



A Vegetation and Soil Survey Method for Surveillance Monitoring of Rangeland Environments

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Ecosystem surveillance monitoring is critical to managing natural resources and especially so under changing environments. Despite this importance, the design and implementation of monitoring programs across large temporal and spatial scales has been hampered by the lack of appropriately standardized methods and data streams. To address this gap, we outline a surveillance monitoring method based on permanent plots and voucher samples suited to rangeland environments around the world that is repeatable, cost-effective, appropriate for large-scale comparisons, and adaptable to other global biomes. The method provides comprehensive data on vegetation composition and structure along with soil attributes relevant to plant growth, delivered as a combination of modules that can be targeted for different purposes or available resources. Plots are located in a stratified design across vegetation units, landforms, and climates to enhance continental and global comparisons. Changes are investigated through revisits. Vegetation is measured to inform on composition, cover, and structure. Samples of vegetation and soils are collected and tracked by barcode labels and stored long-term for subsequent analysis. Technology is used to enhance the accuracy of field methods, including differential GPS plot locations, instrument-based Leaf Area Index (LAI) measures, and three dimensional photo-panoramas for advanced analysis. A key feature of the method is the use of electronic field data collection to enhance data delivery into a publicly accessible database. Our method is pragmatic, whilst still providing consistent data, information, and samples on key vegetation and soil attributes. The method is operational and has been applied at more than 704 field locations across the Australian rangelands as part of the *Ecosystem Surveillance* program of the Terrestrial Ecosystem Research Network (TERN). The methodology enables continental analyses and has been tested in communities broadly representative of rangelands globally, with components being applicable to other biomes.

Here we also recommend the consultative process and guiding principles that drove the development of this method as an approach for development of the method into other biomes. The consistent, standardized and objective method enables continental, and potentially global analyses than were not previously possible with disparate programs and datasets.

Keywords: ecological monitoring methods, vegetation composition, vegetation cover, vegetation structure, soil sampling methods, sample management, electronic data collection

INTRODUCTION

Ecosystems support social and economic well-being and require our vigilance as to their condition and management interventions to ensure continued functionality (Magnusson et al., 2013; Andersen et al., 2014). The diversity of ecosystems has contributed to a multitude of methods used to sample their composition, structure, and function. Despite acknowledgment of the need for integrated measurements and evidence-based decision making (Likens, 2010; Eyre et al., 2011; Likens and Lindenmayer, 2011), endorsing a single approach to ecosystem monitoring remains difficult because managers, researchers, policy makers, and funding agencies have diverse applications for the data collected, and may have invested considerable effort and monitoring time in existing methods. This causes an integration problem when bringing together monitoring data across large areas, and is particularly problematic for programs involving extensive, multi-jurisdictional, logistically challenging, and sparsely populated areas, such as rangelands (Bastin et al., 2009; Herrick et al., 2010).

Underpinning these issues is a need to report on environmental change over decadal, or longer, time periods (Allen-Diaz et al., 1996; Likens and Lindenmayer, 2011), and requires monitoring methodologies that are well-described and flexible to deliver on future, unanticipated needs (Burton et al., 2014; Bayne et al., 2015). The challenge is to agree on a method without complete knowledge of the requirements of future monitoring programs, the threats to ecosystems or the opportunities that may emerge via innovation and technology (Spellerberg, 2005; Lindenmayer et al., 2014).

Rangelands occur on all inhabited continents (**Figure 1A**) with the predominant land-use being low-intensity or nomadic livestock grazing on native pastures (Linstadter and Baumann, 2013). In Australia, variable rainfall is perhaps the major ecological driver of spatial patterns (Stafford Smith and McAllister, 2008), with the influence of variability particularly evident in arid areas (van Etten, 2009; Dickman and Wardle, 2012). Rangelands represent 46% of terrestrial ecosystems globally and 81% in Australia (**Figure 1B**), but remain relatively poorly studied (Sparrow et al., 2014). Understanding broad scale change in rangelands remains difficult due to a lack of monitoring and decadal ecosystem dynamics (White I. A. et al., 2012).

Here we present an overview and rationale of a cohesive and robust ecosystem surveillance method that builds on previous techniques, both in Australia (Watson et al., 2007; Bastin et al., 2009) and internationally (Nusser and Goebel, 1997;

Herrick et al., 2010; Toevs et al., 2011; Taylor et al., 2014; Oliva et al., 2019), for characterizing and monitoring rangeland ecosystems. Specific protocols are described in detail in the AusPlots field manual included in **Supplementary Material S5**, as that material is too extensive to publish within the length of a standard publication (White A. et al., 2012). The method is operational and has been implemented at over 704 sites across Australia (see Box 1 in **Supplementary Material S3**), producing publicly available data for ecological studies of Australian rangelands (Guerin et al., 2016b; TERN, 2019). While the primary purpose of the program is to detect changes over large scales of space and over long periods of time, it also provides readily available resources to answer pressing current questions. For example, this method incorporates data collection (Tokmakoff et al., 2016) to address key long-standing questions for rangeland ecosystems (Morton et al., 2011), including understanding the role of soil and plant traits on productivity (Bastin et al., 2017a; Gallagher et al., 2020). The combination of vegetation data and samples can be used to extract trait data or genomic data to anticipate responses to environmental stressors across large gradients (Westoby et al., 2002; Wright et al., 2004; Guerin et al., 2012; Caddy-Retalic et al., 2017). Similarly, the soil and plant samples, along with the vegetation data, provide an open-access resource to assess emerging priorities such as understanding the multi-functionality of ecosystems, and especially of drylands (Maestre et al., 2012).

