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An assessment framework for measuring agroecosystem health

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ABSTRACT

There are inherent social, environmental, and economic trade-offs in agricultural systems, which by definition have been altered from their natural state by humans for food and fibre production. Consumers are increasingly concerned about the environmental and social impacts of agriculture, and with the increasing influence of social media, agribusinesses and industries can be held accountable for their actions in the public domain. Thus, environmental sustainability reporting is increasingly being viewed as a cost of doing business in agriculture. There are a number of approaches used to measure agroecosystem health (AEH) around the world, but they are generally designed to make comparisons at coarse spatial scales (i.e. nations) or report on specific management actions implemented at the local scale (i.e. farm, catchment, or sub-region). Here we present a simple, yet scientifically robust assessment framework that can be used to benchmark and monitor the specific impacts of agricultural management practices on the environment. The general principles are drawn from environmental monitoring and experiences gained in environmental assessments that are not necessarily agriculturally focussed. However, many commonly used environmental indicators are not suitable for AEH assessment because they do not explicitly link environmental outcomes to management actions; or they fail to separate specific agricultural impacts from broader cumulative impacts resulting from other industries or land uses. We recommend using a combination of diagnostic, outcome-based indicators, in addition to practice- and product-based measures to communicate efforts to improve agroecosystem health outcomes. The framework presented here enables assessments at local scales, but can be aggregated or disaggregated to report at finer or coarser scales. This flexibility ensures that the assessment is relevant to the proponent and stakeholders, while also providing a way to make comparisons between producers, industries, or regions as part of an adaptive monitoring and assessment framework. This also opens the door for industry-based AEH monitoring program to provide, or make use of information from government-funded environmental monitoring programs, with benefits to both.

1. Introduction

There are many different definitions of agroecosystem health (AEH), but underpinning these is the concept that a healthy agroecosystem is economically viable, managed in a socially responsible manner, and environmentally sustainable for present and future generations (Schaller, 1989; Gitau et al., 2008; Ikerd, 2008). However, there are inherent trade-offs among economic, social and environmental outcomes in these systems (Tilman et al., 2002; Ikerd 2008; Gitau et al., 2008). Increasing demand for agricultural production is placing pressures on the environment, with significant negative consequences (Foley et al., 2005; OECD, 2013; Madeau et al., 2014). As a result, the public, media, and non-governmental organisations (NGOs) often have negative perceptions of agricultural industries (Luhman and Theuvsen, 2016). Consumers are increasingly concerned about the social and environmental impacts of agriculture, and with the advent of

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the internet and social media, agribusinesses and industries can be held accountable for their actions in the public domain (Ross et al., 2015). Public campaigns focussing on pollution (e.g. Jay, 2007), human health (e.g. Pew Charitable Trusts, 2012), or animal welfare (e.g. Healy and Burns, 2013) issues can damage an industry's social license-to-operate (Maloni and Brown, 2006; Luhmann and Theuvsen, 2016), and subsequently lead to loss of market access, increased regulatory conditions imposed by government (Jay, 2007), and financial losses associated with damage to brand name (Ross et al., 2015). Thus, environmental sustainability reporting is increasingly being viewed as a cost of doing business in the agricultural domain (Porter and Kramer, 2006). Although the drivers for environmental assessment within the agricultural industry are different than those in a traditional environmental monitoring program, we believe that many of the lessons learned are transferable to the private sector and can be used to develop a rigorous and targeted approach to AEH assessment.

Agricultural endeavours in most countries occur in a market-driven context, where the private economic benefit derived from selling products is a primary driver of decision making (Neher, 1992; OECD, 2013). At the same time, producers are often responsible for the management of large areas of land (Tilman et al., 2001), with consequences for many public-good outcomes, such as clean water, climate regulation and maintenance of biodiversity (Tilman et al., 2002). Although the food and fibre produced on farms is traded in markets, there is little empirical evidence to suggest that the general public is willing to pay a significant price premium for environmentally responsible products in the absence of social, animal welfare, or personal health benefits (Loureiro et al., 2002; Tully and Winer 2014; Verhoef and van Doorn, 2016); or that sustainability performance will lead to increased stock market performance (Porter and Kramer 2006). Instead, there appears to be an expectation that an agricultural industry's standard practice should include operating in an environmentally responsible manner (Maloni and Brown 2006). Yet private industry cannot bear the financial cost of measuring all off-farm, public-good outcomes; instead they must identify and target those outcomes that are most relevant to their business (Porter and Kramer 2006).

There are numerous private benefits for agribusinesses that implement and report on environmentally sustainable management actions. For example, a reduction in water or energy consumption will lead to lower input or overhead costs for many businesses (Ross et al., 2015). Direct financial incentives may also be made available (Pahl, 2007), including tax benefits to producers (Martin and Werren, 2009) who implement environmentally sustainable management practices. Industry may be motivated in other cases to evaluate impacts because of social license-to-operate issues relating to environmental stewardship (Jay 2007) or animal welfare (NPB, 2014). Increasingly, producers are also contractually required to report on the use of environmentally sustainable management actions to suppliers (Lehmann et al., 2012), who in turn sell to major retailers that want to demonstrate and market sustainability in their supply chain (Jay, 2007; Unilever, 2014; Ross et al., 2015). Thus, the challenge for agricultural industries is to identify and prioritize current sustainability issues that increase revenues or market access, reduce costs, or address sustainability issues that put them at greatest risk of public backlash (Ross et al., 2015), while also monitoring future issues as they evolve (Porter and Kramer, 2006).

Environmental aspects of AEH are typically assessed using two general approaches: 1) coordinated regional and national approaches and 2) industry-based efforts. Coordinated efforts include many well-established broad-scale programs designed to make comparisons across regions and nations (OECD, 2013; Madeau et al., 2014), with governments often acting as the proponents of these "top-down" programs. Coordinated efforts are useful for demonstrating the effectiveness of investments and guiding policy decisions at the regional (i.e. groups of nations) or national scale (Commission of the European Communities, 2007). As such, they are typically based on a fixed set of sustainability measures, which allow valid comparisons across regions. For example, the European Union (EU) Common Agricultural Policy (CAP) program measures represent agricultural impacts related to erosion, nitrate and pesticide pollution, greenhouse-gas emissions, and biodiversity, which are assessed and compared across EU nations (EEA, 2005). However, these regional measures are not designed to respond to specific management actions that individual producers have control over and do not necessarily reflect local priorities (Olsson et al., 2009). Thus, the results of a coordinated regional assessment are unlikely to be useful for agricultural marketing purposes, assessing industry-specific impacts, or comparing on-farm management trade-offs (Maloni and Brown 2006).

