RESEARCH ARTICLE

A network to understand the changing socio-ecology of the southern African woodlands (SEOSAW): Challenges, benefits, and methods

The SEOSAW partnership

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[Correction added on 29 January 2021, after first online publication: Heading levels have been fully modified after 3.1.]

Societal Impact Statement

The sustainable management of the southern African woodlands is closely linked to the livelihoods of over 150 M people. Findings from the Socio-Ecological Observatory for the Southern African Woodlands (SEOSAW) will underpin the sustainability of two of the largest industries on the continent: woodfuels and timber. SEOSAW will also improve our understanding of how human use shapes the biogeography and functioning of these ecosystems.

Summary

- Here we describe a new network of researchers and long-term, *in situ*, measurements that will characterize the changing socio-ecology of the woodlands of southern Africa. These woodlands encompass the largest savanna in the world, but are chronically understudied, with few long-term measurements.

- A network of permanent sample plots (PSPs) is required to: (a) address management issues, particularly related to sustainable harvesting for energy and timber; (b) understand how the woodlands are responding to a range of global and local drivers, such as climate change, CO_2 fertilization, and harvesting; and (c) answer basic questions about biogeography, ecosystem function, and the role humans play in shaping the ecology of the region.

- We draw on other successful networks of PSPs and adapt their methods to the specific challenges of working in southern African woodlands. In particular we suggest divergences from established forest monitoring protocols that are needed to (a) adapt to a high level of ecosystem structural diversity (from open savanna to dry forest); (b) quantify the chronic disturbances by people, fire, and herbivores; (c) quantify the diversity and function of the understory of grasses, forbs, and shrubs; (d) understand the life histories of resprouting trees; and (e) conduct work in highly utilized, human-dominated landscapes.

- We conclude by discussing how the SEOSAW network will integrate with remote sensing and modeling approaches. Throughout, we highlight the challenges

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inherent to integrating work by forest and savanna ecologists, and the wide range of skills needed to fully understand the socio-ecology of the southern African woodlands.

1 | INTRODUCTION

"As a scientific project, a... plot is akin to a space-station or a probe to Mars—it is a comprehensive scientific tool used jointly by a large number of scientists from several disciplines. And, like other big science projects, it is costly." (Condit, 1998).

Together, savannas, woodlands, thickets, and dry forests constitute the largest land cover in the tropics (Olson et al., 2001; Pennington et al., 2018). These ecosystems, together termed the dry tropics (Pennington et al., 2018), are chronically understudied (Sunderland et al., 2015). Focusing on southern Africa, here we set out how long-term, repeated, *in situ*, measurements can be used to understand the changing socio-ecology of the vegetation of the dry tropics.

Long-term measurements tracking individual plants can guide land use management, for example sustainable harvesting (Alder & Synnott, 1992), and also address fundamental scientific questions. For ecologists, understanding both individual life histories and changes in community assembly is vital to tackling fundamental questions regarding tree allometry and growth, recruitment and mortality, ecosystem functioning, and responses to global change (Esquivel-Muelbert et al., 2019; Fadrique et al., 2018; Fauset et al., 2012; Rozendaal & Zuidema, 2011; Wolf et al., 2009). The SEOSAW network has been created to address the lack of such a network of measurements in the southern African dry tropics—the focus of this paper—and to improve our understanding of the functioning of the region's vegetation and, in particular, responses to global change.

SEOSAW is in the early stages of implementation (https://seosaw.github.io). We have integrated existing plot data into the network and are establishing new plots using a new, standardized manual, the latest version of which can always be found at https://seosaw.github.io/manuals.html. The manual, the main aspects of which are presented here, was created through discussion at a series of workshops, supported by analysis of the existing data. Thus, in this paper, we (a) provide an introduction to the socio-ecology of the vegetation in the region; (b) set out the rationale for SEOSAW and the key questions it will address; and (c) present the SEOSAW manual, discussing the methodological challenges inherent in making consistent long-term observations in the region and the way we have addressed them, before (d) summarizing our next steps.

2 | BACKGROUND TO THE SOCIO-ECOLOGY OF THE WOODLANDS OF SOUTHERN AFRICA

The woodland region of southern Africa defined by White (1983; Figure 1) is largely comprised of woody savannas, but is interspersed with more open savannas, and denser thickets and dry forests. The terminology describing the vegetation has long been contentious (Frost & Campbell, 1996; Ratnam et al., 2011; Richards et al., 1940) because in many areas the woodlands can form a closed canopy and thus might be described as a dry forest, while in other locations, the same floristic assemblage can have a markedly open canopy and support a continuous grass layer, meeting most definitions of a savanna (Ratnam et al., 2011). We therefore use the term woodland in the sense of White (1983) and note that the region includes much that is of interest to scholars of both dry forests and savannas.

First we describe the biogeography of the SEOSAW region of interest, drawing heavily on the mapping of White (1983). In White's map, woodlands cover 3.2 M km^2 of southern Africa, with associated woodland transitions and mosaics covering a further 0.5 M km^2, and forest transitions covering 1.8 M km^2. Note that these areal estimates do not account for human transformation of these landscapes. Human influence varies widely across the region: approximately a quarter of the land area is cropland (You et al., 2014), and shifting cultivation is common (Grogan et al., 2013). Tree harvesting is also widespread, particularly near cities (Ahrends et al., 2010; Ahrends et al., in press; MITADER, 2018; McNicol et al., 2018). Given variation in both natural and human determinants of ecosystem structure, there is a large degree of structural variation within the floristic vegetation types mapped by White (1983).