Challenges to Broad Scale Monitoring Approaches

Surveillance monitoring is defined as broad in scope, involving measurements of many attributes and species across a spatially and temporally wide-ranging network of field locations, placing it between landscape, and targeted field monitoring in detail and spatial extent (Eyre et al., 2011; Sparrow et al., 2019a). Challenges to the design and implementation of surveillance monitoring programs stem from practical and scientific considerations (Lindenmayer et al., 2014), as well as from the imperative for monitoring. Firstly, it is necessary to identify knowledge gaps, such as in the geographic extent or type of data available (Sparrow et al., 2014), or the questions arising from environmental or societal changes (Sutherland et al., 2015). The large and remote nature and the difficulty in accessing these rangelands (Dickman et al., 2014; Sparrow et al., 2014, 2019b) also provides a significant challenge for these operational

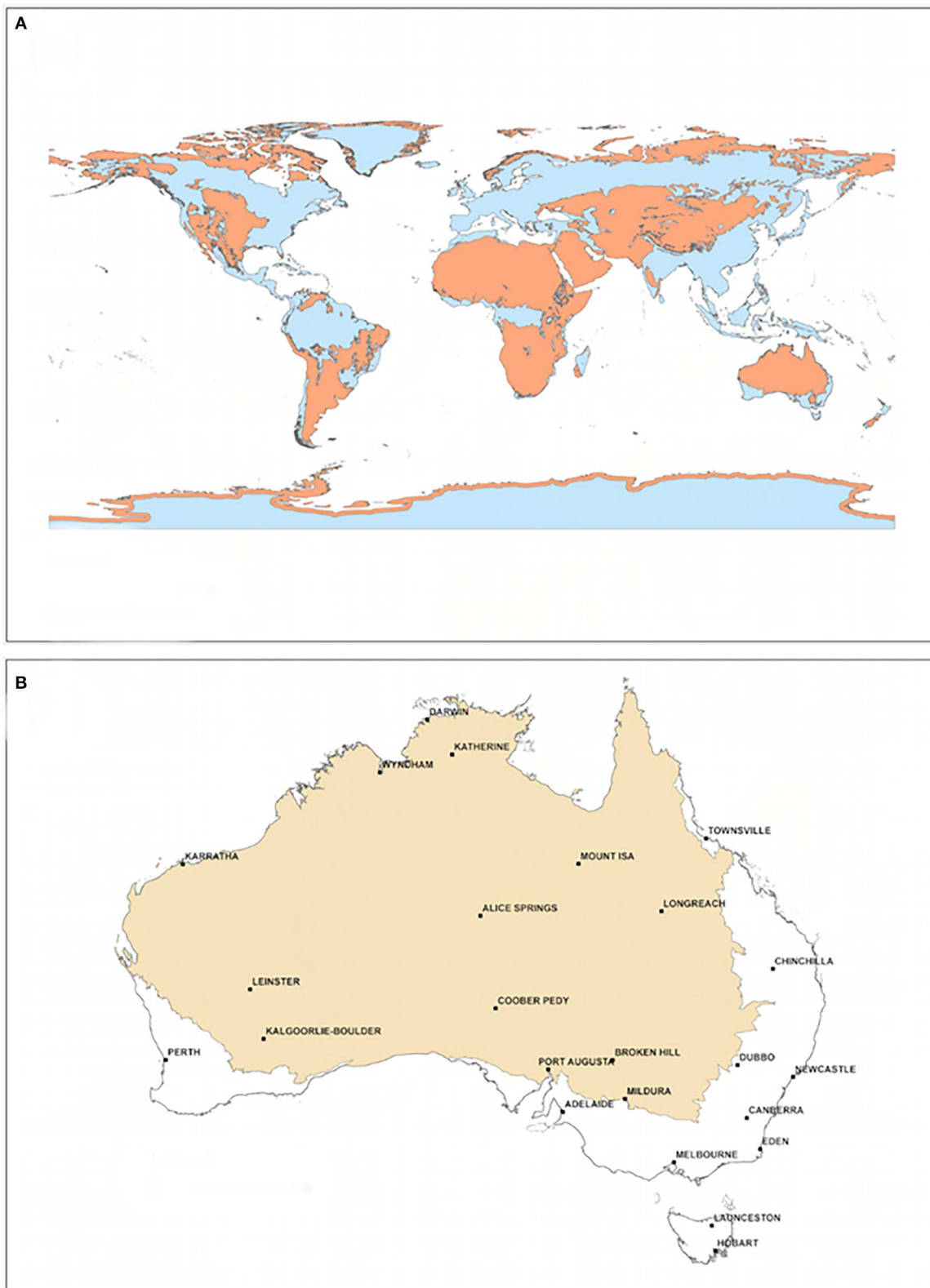


FIGURE 1 | Extent of rangelands: **(A)** globally and **(B)** within Australia (White I. A. et al., 2012).

programs. Secondly, practical constraints must be factored into monitoring protocols. Given the high cost of travel and data acquisition, surveillance monitoring methods need to maximize benefits from each visit, necessitating an efficient and integrated workflow from data collection to delivery of new knowledge (Tokmakoff et al., 2016). The level of information collected using this method was determined by widespread consensus of researchers, government scientists, and land managers from across the country at a series of workshops and subsequent feedback (see **Supplementary Material S2**). The time taken to collect information at each plot is detailed in **Table 1**.

The adoption of new monitoring programs, or integration of existing ones, can be hampered by poor communication of goals. A well-designed method may fail because practitioners are resistant to change or have divergent goals or cultural expectations (Ens et al., 2014). Widespread consultation and involvement is therefore key to successful engagement (see Box 2 in **Supplementary Material S4**). A challenge for these programs is to prioritize time for adequate engagement in the design and evaluation of methods in an environment with pressure to provide rapid results. New technologies and innovations should be considered for inclusion in situations where they provide increased accuracy or efficiencies over traditional techniques.

A key motivation for developing a new rangeland monitoring method in Australia was to overcome the lack of compatibility between existing jurisdictional data collection methodologies

(Foulkes et al., 2014; Sparrow et al., 2019b). Global efforts to monitor terrestrial ecosystems (Bastin et al., 2017a) need to build upon regional and local data collection and ideally include a set of essential environmental variables to provide a common modeling framework and scalable data to build a cohesive global synthesis (Schmeller et al., 2015).

METHOD OVERVIEW AND RATIONALE

Pragmatic Site Selection

A site selection protocol for surveillance monitoring of rangelands needs to be scientifically robust but also practical. Consideration needs to be made for site access, both at the time of initial survey, but also for continued access for repeat measures. We implement a two stage stratification procedure where we; (1) choose a bioregion to sample within (an Australian wide landscape classification similar to ecoregions sensu (Olson et al., 2001), **Supplementary Material S1**, and; (2) determine where within the bioregion to establish plots.

Given the biophysical and anthropogenic context, we use three strategies to determine bioregions within which to sample. (1) Stratified sampling to cover biophysical and disturbance gradients. (2) Setting a minimum number of plots per representative bioregion or vegetation type. (3) Additional sites identified via gap analysis. Strategies one and two were investigated (Guerin et al., 2020) and were shown to perform

TABLE 1 | Modules in the AusPlots rangelands monitoring method.