Industry-based organisations, such as commodity boards, are usually the proponents of "bottom-up" efforts, which are designed to reflect the needs of producers (i.e. risk management, marketing, or social license-to-operate). The need to report on sustainability is a relatively new development for agribusinesses and the result is often a "hodge podge approach" to sustainability initiative selection (Ross et al., 2015), rather than a strategic effort targeted towards industry-specific priority issues (Porter and Kramer, 2006). Sustainability measures are frequently selected based on readily available or inexpensive data that reflect best management practices (MPI, 2013), but these may be poor surrogates for priority environmental outcomes (Porter and Kramer 2006). In addition, there are no overarching standards for assessment frameworks or indicators in these circumstances (Porter and Kramer 2006). Instead, each industry develops their own assessment program and set of indicators, which then makes comparisons between regions or industries difficult (Ross et al., 2015), if not impossible (Olsson et al., 2009). As a result, many industry-based sustainability assessment programs fail to produce the desired outcomes (Porter and Kramer, 2006).

We believe that knowledge gained in environmental monitoring and assessment programs can be used to improve monitoring, assessing, and reporting in agricultural industries (Rao and Rogers, 2006). However, significant differences exist regarding the motivation for monitoring, the environmental processes or management action being measured and the methods used to measure them, as well as the manner in which results are communicated and the audience they are communicated to. Here we describe a flexible assessment framework that can be used to 1) assess the effectiveness of agricultural management actions on the environment; 2) reflect local priorities, while also allowing comparisons to be made between regions or industries at local, national, or regional scales; and 3) communicate results effectively to policy makers, suppliers, NGOs, consumers and the public.

2. A framework for assessing agroecosystem health

Standard environmental assessment frameworks provide a structured set of protocols that are used to meet a set of pre-determined goals (Gasparatos, 2010) and as such, form the basis of many established ecosystem-health monitoring, assessment, and reporting programs (e.g. Williams et al., 2009; Bunn et al., 2010; Connolly et al., 2013; Sbrocchi, 2013). There are many advantages to using a formal environmental monitoring and assessment framework, but to our knowledge these methods have not been used by an agricultural industry to improve environmental sustainability reporting. What follows is an overview of an environmental assessment framework (hereafter referred to as an AEH assessment framework), with step-by-step instructions that can be used to operationalise the assessment at multiple scales (e.g. farm, region, nation). We pay particular attention to indicator selection because many commonly used environmental indicators may not be the most effective choice in agricultural systems.

2.1. Develop an agroecosystem health vision

Although few would argue with the merit of agricultural sustainability as a goal, there will never be enough data to measure it in its comprehensive sense. As in any environmental monitoring program,

Table 1
Components, definitions, and examples within an agroecosystem health assessment framework.

Component	Description	Example
Vision Statement	An explicit statement describing the overarching goal of the program	Productive and environmentally sustainable ecosystems supporting rural communities and culture.
Environmental Assets	Classes of biophysical features in the landscape	Soil, water, biota and atmosphere
Traits	A distinguishing characteristic of assets relating to quantity or quality of ecosystem function and processes that stakeholders value and seek to maintain or improve	Good water quality
Objectives	Measurable goals used to link traits to indicators	Decrease nitrate concentration in rivers by 10% Increase fish stock by 30%
Targets	Spatially or temporally specific value of an indicator or measure, against which indicators are assessed to determine if objectives have been met	Minimum daily flow > 100 cubic feet per second Nitrate compliance threshold defined by legislation
Measure	A summary of practice-based activity, or product-based efficiency metrics.	% of growers implementing best-management practices. Megalitres of water used to grow 1 bale of cotton
Indicators	An environmental outcome-based variable, an index of aggregated environmental variables, or model output that characterizes an environmental trait. Must be measurable in space and time.	Minimum daily flow at a location Nitrate concentration in water, soil nutrient concentration, or bird abundance

decisions must be made about what will be sustained and for how long (Ikerd, 2008). In a landscape that includes agricultural production systems, these decisions are shaped by the needs of producers, but must also reflect societal values (Parris and Kates, 2003; Gómez-Limón and Sanchez-Fernandez, 2010). A clear vision statement provides a context-specific definition of agricultural sustainability, providing an explicit articulation of what the proponents are trying to achieve (Table 1; Fig. 1, Steps 1–3). Stakeholders in an agroecosystem include producers, industry, local communities, the public, government, consumers, and others deriving benefit from the same landscape. We refer to the stakeholder that is driving the assessment program as the *program proponent*. Here we focus on the case of an agricultural industry-led program, which could be motivated by within-industry needs to benchmark environmental impacts or external needs such as demonstrating compliance with environmental regulations, a need to maintain social license-to-operate, or to support marketing of environmentally sustainable products.

The first step in the development of the vision statement is to undertake a thorough review of the 1) industry's current and future reporting needs (e.g. compliance, marketing, or social license-to-operate) and 2) sustainability reporting process for similar agricultural industries (Fig. 1, Step 1). The outcome of the literature review is a concise synthesis of reporting needs, which is then shared with the program proponents during the consultation process (Fig. 1, Step 2). However, the nature of the consultation process will differ depending on who the proponents are. For example, a large agricultural enterprise that owns its own production and processing facilities may simply ask for feedback from employees. In contrast, it is much more critical for an industry body that represents independent growers (e.g. Australian Cotton Research and Development Corporation or the U.S. National Pork Board) to consult with their members (i.e. the proponents) (Clark and Dickson, 2003; Fernandes and Woodhouse, 2008; Ramos and Caeiro, 2010) to ensure the program reflects their values and needs (Gitau et al., 2008). If the vision statement is not relevant to the proponent, it may be short lived, which would be economically and politically costly (Gregory et al., 2006; Gasparatos, 2010).

An AEH vision statement is developed as part of the consultation process (Fig. 1, Step 3) and during those discussions, a broad range of assets that program proponents and stakeholders value are identified (Vadrevu et al., 2008; Bunn et al., 2010; Fig. 1, Step 4). Assets can represent environmental (e.g. soil or water), economic (e.g. profitability), or social (e.g. rural livelihoods, employment opportunities, farm size) values, but we focus primarily on environmental assets here. Nevertheless, environmental, social, and economic assets are not assumed to be independent of one another and can be weighted in different ways to reflect proponents' values and needs (e.g. Buys et al., 2014).