The largest floristic units of the southern African woodland delineated by White (1983) and updated by Olson et al. (2001) are miombo (2.2 M km^2; Campbell, 1996), mopane (0.5 M km^2; Makhado et al., 2014), and Baikiaea woodlands (0.3 M km^2; de Cauwer et al., 2016). These floristic units are all dominated by trees of the recently renamed Detarioideae (LPWG, 2017), a subfamily of the Leguminosae. Miombo woodlands (dominated by trees of the genera *Brachystegia* and *Julbernardia*), are divided into four somewhat distinct geographic blocks (Olson et al., 2001) separated by large river valleys covered by mopane woodland (dominated by *Colophospermum mopane*) and/or flooded grasslands, or by mountain ranges. The Baikiaea woodlands (largely dominated by *Baikiaea plurijuga*) occur across the central southern parts of the ecoregion
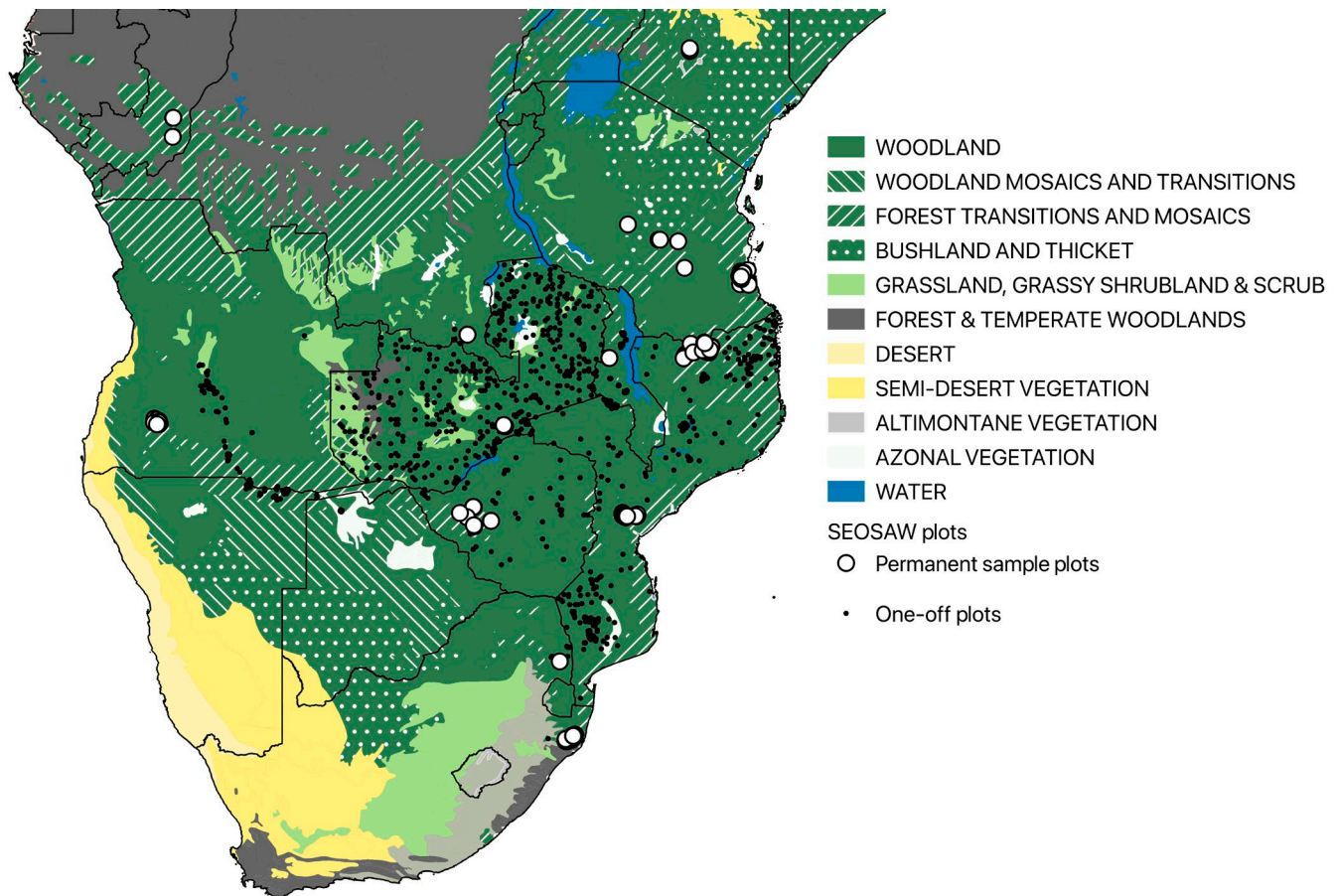
FIGURE 1 The distribution of woodland and other vegetation types in southern Africa, following White (1983). White's (1983) "Major Vegetation Groups" are mapped with some aggregation of the non-woodland types to simplify the legend. The major groups consist of "Forest" with closed canopies, "Woodland" which includes a wide range of mostly open canopy formations, including many that might also be termed savanna, "Bushland," and "Grassland" which has almost no tree cover, as well as the transitions between these groups. Several caveats to the mapping shown here are important. The first is that the data from White (1983) reflect the state of knowledge from the 1960 to 1970s: more recent vegetation maps are available for some parts of the region, but there is no more recent regional-scale map that considers vegetation floristics. Second, the southern boundary of the woodlands is rather arbitrary given the gradual transitions present in the region. Permanent sample plots (PSPs, marked with white circles) are long-term plots where individual trees are repeatedly remeasured and which have been incorporated into the network or installed since the start of SEOSAW. Black dots show "one-off" plots in the SEOSAW database, not suitable for remeasurement, but useful for studies of, for example, species distribution

and start the transition to more arid Kalahari vegetation. Mopane woodlands occur in large river valleys and, similar to Baikiaea woodlands, also across the southern part of the region in more arid zones. A transition to Congolian rainforest occurs to the north, and to more open savannas, shrublands, and bushland to the NE and SW (Linder et al., 2012; Olson et al., 2001; White, 1983). On the eastern seaboard, the heavily transformed coastal forest mosaic (0.4 M km^2) is sometimes included in definitions of the miombo ecoregion (Burgess & Clarke, 2000), although it is floristically distinct (Timberlake et al., 2013; White, 1983). Overall, however, this continental-scale perspective belies a more diverse reality. The vegetation types mapped by White (1983) and updated by Olson et al. (2001) are limited by the data available at the time they were compiled and include a large (0.6 M km^2) "undifferentiated woodland" class, with very varied patterns of floristic dominance. At a finer scale there are complex structural and floristic patterns, including the widespread

presence of non-Detarioid vegetation such as Mimosoid (ex-*Acacia* incl. *Senegalia* and *Vachellia*)- and Combretaceae-dominated savannas (Backeus et al., 2006; de Cauwer et al., 2016; Kalaba et al., 2013; McGregor, 1994; Osborne et al., 2018; Woollen et al., 2012), and rain-forest-affiliated coastal forest (Prins & Clarke, 2007; Timberlake et al., 2013).