Module	Protocol	Time (min)	Application
Plot layout	Accurate layout using DGPS; installation of permanent markers.	30	Accurate relocation; remote sensing validation
VEGETATION			
Photo-panoramas	Collection of 360° photographs from three points	20	Computer vision analysis, point clouds, and measures of basal area
Vouchering	Collection of vascular plant species	60–120	Taxonomy; spatial/temporal analysis of presence—absence
Tissue samples	Collection of single tissue samples from vascular plants (four from dominant species)	30–60	Genetic/isotopic analysis
Point-intercept	Collection of species, height, phenology, growth-form, senescence at 1,010 points	180–360	Change in relative abundance, cover and structure; remote sensing validation
Basal area	Collection by species using basal wedge at nine points	20	Convertible to biomass
Structural summary	Recording of three dominant species in each of three strata (upper, mid, ground)	5	Community descriptions
Leaf Area Index	Collection of at least 50 evenly spaced readings with the LiCor LAI 2200 LAI meter	20	Ecophysiological modeling; remote sensing validation
SOILS AND LANDSCAPES			
Plot description	Record location, substrate, microtopography, erosion/disturbance	10	Assessment of characteristics/impact of disturbance
Soil pit characterization	Collection of soil samples/data at 10 cm increments or identifiable horizons to 1 m	60–120	Characterization and classification. Correlate with vegetation
Sub-site characterization	Collection of nine samples in differing microhabitats at 0–10, 10–20, and 20–30 cm	60–90	Soil variability across plot
Bulk density	Collection of three measures at the soil pit at 0–10, 10–20, and 20–30 cm	60	Conversion to volumetric measures
Soil metagenomics	Collection of nine samples	30	Identify biota

well against a range of statistically focused techniques as well as several spatially even sampling strategies. Strategy three currently uses Generalized Dissimilarity Modeling (GDM) to identify areas where gap filling plots should be established. Initial results from gap filling plots indicates that this is an effective technique, resulting in an increase in environmental space covered by the plot network. Scatterplots of relevant variables can also reveal poorly sampled regions in environmental space (Guerin et al., 2017a, 2020), while ecologically scaled measures of environmental uniqueness can be mapped over poorly sampled areas to identify priority habitats (Arponen et al., 2008; Guerin et al., 2020).

Once target bioregions have been identified, a more detailed process is undertaken at finer spatial scales. Within stratified units, plot locations can be randomized where practical to maximize representativeness and statistical rigor (Michalcová et al., 2011), whereas random sampling without stratification across large areas results in under-represented habitats (Michalcová et al., 2011). Plots can, and regularly are, co-located with those established by third parties (see **Table 2**) or legacy projects to extract value and enhance temporal depth. Political information is often relevant, including policy drivers influencing jurisdictions and opportunities for co-investment. Some land managers see standardized surveillance monitoring as an opportunity to capture robust information on the assets they manage and are receptive to co-investment.

Whether driven by stratification, gap-filling or policy needs, it is essential that site selection accounts for logistical considerations such as access permissions and feasibility, to make the program achievable and increase likelihood that sites will be re-sampled.

Plot Size and Layout

The choice of plot size is guided by the need to optimize the balance of survey resources and scientific rigor. While representativeness and robustness to small-scale variation increase with plot size (assuming vegetation within is homogenous), so does the expense of data collection, equating to fewer plots for fixed resources. Large, single, 50 ha plots have

become standard for the study of demographic dynamics in rainforest biomes (Harms et al., 2001), 1 ha plots are used for other woody ecosystems (Phillips et al., 2009; Miede et al., 2010), whereas grasslands are typically surveyed in smaller 1 m² plots (Borer et al., 2014).

Given the vastness and heterogeneity of rangelands, there is a need for many plots and therefore one-hectare plots were chosen for this method. Additional reasons for this choice included: (1) The potential to capture species vital rates and vegetation processes (mortality, recruitment, fire, grazing, and drought responses) whilst maintaining a practical sampling size; (2) the benefit of consistent results and reduced coefficients of variation in basal area, crown area, and vegetative structure between plots (Clark and Clark, 2000)—capturing small-scale patchiness whilst providing representativeness overall; (3) Enhanced integration with other activities that use 1 ha plots (Phillips et al., 2009; Jurgens et al., 2012; Wood S. W. et al., 2015; Karan et al., 2016), and (4) to provide information at an appropriate scale for validation of medium and high resolution remotely sensed products (Congalton and Green, 2008).

The monitoring plots are established with Differential Global Positioning System (DGPS) technology, to locate and record the coordinates of plot and transect vertices (**Figure 2A**) with sub-meter accuracy and metal poles located at the corners and center to aid in relocation for repeated monitoring. Each plot is located entirely within a relatively homogeneous (at the 1 ha scale) area of a particular vegetation community, and is intended to be representative of that vegetation community.