Environmental assets are *biophysical* features of the landscape (Table 1), which are selected because they are relevant to the AEH vision statement and values of stakeholders. Environmental assets can be classified in many different ways; however, in an agroecosystem it is important to emphasise categories that encompass the unique role of agricultural production alongside the broader social significance of a clean and healthy environment. Here we include three general categories of environmental assets: soil, water and atmosphere. The biota (i.e. living organisms) is treated as a fourth asset because organisms use and modify the soil, water, and atmosphere. Environmental assets are relevant to proponent values (Fig. 1, Step 4), but are too broadly defined to be measurable (Vadrevu et al., 2008). Instead, environmental *traits* must be selected, which describe specific characteristics that program proponents value and seek to maintain or improve (Table 1).

2.2. Establish a scientific underpinning

Developing the scientific underpinning for the program (Fig. 1, Steps 5–8) begins through consultation with scientists who have a thorough understanding of the environmental and anthropogenic processes that affect the environmental assets and traits (Fig. 1, Step 5). The scientists provide advice about potential indicators that could be used to represent different environmental traits (Table 1; Fig. 1, Step 6). Note that, multiple indicators can be used to represent a trait and can encompass both quantity (e.g. area of native vegetation) and quality (e.g. condition or structure of native vegetation) (Sbrocchi, 2013).

Conceptual models for potential indicators must also be developed in consultation with scientists (Fig. 1, Step 7). This step is particularly important because it provides an explicit representation of the hypothesized relationship between the indicator and agricultural management actions, moderated by natural drivers such as climate and topography (Belfiore et al., 2006; Dennison et al., 2007). For example, the conceptual model can be used to describe complex flows of water, energy and matter, as well as the interdependence between indicators, traits, and assets. There are a number of well-established methods that can be used to develop conceptual models and guide indicator selection (Bradley and Kutz, 2004), including the Driving Forces-Pressures-States-Impacts-Responses framework (EEA, 1999). Thus, the conceptual models ensure that there is a scientific underpinning to indicator selection and are especially useful for communicating assumptions about cause-and-effect linkages, both to scientific and non-scientific audiences (Gitau et al., 2008; Ramos and Caeiro, 2010). This iterative process (Fig. 1, Steps 5–7) continues until a final list of potential indicators and conceptual models has been developed. At this point, measurable *objectives* must be set (Table 1; Fig. 1, Step 8) that can be used to assess the effects of management actions (Gitau et al., 2008;

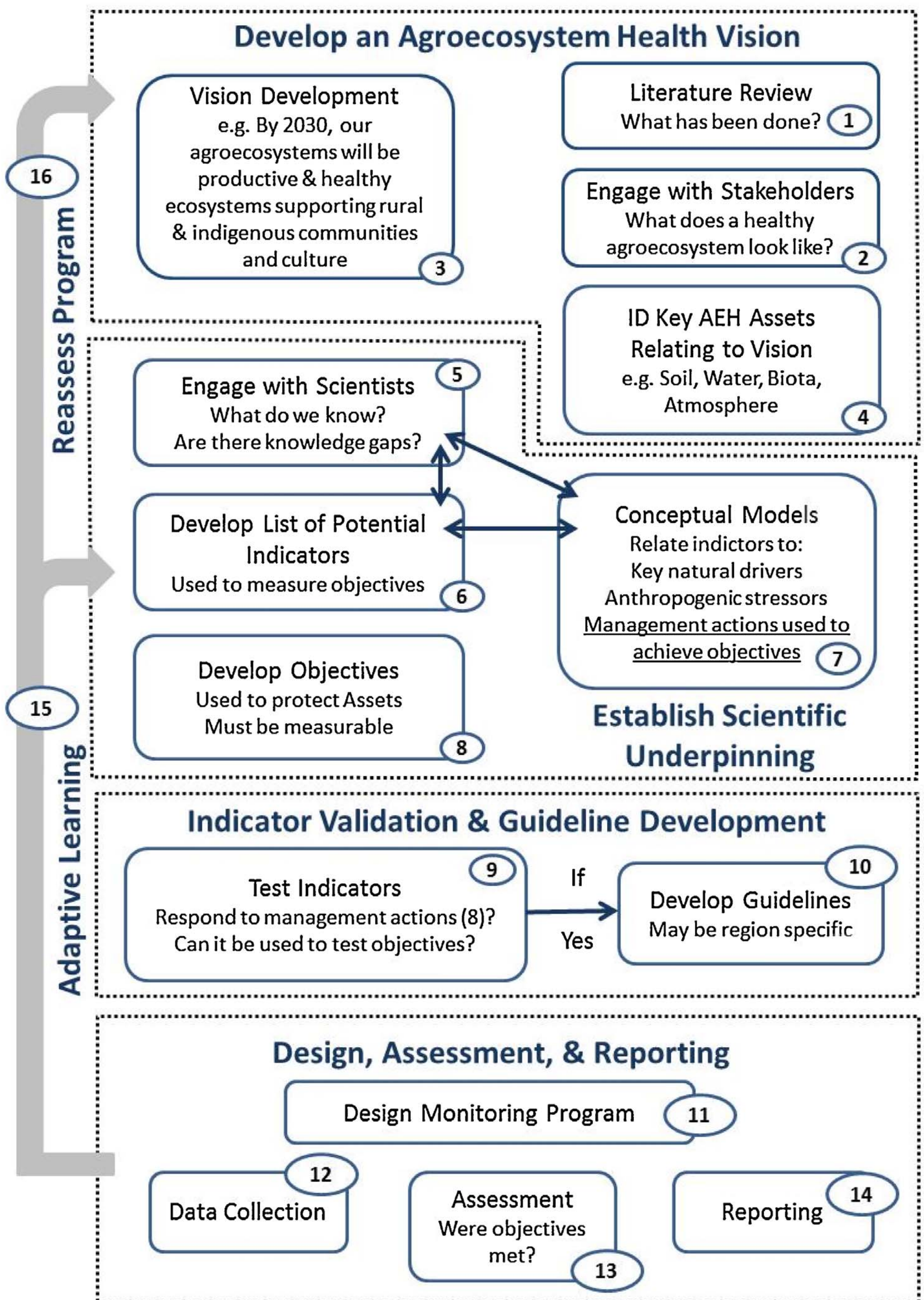

Fig. 1. The agroecosystem health assessment (AEH) framework is similar to conceptual frameworks used to design environmental monitoring programs. The process is broken into four parts: 1) the Development of an AEH Vision (Steps 1–4); 2) the Establishment of a Scientific Underpinning (Steps 5–8); 3) Indicator Validation & Guideline Development (Steps 9–10); and the Design, Assessment, and Reporting (Steps 11–14) phases. At each reporting cycle, the framework allows for adaptive learning, whereby the validity of the conceptual model, the suitability of the objectives, and the effectiveness of management actions can be assessed. The program should also be reassessed periodically (> 5 years) to ensure that it continues to reflect proponent needs and their values.