The importance of southern African woodlands in rural and urban livelihoods has long been recognized, and increasingly, quantified (Cavendish, 2000; Chidumayo et al., 2010; Clarke et al., 1996; Dewees et al., 2010; Ryan et al., 2016). A recent synthesis suggests that in cash-equivalent terms, around a quarter of rural income in the region is derived from woodlands, not including multiple indirect contributions to agriculture (Ryan et al., 2016). Woodlands also provide 80%–90% of the energy consumed in some countries in the region (IEA, 2019), mainly comprising fuel wood in rural areas and charcoal in urban centers (Ryan et al., 2016). Woodland resources are particularly important during crises

and household shocks, when wild food can exceed 30% of calories consumed (Woittiez et al., 2013), and when income from selling timber and nontimber products is particularly important (Pritchard et al., 2020). The scale of the human enterprise in southern African woodlands means that humans are an important component of the ecology of the system: for example, harvesting about 1% of the standing stock of biomass and clearing 2.1%–3.3% of the wooded land for agriculture every year (McNicol, Ryan, & Mitchard, 2018; Ryan et al., 2016). Any attempt to understand changing ecosystem functions needs, therefore, to be informed by the shifting social context (Falcão et al., 2007; Laris, 2011).

3 | THE RATIONALE FOR LONG-TERM OBSERVATIONS

Permanent sample plots (PSPs) have been widely used for research and management in forest ecosystems, and to a lesser extent in savannas and woodlands. Our goal in this section is not to provide an exhaustive summary of such applications (see instead: Alder & Synnott, 1992; Anderson-Teixeira et al., 2015; Condit, 1998; Geldenhuys, 1997; Guerin et al., 2017; Lewis et al., 2009a; Lopez-Gonzalez et al., 2011; Malhi et al., 2002; Picard et al., 2008; Schepaschenko et al., 2019; White et al., 2012), but to summarize what we see as the main benefits of a network of PSPs in the southern African region.

3.1 | PSPs can provide Information for better management

Repeated stem measurements on PSPs are essential for defining sustainable harvesting rates (Alder, 1999) as they provide data on tree demographics (mortality, growth, and recruitment; Lewis, Phillips, et al., 2004; Needham et al., 2018). Data on demographic rates are particularly important in a region where most energy consumed is derived from trees, and where timber and traded wood-fuels are major industries (Dewees et al., 2010; Ryan et al., 2016). Although aggregate demand is not thought to outstrip sustainable supply (Twine et al., 2016), there are areas around major cities where overharvesting is leading to a loss of woody vegetation (Ahrends et al., 2010; Mwampamba, 2007; Scholes & Biggs, 2004; Sedano et al., 2019), and where harvesting rates need to be carefully managed. Currently those who regulate wood harvesting at a national scale set harvesting quotas based on almost no data from the region (Chishaleshale et al., 2019; Marzoli, 2007). Of course there are other barriers to sustainable harvesting, beyond a lack of information on tree demography, but long-term estimates of demographic rates are required and need to be assessed across the environmental diversity of the region (Dewees et al., 2010; Geldenhuys, 1997).

More recently, information on carbon source and sink dynamics in the region has been required for effective management. Carbon projects (Fisher, 2012; Grace et al., 2010; Khatun et al., 2015), national programs to reduce emissions from deforestation and degradation (Bond et al., 2010; Burgess et al., 2010), as well as other interventions that seek to reduce land use carbon emissions (Berry et al., 2013) all need information on changes in carbon stocks over time, both to predict carbon sequestration rates and to report emissions. PSP data can provide such information, and particularly help to quantify processes such as degradation, which is hard to measure with remote sensing (Chidumayo, 2013), and the role of grasses and soil in carbon sequestration, which can exceed sequestration by woody plants (Wigley et al., 2020).

PSP data can also inform management in situations where having too many trees is a potential problem. The thicketization of open savanna (expansion of trees into open habitats, also known as bush encroachment or woody expansion) has important social consequences (Luvuno et al., 2018). Ecosystem services such as grazing and the provision of medicinal plants often decline as tree cover increases (Hargreaves, 2017), and structural changes to vegetation may drive significant changes in mammal assemblages (Smit & Prins, 2015). In the more open savannas in the south of the SEOSAW region, woody expansion is considered a major economic threat impacting both tourism (Gray & Bond, 2013) and livestock industries (Luvuno et al., 2018). It is unclear however, to what extent it is happening in the more wooded areas (Stevens et al., 2017), and what the management implications will be. A network of PSPs will provide vital information on the nature of this woody expansion, which will include the first region-wide evidence for whether tree growth and/or recruitment is increasing, or mortality declining, and whether species composition is changing. This understanding will help model and predict the biodiversity consequences of changes in the woodlands under various land use and climate change scenarios, and inform sustainable land use and biodiversity management (Scheiter & Savadogo, 2016; Scheiter et al., 2019).

3.2 | Research questions that PSP data can address

Long-term plots have provided a wealth of discoveries and challenges to ecological theory, such as the finding of increased tropical forest turnover since the 1960s (Phillips & Gentry, 1994), and the decline in the rainforest carbon sink (Brienen et al., 2015). A long-term observational plot network in the southern African woodlands will allow a wide range of long-standing research questions to be addressed, complementing the rich tradition of long-term manipulation experiments in the region (Chidumayo, 1988, 2013; Furley et al., 2008; Higgins et al., 2007; Kennan, 1972; Trapnell, 1959). Here we highlight four of the main questions the SEOSAW network is designed to answer.

3.2.1 | Question 1: Are woodlands increasing in woody biomass and thus a globally important carbon sink?

There are several reasons to hypothesize that the southern African woodlands may be on a path to higher woody biomass. First, to the

north, in the central African forests, there is evidence of net bio-mass accumulation (Hubau et al., 2020; Lewis et al., 2009a). To the south of the SEOSAW region, savanna thicketization is widely reported (Buitenwerf et al., 2012; Skowno et al., 2017). The situation in most of the southern African woodlands has not been assessed with ground data, and remote sensing analyses disagree on the locations and magnitude of biomass change (McNicol, Ryan, & Mitchard, 2018; Mitchard & Flintrop, 2013). Elevated pCO_2 has been widely cited as a likely cause of woody biomass increases (Bond & Midgley, 2012), but this is disputed, and a range of other drivers (e.g., climate change, overgrazing, altered fire regimes) have been suggested (Venter et al., 2018). A network of PSPs across the region is the only way to resolve discrepancies in remote sensing analyses, and the only way to understand whether woody biomass increases are driven by en-hanced tree growth or by reduced mortality. The distinction is impor-tant both for the future trajectory of the associated carbon sink and for fingerprinting the causes of change (Lewis et al., 2004).