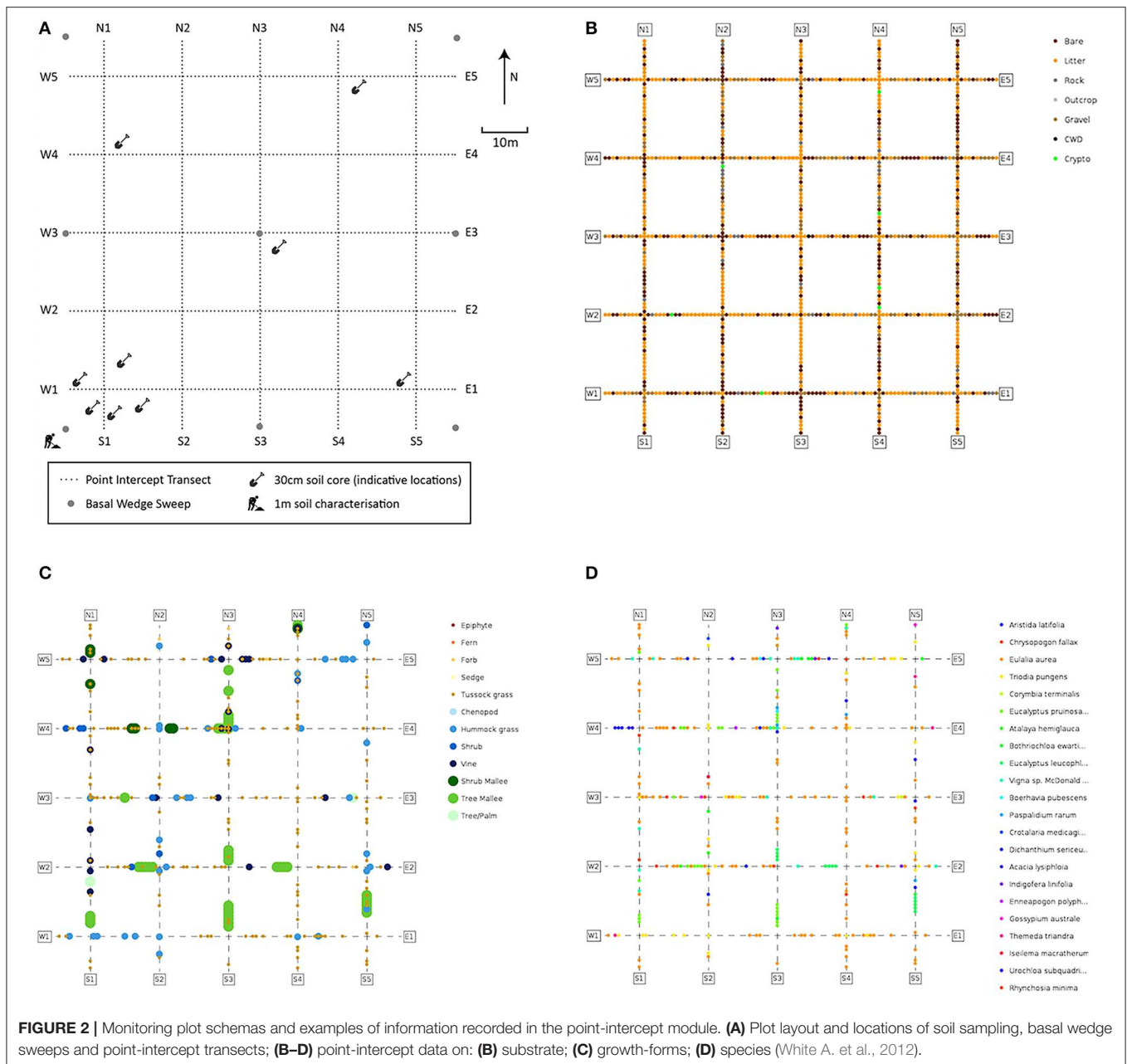
Plots are co-located with existing sites where possible. These sites have been established for a variety of reasons (see **Table 2**), and co-locating with these sites enables data from both programs to be combined or correlated, enabling greater temporal depth, richer contextual information, and often co-investment in site establishment.

Floristics and Vegetation

Plant cover and species composition are key essential variables (Pereira et al., 2013) for any ecological surveillance monitoring program and are core modules in our method. Careful consideration was given to ensuring adequate sampling effort, confirmation of species names by taxonomists, and flexible methods to record both quantitative estimates of abundance for commonly occurring and locally abundant species and occurrences of less abundant species within the plot. To achieve this, several techniques were combined. All vascular plant species observed within the plot are sampled and recorded, with identifications confirmed later by herbarium botanists. These samples are then stored indefinitely enabling taxonomic change to be updated throughout the collection and database. Vegetation is also characterized quantitatively by cover, composition, growth-form, and height. For this, a line point-intercept method is used across 10 × 100m transects in a grid (**Figure 2A**). This configuration ameliorates the skewing effects that site heterogeneity may have on cover, which are difficult to avoid in rangelands (Vetter, 2005). Data collected using this configuration are less sensitive to local heterogeneity or micro-patterning of the vegetation.

TABLE 2 | Co-location of sites with other projects.

Project type	Number of Co-located projects	Number of Co-located Plots
National environmental research infrastructure—process	7	40
National environmental research infrastructure—surveillance	4	43
Jurisdictional process	1	9
Jurisdictional surveillance	10	79
Non-government organization	1	11
Totals	23	182



Many authors recommend the collection of a minimum of 1,000 intercepts in rangelands to quantify cover per species (Lodge and Gleason, 1976; Holm et al., 1984; Friedel and Shaw, 1987; Vittoz and Guisan, 2007). Following this research, our method utilizes 1010 point intercepts along transects to determine vegetation cover per species across the plot. Abundance and presence/absence data are obtained by combining the identified sample data with the point-intercept data, with rarer species not intercepted being scored as present but not assigned a cover score. Each intercept is also attributed with information assessing plant height (used to reconstruct vegetation structure and as a surrogate for recruitment of

woody species) and whether the vegetation intercepted is dead or senescent, to indicate mortality. Mass recruitment/mortality events are also recorded. Height profiles can be created and their changes through time analyzed to indicate changes in vegetation community structure or to assign strata.

Accurate measures of vegetation cover are important for tracking environmental change, and have many applications (Vittoz and Guisan, 2007). Cover can be summarized to family, genus, species, growth-form levels, or as fractional cover—the fraction of photosynthetically active vegetation, dead vegetation, and bare substrate. Relative cover-abundance can be used in downstream analysis, or to classify vegetation, for example into

structural classes such as forest or shrubland based on height and cover of growth-forms. Change in vegetation structure (Figure 2C) or composition can be quantified, for example to detect woody weed encroachment. Raw data can be converted to common cover measures (e.g., opaque canopy cover or projected foliage cover), or summarized by the highest intercepted plant at each point. The location of each point-intercept is recorded (Figure 2), allowing detailed spatial patterning to be investigated as an alternative to gross plot-wide metrics.

Basal area is measured at each plot using a basal wedge sweep, to inform the amount of stored above ground biomass based on allometric equations (Eamus et al., 2000). Basal area is averaged across the plot, while raw tree stem counts are also recorded. A structural summary is also collected, identifying the most dominant species in each of the Ground, Mid-layer and Upper strata following the procedure described in Thackway et al. (2008). This enables the vegetation to be described at the level of an “Association,” equivalent to a Level 5 structural description in the Australian National Vegetation Information System (applicable to all vegetation types), with cover and height information being calculated from the point intercept data.