Williams and Brown 2012). For example, water quality is a trait of the water asset, while nitrate concentration is a water quality indicator that can be assessed against compliance thresholds to determine whether objectives related to nitrate in surface waters have been met (Table 1).

2.2.1. Indicators of AEH

There is no one indicator, or set of indicators, that can meet the needs of every program (Gómez-Limón and Sanchez-Fernandez, 2010). Thus, indicator selection must be undertaken as part of a broader AEH assessment framework (ver der Werf and Petit, 2002; Gómez-Limón and Sanchez-Fernandez, 2010), to ensure that the indicators represent proponent values (Gitau et al., 2008; Olsson et al., 2009). For example, water quality indicators may be particularly relevant in areas of high rainfall, where there is increased risk of surface or groundwater pollution due to agricultural runoff (Benoit et al., 2014; Blann et al., 2009); while in low rainfall areas, soil loss through wind erosion may be bigger concern to stakeholders since there is little risk of runoff (Fryrear, 1985; Geeves et al., 2000; Rosewell et al., 2000). Although indicators may be selected to represent different environmental assets or traits, there are some common characteristics that can be used to identify appropriate indicators in an AEH context (Fig. 1, Step 6).

2.2.2. Key characteristics of an AEH indicator

2.2.2.1. Relevance to program proponent. The diversity of expectations in an agricultural system is greater than in conventional environmental monitoring due to the many trade-offs between private benefits (e.g. the profits from farming) and public benefits (e.g. values from nature to broader society). Consequently, an AEH framework is unlikely to meet everyone's needs, so it is critical to design it to meet the specific needs of the program proponent (Belfiore et al., 2006). The AEH assessment program may also meet broader stakeholder needs, but only to the extent it is necessary to meet the proponents' goals.

2.2.2.2. Diagnostic capability. Indicators effectively link an environmental outcome to one or more management actions (Ehler, 2003), but this relationship must be quantified and validated before it is considered diagnostic (Reuter, 1998; Bockstaller and Girardin, 2003; Gómez-Limón and Sanchez-Fernandez, 2010); otherwise changes to environmental management practices may not produce the assumed change in the indicator. Ideally, validation of indicators and guideline setting is undertaken as part of a pilot study prior to the process of reporting (e.g. Bunn et al., 2010; Fig. 1, Steps 9–10). In some cases it may be possible to test indicators using historical datasets and then re-validate the indicators after the first round of sampling in the new program.

2.2.2.3. Scale appropriate. Agroecosystem health can be assessed at multiple spatial (e.g. field, farm, region, national, etc.) and temporal (single point in time, to seasonally, annually, or decadal) scales. It is therefore important to carefully consider the spatio-temporal heterogeneity and scale of the environmental process, management actions, and indicators of interest during the development of the conceptual models (Fig. 1, Step 7). This ensures that they are complementary (Belfiore et al., 2006) and well matched to the goals of the program (Ramos and Caeiro, 2010).

2.2.2.4. Logistical feasibility. A failure to consider the logistical feasibility of indicators could lead to a program that is impossible to implement (Ehler, 2003). For example, a particular AEH indicator may be logistically infeasible if collecting it at the appropriate scale requires so many samples that it is not time or cost effective (Steele-Dunne et al., 2010). In contrast, collecting fine-scale data may be interesting, but not necessary for a scale-appropriate assessment within the context of the program.

2.2.3. Practice- and product-based measures, and outcome-based indicators

In traditional monitoring programs, environmental assessments tend to be based on indicators that are measured in the field and assessed against a target or threshold (Table 1). However, a wider variety of data may be used in an AEH assessment depending on the needs of the program proponents. Data used to inform an AEH assessment can be classified into three different categories: 1) practice-based measures, 2) product-based measures, and 3) outcome-based indicators. All three have conceptual linkages to environmental assets (Fig. 2), but it is important to understand the differences between them and the differing levels of evidence they provide about environmental impacts.

Practice-based measures describe management actions, such as the proportion of farmers who implement best management practices (e.g. timing or rate of pesticide application). They can also include descriptors of individual management actions (e.g. stocking densities), or metrics on training activities or skills achieved by land managers (Fig. 2). For example, palm oil producers can be certified by the Roundtable on Sustainable Palm Oil (RSPO, 2013), which sets practice-based standards across a number of dimensions, including: soil fertility and erosion; use of pesticides; protection of threatened species; waste disposal, and; greenhouse gas emissions. Practice-based measures are commonly used in AEH assessment because data are readily available or are relatively inexpensive to collect (Porter and Kramer 2006) through farmer surveys or self-reporting. Practice-based measures can also be audited to ensure that producers are implementing specific management practices (Fig. 2). However, an assessment based on practice-based measures alone has no direct measures of environmental outcomes. Instead, it is a proxy for performance (Tilman et al., 2002; Porter and Kramer 2006); it relies on an untested conceptual linkage between management actions and the desired environmental outcome. For example, fencing riparian buffer zones is often used to improve water quality and could be used as a practice-based measure. However, the effectiveness of animal exclusion varies depending on the width and composition of the vegetative buffer, the area of riparian zone excluded, as well as other on-farm management practices such as fertilizer applications or the placement of effluent ponds (Aarons and Gourley, 2012). As such, positive or negative scores for a practice-based measure alone may not lead to an actual change in an environmental outcome (Gleeson et al., 2012). A second shortcoming of practice-based measures is that reporting on the uptake of specific management practices has the potential to stifle innovation by codifying standard practices, rather than allowing managers to achieve better environmental outcomes through alternative, novel, or locally relevant strategies. Nevertheless, practice-based measures may be useful over relatively short-time scales (i.e. 1–2 years) because they provide evidence that a producer or industry is making an effort to be environmentally sustainable (Ehler, 2003). Note that practice-based measures that describe effort are particularly valuable if there is time lag between the implementation of management actions and a positive environmental outcome (Meals et al., 2009).