3.2.2 | Question 2: Is global change altering the floristic composition and associated diversity of the woodlands?

From work in South African open savannas and parts of the Brazilian Cerrado comes evidence that global change is favoring savanna trees over grasses, which is leading to increased tree cover and a more shady understory (Abreu et al., 2017; Skowno et al., 2017; Veldman et al., 2015b). This can lead to a decline in understory (grass and forb) diversity and also to a reorganization of faunal communities (Parr et al., 2014; Peron & Altwegg, 2015). From these findings flow oppo-sition to tree planting as a form of restoration (Veldman et al., 2015a) and also fears of damaging socio-ecological regime change (Luvuno et al., 2018). This hypothesis is sometimes extrapolated to southern African woodlands (Higgins & Scheiter, 2012), despite differences in functional ecology, land use history, and social context between the more open savannas and the woodlands. A network of PSPs quantify-ing understory and canopy-level floristic composition and its change over time will be able to test several component parts of this hypoth-esis, avoiding the need for space-time substitutions. This will help resolve global debates about heterogeneous responses of savan-nas to global change. By quantifying change in floristic composition across space it should be possible to identify the drivers of change in a context-dependent fashion (Esquivel-Muelbert et al., 2019; Fauset et al., 2012), as we would expect different species to be winners and losers under different drivers (Osborne et al., 2018).

3.2.3 | Question 3: How functionally heterogeneous are woodlands in response to global change?

Recent work has highlighted the functional diversity of savannas glob-ally (Lehmann et al., 2014; Moncrieff et al., 2014; Osborne et al., 2018).

This is hypothesized to result at least in part from the different evolu-tionary histories of the dry tropics (Dexter et al., 2015). For example, southern African woodlands contain vegetation types thought to be derived from both wetter, forested, environments as well as drier re-gions within Africa (Maurin et al., 2014). Long-term plots spread across the region will provide an important opportunity to understand how these evolutionarily and functionally distinct vegetation types and plant lineages respond to global change (Osborne et al., 2018). Careful location of PSPs along gradients of abiotic conditions and with soil and vegetation type contrasts will be important to allow the strong-est possible inference from PSP observations. The SEOSAW manual provides further details of how plots should be located.

3.2.4 | Question 4: What is the role of humans in shaping the structure and function of the woodlands?

Effective management starts with basic knowledge of the processes shaping present-day woodlands. Often the role of land use history and human use is poorly understood, reflecting practical difficulties in quantifying these processes in ways that fit with ecological re-search, the tendency for research plots to be located in strictly pro-tected areas, and continuing disagreements about the successional status and paleo history of the woodlands (Ekblom et al., 2014; Ivory & Russell, 2016). PSPs provide an important means of understanding the impacts of past and current management, and for evaluating the impact of large-scale management interventions. This is because ex-perimental approaches to understanding the impact of management regimes are not sufficient, as management approaches often change when they move from small intensively managed experimental plots to the wider landscape (Chidumayo, 1988). Additionally, ecological responses in real, heterogeneous landscapes can be different from those under experimental conditions. PSPs are thus an important component in any landscape approach that seeks to undertake adaptive management.

4 | KEY CHALLENGES TO LONG-TERM MONITORING AND THE SEOSAW APPROACH

To build a network capable of meeting the needs outlined above, SEOSAW collects data across the region in a decentralized but coor-dinated fashion. The coordination is important to facilitate cross-site and regional comparisons, which are currently very rare (e.g., Godlee et al., 2020). The decentralization is also important to allow a diverse group of people to collaborate, given varying interests, expertise, and research funding systems.

A key part of the coordination is a manual that provides guidance on standardized approaches for effective long-term monitoring in the region (the latest version of the manual is available at: https://seo-saw.github.io/). Here we highlight six key methodological challenges, and discuss the rationale behind the relevant guidance in the manual.

The manual is based on: the outcomes from two workshops; analysis of the current version of the SEOSAW dataset; and a review of similar guidance developed for the dry tropics (DRYFLOR et al., 2016; Guerin et al., 2017; Moonlight et al., 2020; White et al., 2012) and wet tropics (Alder & Synnott, 1992; Condit, 1998; Lewis et al., 2009b; Malhi et al., 2002; Phillips et al., 2016; Picard et al., 2008; Poorter et al., 2016). The participants at the workshops, and in subsequent discussions, are listed at the end of the paper. The approaches suggested in the manual are designed for wide applicability and consistency with other vegetation inventory networks (e.g., RAINFOR, DRYFLOR), which should aid inclusion in pan-tropical or global analyses.

4.1 | Challenge 1: The wide diversity of vegetation structure requires methodological diversity

Southern African woodlands are transitional between the more open grass-, bush-, and shrublands of the Kalahari, Highveld and NE Africa, and the dense forests of the Congo basin (White, 1983). Methods that work efficiently at one end of this gradient are unlikely to be effective at the other. This has led to a wide range of approaches, some grounded in the forest literature and widely used in the wetter parts of the region, and others inherited from savanna and grassland science. This methodological diversity has benefits, but also hinders regional synthesis. Key areas of methodological divergence are: plot size, tree diameter thresholds, height of tree diameter measurements, treatment of resprouting stems, and the inclusion of data on grasses and forbs.

4.1.1 | Plot size

The different approaches to the size of long-term plots across the globe reflect the diversity of reasons for establishing sample plots.

A particular challenge in the SEOSAW region is that stem density (of trees ≥ 5 cm DBH) varies over three orders of magnitude (Figure 2). This has important implications for how efficiently metrics such as carbon stocks and tree species diversity can be estimated.

The SEOSAW guidance responds to this by recommending a flexible approach to plot size for PSPs (different considerations apply with sampling designs where the plot is not the unit of analysis, for example, clustered plot sampling, which is not considered here). The most critical aspect of plot size (and the inclusion rules for tree stem measurement, see below) is that a sufficient number of individual stems must be included to allow accurate estimation of important quantities. Two key considerations are that:

- Enough stems are included such that mortality rates can be estimated accurately. There are few data on mortality in the region, but annual mortality rates on PSPs in Tanzania and Mozambique are 4%–5% for stems > 5 cm DBH (T. Brade, unpublished data) and 2%–3% for stems > 40 cm DBH (E. Wood, unpublished data). If an accurate mortality rate is to be calculated over, for example, a 5-year census interval, several hundred stems need to be included in the plot to avoid gross errors when even a single dead stem is missed. This is a particular problem for estimating the mortality of large trees, which are a crucial component of the carbon cycle.