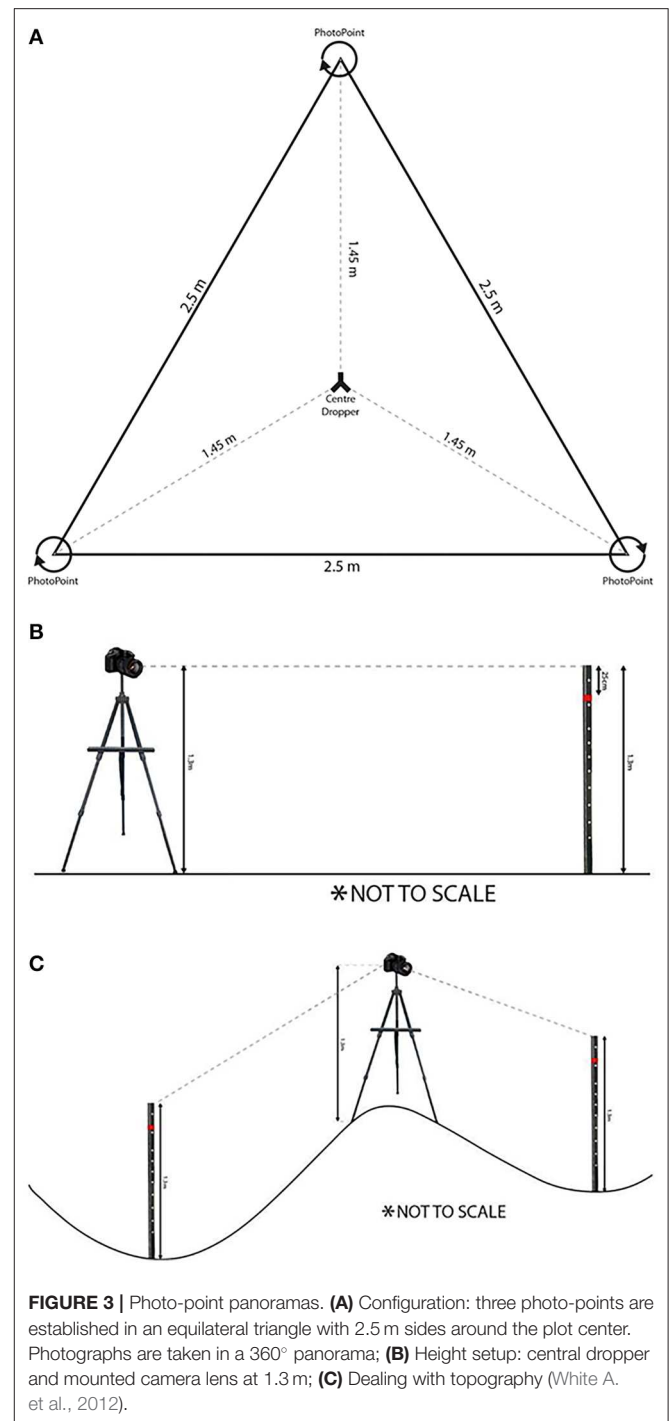
Photo-Points

Photo-points have long been used for monitoring (Watson and Novelty, 2004) and inventory programs (Brandle et al., 2005). In keeping with this tradition, photo-points are created with a new method in which panoramas (a continuous 360-degree sweep of static digital photographs with at least 50% overlap between frames) are collected at three points (Figures 3A–C). These photographs are comparable with historical photographs, and can be analyzed using computer vision techniques to determine basal area (White A. et al., 2012). It is anticipated that other structural metrics will be able to be extracted from these photosets in future.

Soils

The soil protocol quantifies variability within and between plots and over time using a pre-defined standard (National Committee on Soil and Terrain, 2009). This field protocol is undertaken at the same time as the vegetation modules to enable vegetation analyses to consider contemporaneous soil characteristics.

A plot description records erosion, micro-relief, landform pattern and element, drainage, disturbance, and soil surface condition. Four further modules are collected: soil profile pit; bulk density; soil sub-sites; and metagenomic samples. A 1 m deep pit in the southwest corner of the plot (Figure 2A) enables description and photographic recording of the upper soil profile and measurement of pH, electric conductivity, texture, color, and structure (White A. et al., 2012). Soils can then be categorized using a standard such as the Australian Soil Classification (ASC) system (Isbell and Terrain, 2016). Bulk density is measured at three depths of the pit to enable conversion of soil properties to volumetric measures (Table 1). Soil sub-sites are collected at nine locations across the plot, targeting variability in microhabitat, to collect the same information as at the soil profile pit to a depth of 30 cm and analyze small-scale variability (Figure 2A). Soil samples taken specifically to enable metagenomic analysis of



environmental DNA (e.g., targeting soil biota in various phyla or traces of above-ground flora and fauna) are collected from the surface at each sub-pit and stored on silica granules. Soil samples are air dried and retained for further analysis and access by researchers (Grundy et al., 2015).

Samples for Re-Use

Many monitoring methods that record species and taxonomic determination rely on botanists who can identify specimens in

the field and vouchers may only be collected for obtuse species or records of interest (Hosking et al., 2000). Field identifications are prone to error (Scott and Hallam, 2003; Lacerda and Nimmo, 2010) and the requirement for taxonomic expertise can inhibit delivery of plots. To address this issue, the method mandates the collection of herbarium vouchers for all vascular plant species observed, which are tracked using barcode labels. In addition to ensuring consistent identification, barcoded voucher specimens are a resource for ongoing research. Vouchers can resolve taxonomic issues, including the discovery of new taxa, updating species ranges (Hosking et al., 2000), and support studies of ecophysiology and occupancy across space and time (Guerin et al., 2012).

Additional plant tissue is collected from each species and stored in synthetic gauze bags with a barcode linked to the voucher specimen. These bags are used to avoid contamination from foreign plants (e.g., cotton). The bags are rapidly dried from silica granules, ensuring they can be used for genetic or isotopic analysis.

Soil samples (~500 g) are taken from each 10 cm depth from the soil profile pit and sub-sites, and these are barcode-labeled, air dried, and archived in a dedicated facility.

Validating Remotely Sensed Products

To enhance application of collected data to the validation of remotely sensed products, plots are marked out with sub-meter DGPS for spatial accuracy and where possible aligned to a locally accepted map grid (e.g., Map Grid of Australia). This enables the plot to be accurately matched to pixels from remotely sensed imagery. Locating plots in homogeneous areas increases the likelihood that the entire plot falls within a single remote sensing-derived mapping unit.

Cover information validates products from mid-resolution satellite imagery. Our point-intercepts are able to be converted to either opaque canopy cover or foliage projected cover, making the data useful for both ecological and imagery validation purposes. Because cover can be summarized at different levels, from species to fractional cover (Scarath et al., 2015), multiple applications are possible, for example validation of tree cover interpretation from imagery (Bastin et al., 2017a).

The LAI2200 instrument (LiCor, Nebraska, USA) is used to collect and calculate Leaf Area Index (LAI) data. This information can be used to validate international LAI products (Schaefer et al., 2015), and to assist with the calibration between LAI and foliage projected cover derived from remotely sensed products.

Structural information collected, including basal area determined using the basal wedge and photo-points, along with growth-form and vegetation height data from point-intercepts, is useful for validating satellite, airborne, and terrestrial LIDAR systems.