Product-based measures are often used to characterise the sustainability of production using input-efficiency measures, which are expressed as per-unit measures (Fig. 2), such as water- or nitrogen-use per tonne of crop (Pelletier et al., 2014; NPB 2015; RSPO 2015). For example, the New Zealand Wine Company (NZWC) implements a carbon life cycle assessment model for their product, Sanctuary Sauvignon Blanc, using the Carbon Trust methodology (Aura Sustainability, 2011). This certification allows NZWC to benchmark and measure subsequent changes to greenhouse gas emissions from cradle to grave. It also allows them to use the 'Reducing CO2 Label' to communicate their commitment to a reduction in greenhouse gas emissions and grow their market share.

There is often a conceptual linkage between management actions, product-based measures, and environmental outcomes (Fig. 2). For example, no-till soil management leads to both soil improvements (Charman and Roper, 2000; Young et al., 2009) and increased water-use efficiency (Adams, 1966; Rao and Dao, 1996; Raun and Johnson, 1999; Hatfield et al., 2001), which can ultimately result in less nutrient pollution in aquatic systems (Blann et al., 2009; Benoit et al., 2014). One of the strengths of product-based measures is that they represent the combined effects of multiple management actions, which may be interacting in unexpected ways to decrease resource-use over short- to medium-time scales (i.e. the life of the product); thus, reducing the reliance on a single measure or management practice. In addition, they represent aspects of both production (e.g. reduced inputs) and environmental impact (Oleander et al., 2014). However, measuring or estimating a product-based measure is often more expensive and technically complex than practice-based measures, and requires actual measurements of on-farm resource use. In some cases, mathematical or statistical modelling approaches can be used to extrapolate measurements to the whole-of-farm scale (Robertson et al., 2012). However, the focus on per-unit efficiency does not provide evidence of an absolute change in a specific environmental outcome (Schröder et al., 2004). In some cases, such as a reduction in greenhouse gas emissions, this conceptual linkage may be strong enough that stakeholders feel comfortable with the assumption. Yet, even when the mechanistic understanding of the impact on the environment is correct, improvements in per-unit efficiency will not lead to reduced environmental

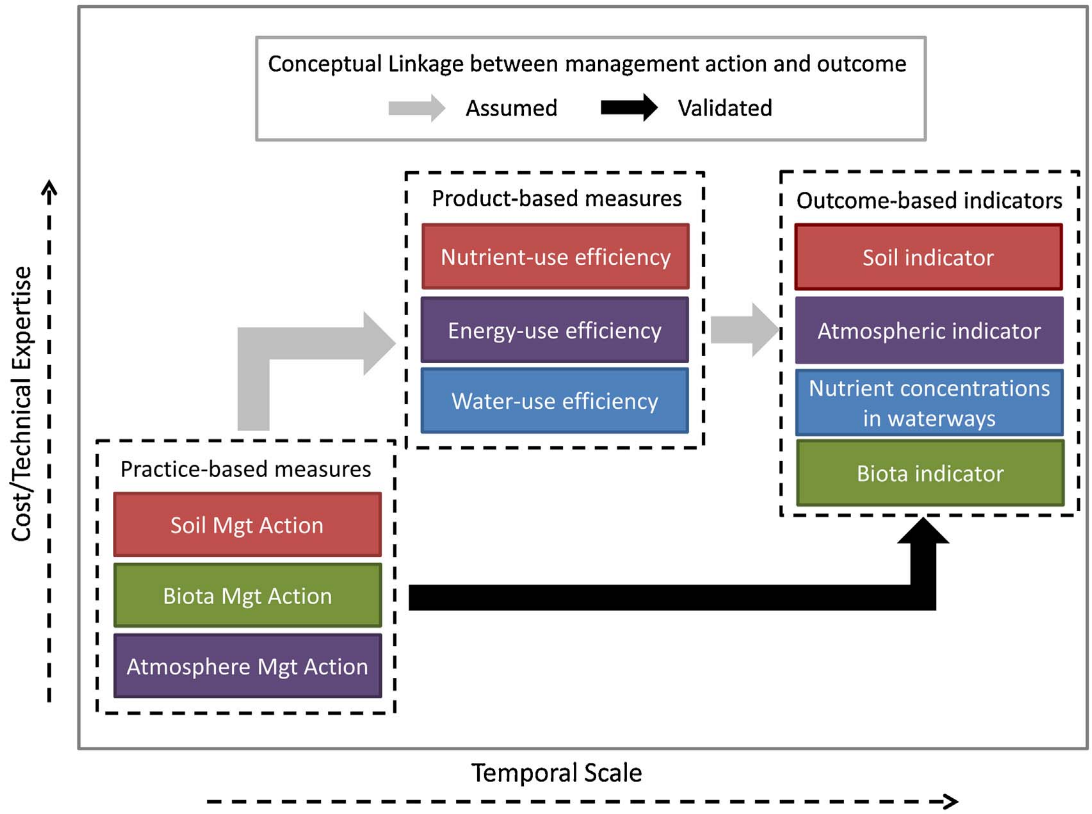

Fig. 2. Practice-based measures, product-based measures, and outcome-based indicators of environmental assets all play a role in an agroecosystem health (AEH) monitoring, assessment and reporting program. The AEH assessment is based on a conceptual linkage between management actions and the measure or indicator, which must be assumed to be correct or explicitly validated. Differences in the potential time it takes to report an outcome typically increase with cost (financial and effort) and technical expertise needed to generate the information, but there will be exceptions. A combination of all three measures and indicators or a combination of one measure-indicator pair can be used to tell an evidence-based environmental story.

impacts if efficiency improvements are overwhelmed by increases in the overall level of production. In addition, if other natural or anthropogenic factors change the conceptualised relationship between the measure and an environmental outcome, the conclusions based on that conceptual linkage may be incorrect (see Appendix A in Supplementary material for an overview of commonly used product-based measures suitable for AEH assessment).