- Enough large stems are included to capture some of the random variation in their biomass. The allometry of large stems is very variable: typically the variance of the biomass of stems increases exponentially with diameter, and most allometric equations are parameterized based on only a few large trees (Chave et al., 2014; Kachamba et al., 2016; Mugasha et al., 2013). Therefore, if estimates of biomass are to be made with high certainty, there should be a reasonable sample of large trees on the plot, such that some of the random variation in allometry cancels out. We suggest that if trees > 40 cm DBH are present, plots should be large enough to include, on average, five or more trees of this size.
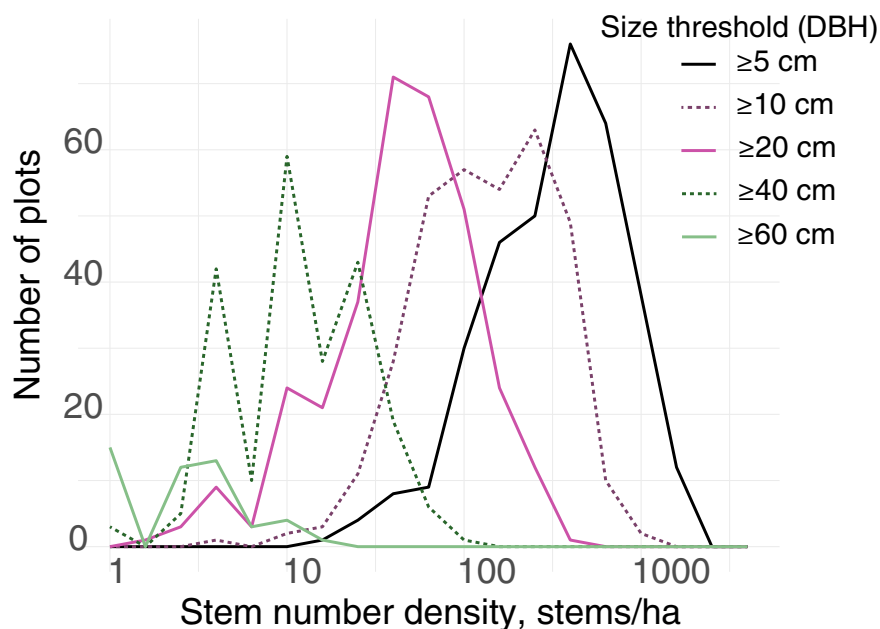

FIGURE 2 Stem number density (stems per hectare) for plots > 0.2 ha in the SEOSAW dataset. Note the logarithmic scale on the *X*-axis
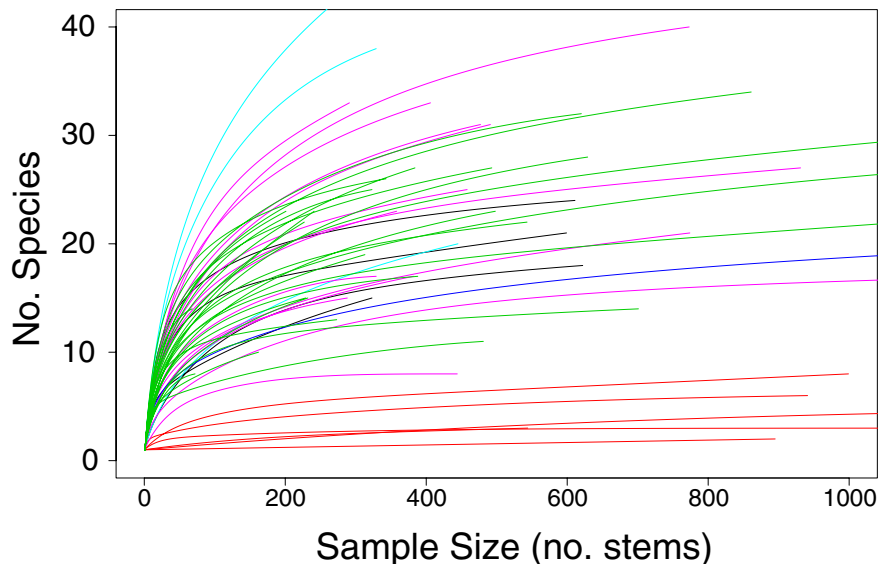
FIGURE 3 Species accumulation curves on the large (≥1 ha) plots in the SEOSAW dataset. Each plot is shown by a single line, colored according to the site. Cyan = DR Congo, protected wet miombo (Muledi et al., 2018, 2020); Pink = Tanzania dry miombo (McNicol et al., 2018); Black = Angolan dry miombo/Baikiaea (Godlee et al., 2020); Green = Mozambique dry miombo and mixed woodland (Ryan et al., 2011); Blue = South African Mimosoid savannas (Scholes et al., 2001); Red = Congolian Beteke savanna (Nieto-Quintano et al., 2018) . Note that for clarity the figure has been clipped to 1,000 stems and 40 species. Species accumulation curves were produced using the vegan package (Oksanen et al., 2020) in R (R Core Team, 2020)

With the goal of accurately estimating demographic rates, and taking 200 stems as a target sample size, we can examine the SEOSAW dataset to understand the utility of different plot sizes. If the current SEOSAW plots can be considered a random sample, 1 ha plots in southern African woodlands will contain 200 stems > 5 cm DBH in 66% of cases. A 0.5 ha plot would contain 200 stems of this size 59% of the time. These probabilities are much higher (93% and 91%) in the mopane areas, as mopane often has much higher stem density than other woodland species (but note that the SEOSAW dataset does not include many plots with large stature mopane). Looking only at plots where large (>40 cm DBH) trees occur, 90% of 1-ha plots will typically have ≥ 5 large trees while 86% of 0.5-ha plots will. These large stem probabilities are consistent across vegetation types. The SEOSAW manual thus suggests that 1 ha plots are a good starting point, with all stems > 5 cm DBH censused. However, this plot size can be altered, or the stem size threshold changed, to accommodate unusually sparse or dense systems. We also suggest random placement of plots within strata, whilst ensuring that the plot area itself is relatively homogeneous with respect to soil type and land use. Lastly, we note that plots < 0.5 ha are difficult to link to remote sensing (Réjou-Méchain et al., 2014b), particularly to radar sensors, which are important for biomass estimation (see section 4 below).