Data Availability

Data from the program are collected directly on an Android tablet and sent to a database when the field officers have mobile phone coverage (Tokmakoff et al., 2016). Data are subsequently combined with confirmed species identifications received after

samples have been submitted to a relevant herbarium, and the combined dataset is curated in preparation for publication. As sites are finalized, they are identified as ready to publish and pushed to TERN's AEKOS data delivery portal. During this process, the location of threatened or highly collectable species is de-natured (Lowe et al., 2017). The data are then made freely available on the web portal for discovery, download and re-use (Turner et al., 2017) using a Creative Commons (CC BY 4.0) by attribution license, or via the R package *ausplotsR* (Guerin et al., 2019c).

DISCUSSION OF METHODOLOGY AND APPLICATIONS

The standardized, quantitative surveillance monitoring method and innovative workflow we outline can be employed across jurisdictional borders, allowing the measurement of diverse environments at continental and global scales to answer questions that would be difficult to address using disparate datasets. Streamlined data collection and management ensure rapid delivery to end-users and help minimize error (Box 1 in **Supplementary Material S3**). The archiving of samples means that data and results can be verified downstream, allowing resilience to nomenclatural change and innovative future re-use of samples, for example bio-discovery (Lemetre et al., 2017).

Our approach is multi-disciplinary, collecting data relevant at multiple levels of ecological analysis from population genetics to remote sensing. By collecting these measures at the same plot using consistent methods, interactions among patch-level variables can be investigated.

The photo-points module is innovative in allowing traditional photo-point based change analysis whilst enabling three-dimensional computer vision analysis. Technology is also embraced in the collection of LAI data, using a DGPS to mark out plots and the use of a purpose data collection app to robustly collect data and minimize data transcription and collection inaccuracies [described in detail in (Tokmakoff et al., 2016)]. Our electronic workflow and data management processes from the point of data collection to data publication (Tokmakoff et al., 2016) also provides increased accuracy and efficiency over traditional methods.

Infrastructure Stimulating Ecological Research

The methods described in this paper have enabled a great many studies (see **Table 3**) in a wide variety of disciplines. Having said that the monitoring program is still young, with the majority of sites having only been visited once (see **Table 4**). Over the past few years site re-visits have commenced concurrently with strategic gap filling, with re-visits anticipated to become more prevalent in the coming years. Whilst use of our method and data from it has been widespread we anticipate much greater uptake in future years as the network matures and increases its spatial and temporal depth of information. There are a wide variety of ways the data can be used with a few specific examples provided below.

TABLE 3 | Some examples of publications enabled by data obtained using the method.

Resource category	Reference	Publication status	Journal	Theme	Findings
Standardized method	Wood S. W. et al., 2015	Published	Report/Manual	Forests	Provides an alternate 1 ha method most appropriate for Tall Forests and assessing change in biomass
Standardized method	Wundke et al., 2015	Published	Report/Manual	Condition	Provides additional modules for the core method for anyone interested in assessing environmental condition
Standardized method	Karan et al., 2016	Published	Science of the Total Environment.	Method development	Adapts these Ausplots Rangeland methods for use at TERN Ecosystem Processes intensively sampled sites
Standardized method	Sparrow et al., 2016	Published	Report/Manual	Woodlands	Provides additional modules to the Ausplots Rangelands methods that are most appropriate for woodlands and assessing change in biomass
Standardized method	O'Neill et al., 2017	Published	Report/Manual	Fauna	Provides a companion method to the Ausplots method for the inclusion of vertebrate fauna sampling
Standardized method	Bendig and Lucieer, 2019	Published	Report/Manual	Unmanned Aerial Vehicle (UAV) data collection	Details methods needed to collect multispectral UAV data over Ausplots to be compatible with other data collected at the site
Standardized method	Capon et al., 2020	Published	Report/Manual	Aust Gov Regional Land Partnership Program	Indicates that Ausplots methods along with data collection and management procedures could be useful to assess the efficacy of investment in on ground Regional Land Partnerships projects
Standardized method	O'Neill et al.	In Prep	In Prep	Invertebrate sampling	Provides a companion method to the Ausplots method for the inclusion of ground dwelling invertebrate fauna sampling
Property Reports	The Ausplots Team	Published	TERN Website	Property Reports	Provides property owners and land managers with details of the surveys that we have conducted on their land
Plot Network	Wood S. W. et al., 2015	Published	PLoS One	Baseline	Describes the baseline after data collection using the method described in Wood S. W. et al. (2015)
Plot Network	Guerin et al., 2018c	Published	Transactions of the Royal Society of South Australia	Generalized Dissimilarity Modeling	Details areas that are most susceptible to climate change in South Australia
Plot Network	Guerin et al., 2018b	Published	Swainsona	Climate change modeling	Value of surveillance plots as a baseline for monitoring change, particularly when aligned along environmental gradients
Plot Network	Guerin et al., 2019a	Published	Acta Oecologica	Environmental Gradients	Zones of rapid compositional turnover in species were evident in gradients in a variety of environments
Plot Network	Dong et al., 2020	Published	New Phytologist	Plant Functional Traits	Shows that environmental conditions influence leaf traits by sampling along an environmental gradient of Ausplots
Plot Network	Guerin et al., 2020	In Review	Preprint @ bioRxiv	Gaps	Early Ausplots stratification method performed well in comparison to statistically oriented and spatially even sampling strategies
Plot Network	Guerin et al., 2020	In Prep	In Prep	Identifying gaps	Details how gaps in the Ausplots network are identified with GDM, and how focusing survey effort in these areas has improved the networks environmental coverage of Australia

(Continued)

