of FEPs prepared/ completed/ covered	24	- Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Resource consent information - Acquisition of farm data through farm business surveys for actions implemented - Project reports for funded projects including those by catchment collectives and regional council	(Australian Government & Queensland Government 2016; CEAP 2015; Central Plains Water Ltd 2018; Federated Farmers *et al.* 2018; Living Water 2016; Manderson 2018; Manderson *et al.* 2007; Origin Green Ireland 2016; Savage *et al.* 2013; State of Queensland 2018)
		Area/ # of FEPs prepared in priority areas	23		
		Area/ # of FEPs actively implementing works	25		
		Area/ # of FEPs audited (as required by regulation or market assurance systems)	26		
	Establishment of Good Management Practices (GMP)	Area/ % of land falling into/ # of landowners using 'poor/basic/good/premium' practice	25	- Farm audits - Landowner reporting (e.g., actions in FEP, industry reporting) - Resource consent information - Acquisition of farm data through farm business surveys for actions implemented	
		# of new sustainable GMP solutions trialled	18		
	Participation	#/ % of land managers involved in/ adopted projects	21	- Project reports for funded projects including those by catchment collectives and regional council	(Chesapeake Bay Program 2015; Gourley *et al.* 2012; Novo *et al.* 2017; NZ Landcare Trust 2012, 2016; State of Queensland 2018; WOCAT 2007)
		# of adoption strategies within a project	22		

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