Another consideration for plot design is the number of species likely to be included in a plot and the degree of floristic sample completeness. Generally, the many-small-plots paradigm is more effective at discovering the presence of tree species in a landscape compared to the few-large-plots approach that is required for phytodemographic studies (Baraloto et al., 2013; Phillips et al., 2003). However, 1 ha plots have been found to offer a good compromise in rainforests (Baraloto et al., 2013; Phillips et al., 2003). In the SEOSAW dataset, 1 ha or larger plots give good sampling completeness (observed number of species as a percentage of estimated richness is always between 85% and 96%; Figure 3).

4.1.2 | Tree size thresholds

In current practice, the size threshold above which tree stems are measured and counted as new recruits varies greatly. In some systems, trees rarely exceed 10 cm DBH (Nieto-Quintano et al., 2018), and so a smaller threshold is needed to gain information on their dynamics. However, small size thresholds may not produce useful information on population dynamics when turnover rates (mortality and recruitment) are very high in small size classes, unless census intervals are short, for example, 1–2 years. For example because stems of 5 cm DBH have only a 50% chance of surviving fire (Ryan & Williams, 2011) they typically have short lifetimes and rapid turnover, and a small stem may be recruited and then die before it is censused. Small size thresholds also markedly increase the required survey effort (Table 1). For example, moving from a 10 to 5 cm threshold can easily triple the number of trees that need to be recorded and tagged, especially in heavily disturbed woodlands. However, there is sometimes a large pool of woody species that never attain a large DBH, and these will be missed when large size thresholds are used (Table 1; Nieto-Quintano et al., 2018; Pritchard et al., 2019).

To achieve some standardization, the SEOSAW manual recommends either a 3 cm or 5 cm diameter threshold for inclusion (D_t),

TABLE 1 Stem numbers and observed species richness for six sites, subsampled by different stem diameter thresholds. ± indicates SEM. Note that in datasets 1 and 4, the diameter of all stems were measured just above the basal swelling (approx. 0.3 m height) while at the other sites, the point of measurement (POM) was 1.3 m height

dataset location and citation/ owner	Description	No. Plots	Plot Area (ha)	Min diam. (cm)	Stem number density (stems/ha)				No. tree spp			
					>3 cm	>5 cm	>10 cm	>20 cm	>3 cm	>5 cm	>10 cm	>20 cm
South Africa, Kruger National Park (Scholes et al., 2001)	Elephant-dominated open Acacia and Combretum savanna in National Park	1	4.0	0	222	154	99	43	22	21	20	16
Malawi, Chimaliro, S. Makungwa/FRIM	Mature, poorly regenerating, miombo woodland in forest reserve	38	0.25	3	485 ± 40	444 ± 34	309 ± 23	107 ± 11	19 ± 1	17 ± 1	12 ± 1	6 ± 0
Zimbabwe, Wedza (Pritchard et al., 2019)	Heavily harvested miombo in communal area	76	0.125	3	1,258 ± 116	559 ± 55	137 ± 18	21 ± 4	15 ± 1	10 ± 1	4 ± 0	1 ± 0
Zimbabwe, Hwange (Holdo, 2005)	Mopane and Combretum woodland impacted by elephants and frost	18	0.1	5	—	1,052 ± 77	172 ± 13	24 ± 5	—	10 ± 0	4 ± 0	1 ± 0
Tanzania, Kilwa (McNicol, Ryan, Dexter, et al., 2018)	Miombo woodland and coastal forest in remote village land	25	1.0	5	—	482 ± 71	175 ± 25	53 ± 7	—	21 ± 1	16 ± 1	11 ± 1
Angola, Bicuar (Godlee et al., 2020)	Miombo and Baikiaea woodland in National Park	15	1.0	5	—	520 ± 57	214 ± 21	61 ± 7	—	14 ± 1	9 ± 1	5 ± 1

with the diameter measurement being made at either 0.3 or 1.3 m height (a.k.a. the point of measurement or POM; NB the POM should always be moved if there is a deformity or swelling at the standard height). This provides the flexibility to include the small fire-trapped stems and species which never attain large stature, while the lower POM reduces effort in heavily coppiced vegetation. See Godlee et al. (2020) for a conversion factor between diameters measured at different heights.

Smaller stems with a diameter (D) less than D_t (variously called poles, saplings, etc.) can then be sampled on multiple subplots. Both the fully censused stems ($D \geq D_t$) and the sampled poles ($0 < D < D_t$) should be marked or tagged to allow accurate remeasurement (see the SEOSAW manual for details). Stems that do not obtain the height of the POM (sometime called seedlings, resprouts, or regeneration) can be sampled in small plots and counted rather than marked and measured for diameter. With count data, these smaller individuals can be incorporated into stage-structured demographic models.

4.1.3 | Tree measurements

The common set of tree stem attributes that need to be recorded are diameter, height of the diameter measurement (POM), species iden-tity, alive or dead, standing or fallen (i.e., nonself supporting), root-stock ID (to identify multistemmedness), and ideally also wounding, height, and spatial location within the plot. Many other attributes can of course be measured, but there are subtleties to even this short list that can hinder cross-comparison among datasets. Throughout, it is important that stem-level (not tree-level) data are collected and that multiple stems that originate from the same base are recorded as such (see Challenge 4). Key points are:

- Marking the POM improves the signal to noise ratio of repeated diameter measurements. Paint does not last through many re-peated fires, but a metal tag loosely nailed, for example, 20 cm above the POM can be an effective way to ensure accurate remeasurement.
- Wounded stems are more likely to die before the next census (Bowers, 2017; Nieto-Quintano, 2019). However, consistently and objectively recording wounds is difficult. The proportion of the stem where the bark is missing is a reasonably objective indicator of wounding, and the presence (or absence) of bracket fungus is a simple indicator of rottenness.
- Species determinations are one of the most time-consuming and expensive activities in setting up a long-term plot. One pragmatic approach that reduces the barriers to initial plot set up is to ini-tially use local names or ecologists' determinations and then re-visit the plot with a taxonomist, improving the identifications over time with each census. The determinations should be supported by the collection of voucher specimens, from at least one indi-vidual per species per plot, ideally with fertile material, that are sent to local and international herbaria if at all possible. A criti-cal step in the collaborative research loop is to ensure that any

identifications determined outside the country are relayed back to the in-country scientists.