TABLE 3 | Continued

Resource category	Reference	Publication status	Journal	Theme	Findings
Plot Network	Guerin and Lowe, 2013	Published	Environmental Monitoring and Assessment	Survey methods	Assesses point intercepts are more precise for cover estimation, but use is determined by available resources as it is more labor intensive
Plot Network	Guerin et al., 2014	Published	Journal of Vegetation Science	Surveillance monitoring and spatial differences along plot network	A spatially predictive baseline for monitoring multivariate species occurrences and phylogenetic shifts in Mediterranean southern Australia
Plot Network	Muir et al., 2015	Published proceedings	Silvilaser proceedings	Photopoints	Analysis of photopoint data showed a high level of agreement with field measured information on basal area
Plot Network	Bastin et al., 2017a	Published	Science	Forest estimation	Increase in global forest cover of 9%; Field method enabled robust accuracy assessment
Plot Network	Bastin et al., 2017b	Published	Science	Response to de la Cruz et al.	Justified focus on FAO definitions for worldwide applicability
Plot Network	Bastin et al., 2017c	Published	Science	Response to Griffith et al.	Justified focus on FAO definitions for worldwide applicability
Plot Network	Bastin et al., 2017d	Published	Science	Response to Schepaschenko et al.	Justified focus on FAO definitions for worldwide applicability, refuted higher availability of high-resolution imagery in Australia (Aust 74% plots v's 82% Plots worldwide)
Plot Network	Caddy-Retalic et al., 2017	Published	Ecology and Evolution	Transects	Argues that networked and replicated transects with the addition of experimental treatments provide novel insight on ecological change
Plot Network	de la Cruz et al., 2017	Published	Science	Comment	Critiqued definition of drylands
Plot Network	Gibson et al., 2017	Published	PLoS One	Species turnover	Species turnover increased rapidly with increasing extent along an environmental transect
Plot Network	Griffith et al., 2017	Published	Science	Comment	Critiqued definition of drylands, specifically in reference to savanna ecosystems
Plot Network	Guerin et al., 2017b	Published	PLoS One	Species abundance distributions	An overview of breath of sampling, and analyses the value of point intercept data
Plot Network	Martin-Fores et al., 2017	Published	PLoS One	Weed abundance	Weed abundance is positively correlated with the diversity of native plants in South Australian grasslands
Plot Network	Nolan et al., 2017	Published	Functional Plant Biology	Plant Traits	Photosynthetic traits correlate with water availability for trees and shrubs in arid Australia
Plot Network	Schepaschenko et al., 2017	Published	Science	Comment	Critiqued dryland definition, Suggested Accuracy assessment using Ausplots biased due to high availability of high resolution imagery over Australia
Plot Network	Baruch et al., 2018	Published	PLoS One	Vegetation Classification	Analyses vegetation patterns at the national scale
Plot Network	Bruelheide et al., 2018	Published	Nature Ecology and Evolution	Plant Functional Traits	Plant traits seem mainly filtered by local factors

(Continued)

TABLE 3 | Continued

Resource category	Reference	Publication status	Journal	Theme	Findings
Plot Network	Caddy-Retalic et al., 2019	Published	Diversity & Distributions	Species composition	Plant and ant assemblages predicted to decouple under climate change
Plot Network	Gellie et al., 2018	Published	Phytocoenologia	Plot survey review	Development of a consistent vegetation classification system across Australia and how Ausplots can contribute
Plot Network	Guerin et al., 2018a	Published	Ecography	Beta diversity	Uses GDM's to show that untransformed herbaria data are not appropriate to assess beta diversity as turnover is related to sampling intensity
Plot Network	Muir, 2018	Published	PhD Thesis	Photopoints	Accuracy of photopoint method in comparison with terrestrial Lidar
Plot Network	Beland et al., 2019	Published	Forest Ecology and Management	Vegetation Structure	Provides information on the applicability of LiDAR in assessing vegetation structure and indicates its value for research infrastructure collection
Plot Network	Bruelheide et al., 2019	Published	Journal of Vegetation Science	Database description	Details an international vegetation database that Ausplots contributes to
Plot Network	Guerin et al., 2019b	Published	Applied vegetation Science	Invasion ecology	Weed species change the structure of Australian grasslands
Plot Network	Melville et al., 2019	Published	International Journal of Earth Observations and Geoinformation	Remote Sensing Validation	Scaling between field observations and satellite imagery
Plot Network	Nevill et al., 2020	Published	Plant Methods	Genetic plant ID	Investigates use of genetic material for plant identification in WA
Plot Network	van der Sande et al., 2020	Published	Global Ecology and Biogeography	Invasion ecology	Investigate the abundance of invasive trees in their native and invasive ranges and find that they occur primarily in areas with functionally similar co-occurring species
Plot Network	Slik et al.	In Prep	In Prep	The origin of forest biodiversity	Support the "Out of the Tropics" hypothesis
Infrastructure	Cleverly et al., 2019	Published	Environmental Research Letters	Research Infrastructure	Explains how this infrastructure contributes to forecasting ecosystem responses to climate change and variability
Data	Tokmakoff et al., 2016	Published	Future Generation Computer Systems	Data Management	Details data collection, curation, management and delivery system for Ausplots
Data	Lowe et al., 2017	Published	Science	Open Publishing	Responsible open publishing
Data	Turner et al., 2017	Published	Book Chapter	Aekos Intro	The importance of context and fully described data, advocated for process described in Tokmakoff et al. (2016)
Data	Guerin and Lowe, 2015	Published	SoftwareX	Plant biodiversity distribution—example data for method	Mapping phylogenetic endemism in R using georeferenced branch extents
Data	Guerin et al., 2016a	Published	PLoS ONE	Plant biodiversity distribution—mapping	Identifying plant biodiversity centers in South Australia
Data	Guerin et al., 2019c	Published	Computer Code	R Package	Public access to operational database + data pre-processing directly in R

(Continued)

TABLE 3 | Continued

Resource category	Reference	Publication status	Journal	Theme	Findings
Data	Gallagher et al., 2020	Published	Nature Ecology and Evolution	Trait science	Articulates open science principles for trait research
Collections	Grundy et al., 2015	Published	Soil Research	Digital soil mapping	The Soil and Landscape Grid of Australia (SLGA) first continental soil map, utilizes soil samples, and data
Collections	Bissett et al., 2016	Published	Gigascience	Genomics	First Australian soil microbial diversity database
Collections	Dong et al., 2017	Published	Biogeosciences	Climate adaption	Indicates adaptability due to phenotypic plasticity and species replacement over environmental gradients and for nitrogen content per unit leaf area this is relatively evenly split
Collections	Lemetre et al., 2017	Published	PNAS	Genomics	Identifying latitudinal basis for differences in soil borne therapeutically relevant compounds
Collections	Andrae et al., 2018	Published	Geophysical Research Letters	Isotopes	Identifies that C4 plants in Australia initially expanded in the late Pliocene
Collections	Baruch et al., 2017	Published	Austral Ecology	Plant Traits	Specific Leaf Area for this species varies in relation to latitude
Collections	Howard et al., 2018	Published	Organic Geochemistry	Leaf wax persistence in soil	Information on vegetation structure are preserved in n-alkane stored in soils
Collections	Falster et al.	In Prep	In Prep	Plant Functional Traits	Foundation article for AusTraits—includes photosynthetic pathway assignment from Munroe et al. “AusTraits: a curated plant trait database for the Australian flora”
Collections	Munroe et al.	In Prep	In Prep	Isotopes	Cause of C4 species distribution across Australia

The resource category column groups publications dependent on the method component to which they most closely relate. “Standard Method” details those publication that expand or leverage the methods detailed here. “Plot Network” are publications based on, or including the field data collected in the program. The “Infrastructure” category details a publication focused on the value of the created research infrastructure. “Data” focuses on publications that discuss, leverage or include data collection, curation, management, and delivery principles used in the program and “Collections” are publications enabled by the range of physical samples collected and stored by the program.