Outcome-based indicators are more akin to environmental indicators than practice- and product-based measures. An "indicator" is different from a "measure" because it is used to detect a change in an on-the-ground environmental outcome (Ehler 2003), such as biodiversity, water quality, soil structure, or air quality. In addition, an outcome-based indicator must be diagnostic, which ensures that the indicator will respond to management actions the stakeholder has control over and that the final assessment will reflect those actions. Despite these advantages, outcome-based indicators are used much less often than practice- and product-based measures in AEH assessment. This is likely due to a lack of data (European Commission, 2005) and the perceived or actual cost (e.g. time, financial, and technical expertise; Tilman et al., 2002) of collecting environmental datasets (see Appendix A in Supplementary material for a review of outcome-based indicators and an assessment of their suitability for AEH). Although there are exceptions, changes in outcome-based indicators often take place over longer time scales (i.e. 3–10 years) than practice- and product-based measures (Fig. 2). This is due to natural variability in the system and measurement error, which can make it difficult to detect trends in environmental performance over short time periods (Darnell et al., 2012).

2.2.4. Selecting measures and indicators to communicate evidence of improved practice and outcomes

Each of the measures and indicators described above provides unique information about agricultural impacts on the environment at specific time scales. An understanding of the strengths and weaknesses of each measure and indicator type will allow program proponents to make informed decisions based on costs and motivating factors. A program based on practice- and product-based measures alone provides information about efforts to reduce environmental impacts. This level of information may be sufficient for marketing, but in cases where compliance or social-license-to operate issues are the motivating factor, outcome-based indicators must be included to communicate where improvements to practice are providing real environmental benefits. Moreover, a combination of measures and indicators will provide the most comprehensive AEH assessment. The three types of information may describe characteristics of the same Asset, or may represent practice- or product-based measures related to different assets than the one associated with the outcome-based indicator. For example, implementing no-till agriculture practices (practice-based measure) would be expected to increase water-use efficiency (product-based measure), which in turn decreases nutrient losses and pollution in nearby waterways (outcome-based indicator). On the other hand, there are cases where it may be reasonable to omit a measure or indicator from the assessment. For instance, proponents may want to demonstrate that management actions are not excessively contributing to greenhouse gas emissions, but the mismatch in scale between management actions and the outcome-based indicators, as well as the high cost of sampling and imprecise estimates (Oleander et al., 2014) may make it logistically infeasible to include. In these cases, reporting on practice- and product-based measures that have a well-established conceptual linkage to the outcome may be the best option. The key to the successful use of this approach is that there is a scientifically based, conceptual linkage between the three components that describes the management efforts being made by stakeholders and the positive environmental outcomes that result from those efforts (Fig. 1, Step 7); thus providing a cohesive environmental narrative.

2.3. Monitoring program design, assessment, and reporting

Successful monitoring programs are underpinned by statistical methods, which play a key role in the design, assessment, and reporting (Fig. 1, Steps 11–14). Decisions made early in the design phase are important because they affect the accuracy of the results and the ability to make defensible assessments within and across multiple scales. Some important statistical design questions include: 1) how will natural spatio-temporal variability in climate and other regional differences be accounted for?; 2) how will assessments at the field scale be scaled-up to a farming enterprise, and then to a region?; 3) how is statistical uncertainty accounted for in the overall assessment?; and 4) how can the results be aggregated over space and through time? Each of these issues can impact the success of the program and as such, warrant careful consideration. Although a full review of statistical design in the context of environmental monitoring is outside the scope of this paper, we highlight a few aspects below that have major implications for the outcomes of the AEH assessment program.

One important, but under-appreciated aspect is survey design (Fig. 1, Step 11), which determines where, when, how, and how often data should be collected (Fig. 1, Step 12) to produce a scientifically defensible assessment of AEH over a defined area or time period. Whilst the idea of using pre-existing data is appealing, this is rarely successful, for a number of reasons. Existing datasets seldom describe the full range of spatial or temporal variability of the area of interest, making it difficult to tease out the confounding influences of natural variability related to climate, topography, and anthropogenic stressors that are unrelated to the specific agricultural practices of interest. Also, data derived from multiple sources are unlikely to be collected using consistent methods (OECD, 2001). This limits and, in some cases, makes it impossible to make scientifically defensible assessments using existing datasets (e.g. SOE, 2011; DAFWA, 2013).

It can be useful to standardise indicators to values between 0–1 or 0–100 before they are assessed against targets (Fig. 1, Step 13) and communicated in the reporting phase of the program (Fig. 1, Step 14). This way assessors can adopt indicators that reflect local priorities (Gomez et al., 1996; Schröder et al., 2004), while also allowing comparisons to be made across indicators, asset types, industries and regions over space and time (Rao and Rogers, 2006; Fernandes and Woodhouse, 2008; Sattler et al., 2010). For example, water-use efficiency may be particularly relevant in systems where water is scarce or over-allocated, while sediment load may be particularly relevant in high rainfall areas. When indicators are standardised, the audience intuitively understands that a score of 80% for water-use efficiency is better than a score of 40% for sediment loads. Although these local outcome-based indicators are measuring different water-related characteristics, they can be used to make comparisons across regions once they have been standardised (Gomez et al., 1996).

In an environmental monitoring program, indicators are typically standardised based on a reference condition (Bunn et al., 2010), which represents conditions at a location if it were in pristine state. However, this is usually not appropriate in an agricultural system, which by definition has been modified for food and fibre production. Alternatively, an indicator can be standardised using a measurable target or threshold value (Gitau et al., 2008; Madeau et al., 2014), which is designated as the best attainable value given human uses. In some cases, the scores are standardised based on both the target and a ‘worst case scenario’, which represents either the published limits of ecological or biological harm, compliance thresholds, or the 90th percentiles of data (e.g. threshold of best 10% of data; Flint et al., 2014). There may be different reference conditions or targets in different regions to account for natural variability in climate or soil type, while targets may vary for the same indicator used to assess different industries. Regardless of which approach is used, the methods used to convert the indicator from its natural scale to the standardised scale must be transparent (Gómez-Limón and Sanchez-Fernandez, 2010); this helps the audience understand how the indicator was calculated and assessed, highlights the assumptions that were made, and promotes overall confidence in the assessment.