- Height measurements can improve the accuracy of woody bio-mass estimation from allometric equations (Chave et al., 2014), but are time-consuming. One approach is to make such measurement on a subset of ~100 trees to establish if there is a strong local relationship between height and diameter which can then be used in lieu of height measurements on all stems.
- Recording the spatial location of each stem provides important information about biotic interactions (e.g., competition and facilitation), aids cross site comparison (by allowing spatial subsampling and the comparison of different sized plots), and can help reidentify stems if tags are lost.

4.2 | Challenge 2: Chronic disturbance from people, fire, and herbivory

Disturbance is an integral and characteristic feature of many of the ecosystems of the dry tropics (Pennington et al., 2018). From a long-term measurement perspective, chronic disturbance presents challenges, including the need to record the type, intensity and frequency of disturbance, and logistical issues. The repeated impacts of fire and elephants, for example, limit equipment that can be left on plots. Human use is also a characteristic feature of these systems, which cannot be avoided if we are to gain a representative sample of the vegetation and its change. Biases may occur when human use of PSPs is different from use of the surrounding vegetation, either because they are left alone (perhaps from a fear of "messing up the science") or because they are preferentially overutilized (perhaps from a fear of pending land expropriation). To avoid both of these scenarios, good communication with the *de facto* and *de jure* users of the land is essential, but this is often difficult where tenure is contested and overlapping, and common uses are illegal or illicit. In some cases, "cryptic" plots may be required (with buried markers and tree tags), where there are no visible signs that the plot is being used for long-term measurements. The SEOSAW manual stresses the need for meaningful and ethical engagement with land users.

Marking long-term plots so that they can be remeasured accurately over several decades is difficult, particularly if the plots are "cryptic." One approach is to completely embed metal reinforcing bar in concrete blocks approx. $10 \times 10 \times 30$ cm and to bury these in each corner with 3 cm of the block protruding above the ground. The metal bar allows the blocks to be relocated with a metal detector and the concrete improves protection against rust. Adding metal bars at 10 m intervals around the boundary can help accurate relocation of borderline in/out stems, but such bars will need replacing at around decadal intervals. As yet, consumer affordable GPS technology is not sufficient to accurately relocate plots or stems.

Accurate measurement of stem recruitment and mortality is as important as accurate growth estimates (Alder & Synnott, 1992; Needham et al., 2018). However, in the dry season it can be difficult to ascertain whether a stem is alive or fully dead. For this reason,

such measurements can profitably be continued for two censuses after the initial declaration of stem death (a.k.a. topkill). Similarly, a rootstock that has no live aboveground parts may resprout in subsequent years. It is also helpful to tag or otherwise mark dead and fallen stems to make it easier to identify newly deceased and fallen stems in subsequent censuses. Recording if the base of the stem is still alive and if it has the potential to resprout can help subsequent censuses correctly identify resprouts versus new organisms; the SEOSAW manual describes a system for tracking both whole organism and stem mortality.

4.3 | Challenge 3: Looking beyond the trees

Savannas, including woodlands, are shaped by tree–grass interactions (Higgins et al., 2000; Scholes & Archer, 1997; Weltzin & Coughenour, 1990), and forbs often play a very important role in the plant diversity of the system (Siebert & Dreber, 2019). However, it is surprisingly rare in the SEOSAW region that grass and forbs are measured at the same location as trees, particularly in a repeated manner over time. Understory nonwoody plants need to be included in long-term measurements, but there are practical challenges relating to the time of year when they are visible aboveground (which for some forbs can often be for only short time periods) and best identified (which normally differs from woody plants). Understanding woody and nonwoody parts of the ecosystem requires diverse skills and sampling approaches that are rarely present within a single research group.

To account for the difficulty in capturing the diversity and dynamics of the ground layer, in the SEOSAW manual we detail a hierarchy of ground layer measurements that would enable the user to capture aspects of ground layer diversity and structure. The gold standard is repeat surveys throughout a growing season to capture the full diversity of the ground layer, in terms of all grasses, forbs, and prostrate shrubs, subsequently matched with ground layer biomass harvests at the end of the growing season. Ideally, repeat surveys every 2 months from before the rainy season through to the end of the rainy season/first fires are required to understand the diversity of forbs.

Clearly, capturing ground layer diversity and productivity is a substantial undertaking, and different groups are likely to have different priorities for their PSPs: a key decision is whether the methods selected for ground layer survey are sustainable and repeatable. Even one-off surveys of the seasonal expression of diversity will provide useful information, given how systematically undersurveyed ground layer diversity is in the region. Ongoing repeat sampling may scale back from the "gold standard" above to present a more sustainable sampling option and one that would still sample the same ground area, but with different levels of detail. Options could be to undertake: (a) a single survey at peak understory greenness recording diversity and clipping for productivity. This single survey toward the end of the wet season would capture most grass species diversity (but is unlikely to capture forbs) and would be a good reflection

of ground layer productivity (in a fire determined system only); (b) a rapid survey of dominant grass species in tandem with biomass clipping where only the top three dominant species are noted; or (c) clipping of ground layer biomass with no species information being compiled. The detail of these methods is provided in the manual, and users will have to decide which approach best suits their interests and resources.

4.4 | Challenge 4: The party is going underground

In a disturbance-prone environment, it pays to keep your head down and bounce back quickly (Luoga et al., 2004; Mograbi et al., 2015). As such, the ability to resprout is widespread among woodland trees, and multistemedness (i.e., polycormy) is common, particularly in the subcanopy. Long-term measurements need to quantify the life, growth, and death of both the whole organism and the individual stems, as these often differ greatly with the lifetime of the whole organisms being several orders of magnitude longer than that of any individual stem. An extreme example of this is the underground forests found across the Zambezian region, where most of the woody biomass is found below the soil surface (Gomes et al., 2019; Maurin et al., 2014).