TABLE 4 | Sites collected using the method in the TERN Ecosystem Surveillance program, quantified by the Major Vegetation group in which they occur, along with information on the number of sites revisited.

Major vegetation groups	Sites visited once	Sites visited twice	Sites visited three times
Rainforests and vine thickets	1		
Eucalypt tall open forests	1	3	
Eucalypt open forests	15	10	2
Eucalypt low open forests	5	3	1
Eucalypt woodlands	98	17	2
Acacia forests and woodlands	30		1
Callitris forests and woodlands	6		
Casuarina forests and woodlands	14	4	
Melaleuca forests and woodlands	22		
Other forests and woodlands	8		
Eucalypt open woodlands	37	7	2
Tropical eucalypt woodlands/grasslands	6		
Acacia open woodlands	13	1	3
Mallee woodlands and shrublands	24	9	1
Low closed forests and tall closed shrublands	1		
Acacia shrublands	49	5	8
Other shrublands	41	6	2
Heathlands	15		
Tussock grasslands	70	4	3
Hummock grasslands	16	2	4
Other grasslands, Herblands, Sedgelands and Rushlands	7	8	2
Chenopod Shrublands, Samphire Shrublands and Forblands	79	8	2
Cleared, Non-native vegetation, buildings	1		
Regrowth, modified native vegetation	6		
Other open woodlands	6		
Mallee open woodlands and sparse mallee shrublands	20	6	1

Leaf Samples

Genomic sequencing technologies now provide cost-effective information on species identification (DNA barcoding) and population genetic structure that allows rapid species identification, the detection of cryptic species and identification of regions of high genetic diversity, all of which are useful in a conservation context. The archiving of plant tissue samples ensures material will be available even if the populations do not persist. Access to samples facilitates work by independent researchers that may otherwise be impeded by the cost of sample collection from remote locations. Leaf samples have been incorporated in a number of studies (Christmas et al., 2017). Leaf samples are also available for isotope analysis and the study of leaf chemical components such as the study of Dong et al. (2017) where these samples were used to demonstrate that Leaf Mass per unit area increases with aridity.

Soils

Investigation of soils has typically focused on agrarian zones, meaning soil characteristics for rangelands have largely been interpolated from sparse data, with this being particularly so

in Australia. In addition to basic characterization, the method archives soils for future analysis (e.g., DNA metabarcoding and chemical analyses). Soil surface samples are collected, from which biological activity can be quantified and related to soil parameters. These samples facilitate research on soil-vegetation interactions, typically conducted in local research projects. For example (Lemetre et al., 2017), analyzed these soil samples and reported that turnover in bacterial biosynthetic composition followed a latitudinal pattern but did not appear to be driven by changes in major vegetation type, a finding that directs approaches to future sampling of soils for natural product discovery.

Floristics and Vegetation

Vegetation data collection has been designed for multiple purposes. For example, standard community ecology analytics such as ordination of vegetation and environmental variables can provide insight into spatial patterning of species composition (Figure 2D) and its drivers. The data also enable tracking of composition and cover dynamics with high reliability, enabling practical outcomes like reporting on responses to disturbance or

grazing impacts. The collection techniques also provide a useful inventory, providing information on distribution and abundance of species, with management applications such as providing information on the distribution and abundance of problematic woody weed species.

The analysis opportunities for vegetation data from this program have been identified in more detail in Guerin et al. (2017a), including assessment of cover and species dominance analysis. The future opportunities enabled by the multi-disciplinary method described here are also articulated. Vegetation classification studies have also been conducted using the dataset (Baruch et al., 2018).

Validating Remote Sensing Products

The method provides information useful for validating remotely sensed image products at multiple scales, such as vegetation and soil products derived from mid-resolution satellite imagery. By recording the shortest distance to another vegetation type, plots can represent a bigger spatial footprint and be useful for validating lower spatial, but higher temporal, resolution imagery. The data have further potential to validate high-resolution spatial and spectral image products, as well as radar and LIDAR imagery.

Growth-form and cover data from this method were compared by Bastin et al. (2017a) to values obtained from visual estimates of very high resolution imagery over the same sites. This information was then used to quantify observer estimate errors and errors between different observers for this study that quantified the amount of forest occurring in dryland biomes globally. Bastin et al. identified that previous estimates of dryland forest cover were between 40 and 47% lower than their study indicates, leading to an increase of around 9% to estimates of forest cover globally compared to previous knowledge.

Sampling Other Environments

Whist the program was initiated in Australia's rangelands it has been implemented successfully in a wide variety of structurally diverse vegetation types throughout the country (Table 4), broadly representative of a variety of rangeland vegetation types globally. Rainforests and Tall Eucalypt Forests provide some challenges to the point intercept modules and prompted the development of forest specific protocols (Wood S. et al., 2015). Additional optional modules have been developed for woodlands where researchers intend to track tree growth through time (Sparrow et al., 2016).

CONCLUSION

We present a surveillance monitoring method for rangeland ecosystems developed in Australia but applicable to global context. The method is now implemented as part of the surveillance monitoring program of TERN, under the guiding principles of widespread consultation, continual adaptation and coverage of variables/attributes relevant to multiple disciplines, to meet the needs of a diverse ecosystem science community (Pereira et al., 2013). The method is standardized, quantitative

and modular, providing robust baselines and clear protocols for sample and data management. The method embraces new technologies such as a novel photopoint method and robust electronic data collection using a field app alongside more traditional techniques. Sample archiving ensures continued utility of collected data and enables subsequent analysis. A streamlined and accurate dataflow enables rapid open access data provision. The method has had proven application to analyze rangelands systems globally (Bastin et al., 2017a), and many components are suitable for other environments. In future, we anticipate adding additional variables on other environmental parameters including fauna sampling, for which protocols have been prepared and are undergoing consultation, to be implemented as resources permit.

AUTHOR CONTRIBUTIONS

BS, JF, and AL developed the concept. BS, JF, EL, GW, SC-R, GG, and SL contributed to field testing. BS, JF, EL, GW, SL, AT, and AL contributed to method development. BS, JF, NT, and AL contributed to obtaining funding. BS and JF drafted the manuscript. All authors contributed to method critique, sections of text for the manuscript and contributed critically to the drafts and gave approval for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2020.00157/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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