2.4. Communicating the results

Results of an AEH assessment must be synthesized and communicated to a broad audience of stakeholders in a concise format that is easy to understand, so that information gained from the assessment can be used to influence action (Becker, 2004; Fig. 1, Step 14). The communication strategy for an AEH program should be considered early in the planning phase (Dennison et al., 2007) and should explicitly state who the target audience is, what will be communicated and how often, as well as methods of communication (e.g. websites or social media, reports, factsheets, or workshops) (Ramos and Caeiro, 2010). However, there are many different ways to communicate results and some are more effective than others in any given context. Here we will focus on environmental report cards because they typically incorporate multiple methods of communication and are effective tools for scientific communication (Dennison et al., 2007).

Report cards use letter grades (e.g. A-F) or condition categories (e.g. good, fair, and poor) to convey information about environmental status and trends. They have become a popular communication tool for environmental assessments (Blatt 2011; EHMP 2013; University of Maryland Center for Environmental Science, 2013) because they successfully synthesize large amounts of environmental data and use intuitive visualization techniques to communicate information to a wide variety of audiences. This allows resource managers to prioritize management decisions that help to achieve the program vision (Thomas et al., 2006). However, report cards are little more than pretty pictures if they are not based on a scientifically robust assessment framework (Fig. 1). Although they look simple, designing an effective report card is much more complicated than simply displaying a standardised score. Hierarchical levels of information should be included in the assessment so that results can be communicated to users who require different levels of detail (IISD, 2006; McKane, 2003; Auricht, 2004; EHMP, 2013). For example, a reader should be able to get a general appreciation of AEH at-a-glance, but also gain a more in-depth assessment to inform deliberative decision making. This is important because a report card is more credible if the users can develop their own insight into the factors driving an overall AEH score (Johnson, 2006); thus, increasing transparency and credibility in the assessment process (Lehmann et al., 2012; Luhmann and Theuvsen 2016).

It is a challenge to present multiple levels of information in a concise, straightforward, and intuitive manner (Auricht, 2004). To achieve this, the report card should include a careful balance of numbers, symbols, colours, maps, graphics, and text to communicate successfully with the audience (Tufte, 1983; Brewer, 1999). For example, some report cards use an intuitive traffic-light colour format to communicate results or grades based on the colours red (e.g. poor condition or declining trend), yellow, and green (e.g. good condition or improving trend) (Bunn et al., 2010; University of Maryland Center for Environmental Science, 2013). A well-designed report card can successfully convey an overview of monitoring results within one or two pages. For example, the Western Australia Report Card on Sustainable Natural Resource Use in Agricultural Areas (DAFWA, 2013) uses colour codes and symbols to communicate quantitative and qualitative assessments of resource status and trends for different agricultural ‘themes’, along with a qualitative estimate of uncertainty. Careful consideration of these communication aspects ensures that a report-card successfully informs the public and provides useful information for policy makers.

2.5. Adaptability

An AEH assessment framework must explicitly include a mechanism for adaptability over time in order to maintain relevance to stakeholders and ensure that the program is sustainable (Gregory et al., 2006; Fig. 1, Steps 15 and 16). As management actions are implemented, more information about the system is gained, which will help users adapt their management decisions as environmental and economic conditions change (Morghan et al., 2006). It will also quickly become apparent if best management practices are not having the desired effect in a particular context when the system is actively monitored and assessed. In some cases this may highlight the need for research into new management approaches (Halbert, 1993) or the need to refine the initial conceptual model (Gregory et al., 2006; Fig. 1, Step 7). This iterative cycle of decision making and adaptive learning should be interrupted periodically to reassess whether the vision statement, values, and objectives still meet the proponents' needs (Williams and Brown, 2012; Fig. 1, Step 16). There may also be new social or institutional pressures that the program needs to adapt to, or the emergence of new management options that are better suited to achieve the outcomes (Williams and Brown, 2012). On the other hand, it is important not to reassess the AEH program too often (e.g. < 5 years) because changing the objectives and the indicators can compromise the validity of the assessment (Williams 2011) and undermine previous efforts. The AEH assessment framework described here is particularly suited for this adaptive learning process because proponents have the flexibility to alter management actions based on the results of the program (Gregory et al., 2006). In fact, this formal framework of adaptive learning from outcomes has long been an inherent part of the farming enterprise, where growers adapt management practices to achieve greater profitability in the short and long term. The AEH framework presented here simply provides a mechanism for incorporating environmental decision making into that process.

3. Opportunities of AEH assessment from a scientific and operational perspective

3.1. New technologies

Ground-based surveys have historically been labour-intensive and costly to undertake (McKenzie et al., 2008). However, innovations in sampling technologies, such as *in situ* sensors and sensor networks, have the potential to revolutionize the way that data are collected in soils (Nandurkar et al., 2014; Sakthipriya, 2014), water (Atta et al., 2011; Gaddam et al., 2014), atmosphere (Wang et al., 2011), and biota (Cai et al., 2007; Thomsen and Willerslev, 2015). For example, Majone et al. (2013) deployed soil moisture and temperature sensors throughout an apple orchard in Italy's Alpine region to explore how different irrigation schedules affect the spatial and temporal distribution of soil moisture. Sensors have also been extensively employed in precision agriculture (Gebbers and Adamchuk, 2010; Liaghat and Balasundram, 2010), where data are used to optimise farm inputs and increase yields (Mulla, 2013). The fine-scale spatio-temporal optimisation of herbicides, fertilisers, and fuel may reduce negative environmental impacts related to over-use of farm inputs, but at present the environmental outcomes are not usually measured; nevertheless, the same principles and technology that growers are already familiar with can be used to directly measure management actions *and* environmental outcomes for an AEH assessment.

The ability of farmers to monitor agroecosystems is expected to dramatically increase in the near future. Agricultural robots, unmanned aerial vehicles (UAVs), and groups of multi-cooperative robots and UAVs are currently being developed (Floreano and Wood, 2015), which can be used as mobile platforms for a suite of sensors; allowing farmers to collect fine-scale environmental measurements through space and time as machines move through, and over fields (Barrientos et al., 2011; Floreano and Wood, 2015). Similarly, biological data have traditionally been expensive to collect because extensive field surveys and advanced technical expertise were needed to identify individual species through space and time. However, the cost for some types of biological sampling is already beginning to decrease due to new technological advancements, such as environmental DNA samples and the growing number of DNA databases (Thomsen and Willerslev, 2015) and the increased classification capabilities of audio sensors (Depraetere et al., 2012; Walters et al., 2012). Advancements in the "-omics" (i.e. genomics, phenomics, and proteomics) also provide vast amounts of data about composition and function of the biota (Mortensen et al., 2007; Poynton et al., 2012; Raes et al., 2011; and Willerslev, 2015). All of these technologies produce massive spatio-temporal datasets and advances in the development of big data analytics are currently underway to take better advantage of these approaches in the near future (National Research Council, 2013).

3.2. Integration with existing monitoring programs

There are many different assessment frameworks in use and few producers or industries have the luxury of switching methods as assessment priorities, farming practices, or data sources change. In addition, many farming enterprises belong to more than one farm industry sector (e.g. mixed farming enterprises simultaneously producing crops, wool, and meat), which makes the overhead of using more than one assessment framework burdensome. Thus, there is a need for complementary programs across industries that simplify these choices.

Common environmental issues-of-concern exist across producers and industries. For example, nutrient pollution in waterways is an environmental issue for industries such as dairy (Jay, 2007), cotton (Locke et al., 2015), and sugar cane (Thorburn et al., 2013), while greenhouse gas emissions may be relevant to multiple farming enterprises, including livestock producers (Herrero et al., 2013) and grain growers (Rodriguez et al., 2003). Industries may also have environmental concerns related to the same asset (e.g. biota), but different local priorities (e.g. amount of native vegetation versus bird diversity). In each of these cases, different practice- and product-based measures, as well as outcome-based indicators can be used, with industry- and region-specific targets used to standardise scores so that they are comparable.

Common environmental issues-of-concern may also exist between entities monitoring for public and private good. For example, the amount of native vegetation may be relevant for both industry-related assessments and monitoring programs (Sbrocchi, 2013), even though different targets may be appropriate for on-farm vegetation compared with that in a nature reserve system. Similarly, water-borne nutrients are frequently measured as part of broad-scale monitoring programs (EEA, 2005; Bunn et al., 2010; USEPA, 2000) and are often of concern to agriculturalists as well. In these cases, the use of the same general assessment framework creates opportunities to integrate information from multiple assessment programs. For example, water quality data collected in agricultural systems could be used to augment end-of-catchment samples in order to gain a better understanding of environmental impacts in mixed-use landscapes. The ability to integrate across monitoring programs allows proponents to draw on multiple sources of data to increase the spatial and temporal density of an AEH assessment, while also allowing industries to control their own voluntary programs. However, governments could provide financial incentives to encourage producers to participate, or provide access to government funding depending on participation in the program (van Grieken et al., 2013).

Complementary programs are an attractive alternative to coordinated regional monitoring programs, where indicators do not necessarily reflect local stakeholder values. If stakeholders can agree on a common framework to operate within such as the AEH framework described here, along with a similar vision statement, a complementary approach will enable comparisons across industries, regions and indicators. In addition, standardising scores also makes it possible to integrate information gained from environmental assessments with economic and social assessments in agricultural settings; thus allowing producers and industry to broaden the AEH assessment approach described here by considering the economic, social, and environmental benefits in order to better assess and report on sustainability.

4. Conclusions

The number of private industries required to monitor their impact on the environment is increasing (Porter and Kramer 2006; Lehmann et al., 2012; Ross et al., 2015) and there are advantages for industries and agribusinesses that can strategically identify and target industry-specific priority issues (Porter and Kramer, 2006). The AEH assessment framework presented here is underpinned by experience and knowledge gained from environmental monitoring, assessment, and reporting programs, but it has been modified to address the unique needs of an industry-based assessment. It includes four phases (Fig. 1): 1) development of an AEH vision; 2) establishing a scientific underpinning for the program; 3) indicator validation and guideline development; and 4) design, assessment and reporting. Unlike many current industry-based programs, the assessment can be tailored to locally relevant or industry-specific issues. However, an effective AEH assessment must rely on measures and indicators that have diagnostic capability, are relevant to proponents, scale appropriate, and logistically feasible. The use of a well-designed quantitative approach also makes it possible to scale up and drill down (spatially and temporally) in the assessment. Thus, valid comparisons can be made across indicators, multiple scales (e.g. farms, catchments, states, or nations), or industries (e.g. grain versus grazing). In addition, explicitly incorporating a mechanism for adaptive learning further ensures the program will remain relevant to proponents over time as market, policy, and environmental conditions change.

Proponents must prioritize environmental issues-of-concern and target sustainability investments on issues that create the biggest benefits, or mitigate the biggest risks to business. With the exception of resource-use efficiencies, direct financial benefits can be difficult to measure. However, evidence suggests that there are numerous indirect benefits associated with sustainability reporting. For example, a transparent reporting system improves the reputation of agribusinesses and builds trust with consumers. Such a system also makes a company more resilient when unexpected sustainability issues do arise (Ross et al., 2015). However, the relative risk associated with environmental issues is expected to differ and change through time. For example, public exposure to agricultural pesticides in drinking water would likely rank as a higher priority than impacts on biodiversity, but agricultural impacts on iconic species can suddenly create a risk to industry's social license-to-operate. Thus, industry must explicitly identify and prioritize the 1) stakeholders they are trying to communicate with, 2) sustainability messages those stakeholders have an interest in, and 3) what the industry wants to achieve through their AEH assessment program. Once this process is complete, we recommend using a combination of practice- and product-based measures to highlight management efforts to reduce environmental impacts that are of low or moderate risk, but of significant benefit. When issues represent a significant risk to business, outcome-based indicators must be combined with these measures to clearly link evidence for environmental improvements to improved practices. This approach provides a way for results to be communicated transparently and concisely, which promotes confidence in the assessment and wide acceptance.

As the number of private industries monitoring the environment increases, opportunities will emerge to strengthen public-private partnerships. Government agencies are under pressure to provide better information about environmental status and trends, as well as the effects of management actions, at a time when public funding for monitoring tends to be falling. As new technologies emerge and crowd-sourced data becomes more common, we expect the cost of collecting outcome-based indicators to decrease so that they become feasible for low- to medium-risk issues. The AEH framework proposed here could be used to integrate industry-based data into public environmental-monitoring programs in a statistically rigorous manner, and vice versa; thus, increasing the spatio-temporal coverage of data for both public and private monitoring programs, at little cost. We expect partnerships between industry, government, and potentially citizens to play a more central role in improving land management practices in the interest of more sustainable environmental outcomes in the future, and the AEH framework proposed here provides guidance about how to do that.

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Appendix A. Supplementary data

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