Given the importance of resprouting after topkill, information on the relationship between the stem and the parent organism is important. However, detailed work shows that it is often impossible to establish such relationships without large-scale excavation (Holdo, 2005), which is impractical and destructive. A pragmatic compromise is suggested in the manual, whereby stems that are visibly connected to the same base are recoded as such, and the rootstock/base is given a unique identity. The relationship between newly recruited stems and existing organisms will then provide useful information on regeneration dynamics. Storing and analyzing these data can present challenges to data processing systems as it requires the relationships between stems to be stored consistently, and the organisms and stems to be represented in separate data tables. The SEOSAW manual provides an approach to recording and storing such data.

4.5 | Challenge 5: Humanizing savanna ecology

African woodlands are, arguably, an anthropic biome, or at least one where social processes must be considered to understand ecosystem structure and function (Laris, 2011; Scheiter et al., 2019; Tredennick & Hanan, 2015; Twine et al., 2016). Humans have shaped the ecosystem through the use of fire (Bird & Cali, 1998), cultivation, hunting, honey collecting, and tree harvesting (Campbell, 1996; Chidumayo, 1997; Chidumayo et al., 2010). We continue our influence in both obvious and subtle ways, including modifying all aspects of the fire regime for at least 100,000 yrs (Archibald et al., 2011); reorganizing herbivory on a continental scale (Hempson et al., 2015); through deforestation and tree harvesting (McNicol, Ryan, & Mitchard, 2018) and global changes to climate and atmospheric chemistry (Ryan et al., 2016).

In other biomes, long-term plot measurements have often been focused on relatively undisturbed locations with minimal direct human impacts (e.g., in remote or protected areas; although see 2ndFOR network (Poorter et al., 2016)). This approach is not suitable in the southern African woodland region as such a network would provide little information about many of the key processes and changes underway. However, working in human landscapes brings new challenges including logistical issues, the need to collect information on social processes, the need to adapt methods and, most fundamentally, the need to engage with those who live and work in the areas where such measurements are undertaken. Fortunately there is a rich tradition of socio-ecology in the region on which we can draw to address these challenges (Campbell, 1996).

The SEOSAW manual includes a structured list of simple questions that are aimed at consistently capturing information about how the plot is, and has been, used by people. This covers the harvesting of woody and nonwoody wild products, grazing, and a wide variety of management activities. It is our intention to expand this guidance further, as more socio-ecologists engage with SEOSAW.

4.6 | Challenge 6: Data management and quality control

The collection of long-term PSP data generates large datasets that are time-consuming and expensive to manage and curate. While such datasets may not yet be at the scale of "big data," they are often at the limit of what can be simply managed and quality assured by hand. Several approaches have been developed to support data management of long-term plot data, including www.openforis.org, ForestPlots.net (Lopez-Gonzalez et al., 2011), sPlot (Bruelheide et al., 2019), and many others. Some of these platforms include a rigorous set of data quality checks and enforce a restricted vocabulary and floristic nomenclature. In the case of SEOSAW, we are using the African Plant Database (https://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php) as our "taxonomic backbone." The data from the PSPs in the SEOSAW network are currently being curated at www.forestplots.net, which has been extended to work with inventory data from savannas and woodlands.

We have developed a set of manuals, data sheets, and digital data capture forms using the Open Data Kit to allow SEOSAW data to be directly entered on an Android mobile phone or tablet. This is aimed at offering straight-to-digital data capture methods which have the potential to reduce errors, allow *in situ* checking of unusual values (e.g., the classic 5.0 vs. 50 cm stem), and speeds data capture and input. However, there are still technological challenges to using these systems including battery life, robustness, and reliability. One simple approach we highlight as crucial to improving data quality is to have the field data and notes from the previous census available during recensus. This allows errors in past censuses to be flagged, but should not be used to correct observations in real time as this is likely to introduce biases (Kloeppel et al., 2007), for example, where stems that have shrunk are "corrected" to show positive growth.

5 | NOT BY PLOTS ALONE

The discussion above, and the detail provided in the SEOSAW manual, will hopefully go some way toward supporting the development of a regional network of consistent observations, without providing undue limitations on methodological creativity. Such a network allows us to understand the variability in the phyto-demography of the region, and because the methods are comparable to other regional networks (see Moonlight et al., 2020, this issue), compare the SEOSAW region to other parts of the dry and wet tropics. There are, however, limitations to what can be achieved with long-term plots, and also new opportunities to synergize with emerging approaches.

5.1 | Remote sensing

There are two-way linkages between plot measurements and satellite remote sensing (Earth Observation, EO) data. Most straightforwardly, plot data can be used to calibrate and validate remotely sensed estimates of stand-level tree cover, height metrics, biomass, and stem density. Plot data are essential to the creation and validation of maps of these attributes across space and time.

Often of more interest to the global scientific community are maps of change in these factors, rather than static one-time maps. Here, long-term plots are potentially very useful, as they can be uniquely used to assess the accuracy of remotely sensed estimates of *changes* in these attributes. Currently, this appears to be a missed opportunity, as major products on ecosystem structural change do not seem to use available field plots for validation (Baccini et al., 2017; Brandt et al., 2018; McNicol, Ryan, & Mitchard, 2018), often due to the difficulty of accessing analyzed plot data, or mismatches of spatial scale or time frame. This is unfortunate, because such comparisons would greatly add confidence to maps and increase their utility.

Beyond simple calibration and validation, detailed plot data can be used to help us understand the processes governing the interactions between electromagnetic radiation and the land surface. This will improve the generation of ecological data products and their accuracy outside the location and range of values of the field plots, and is particularly needed for radar data, where the mechanisms by which trees influence the signal at different wavelengths and in different vegetation structures is less well understood than for LiDAR and optical data (Quegan et al., 2019).

The challenges in linking plot data with EO data have been well discussed (Réjou-Méchain et al., 2014a; Schepaschenko et al., 2019), and relate to geolocation accuracy of both the plot and EO observations, scale mismatches between the EO data pixel size and plot, and sensor point spread functions (i.e., the tendency for some portion of the recorded signal of each pixel to originate outside the area represented by that pixel). These issues all lead toward a need for larger plots, or intermediate scale information from, for example, UAVs (Mlambo et al., 2017) or high spatial resolution remote sensing (optical or LiDAR data) to enable plot-level information to be scaled up to a resolution comparable to the satellite dataset.

5.2 | Modeling

Models of tree and grass processes are core tools for developing and testing understanding of ecosystem dynamics, for underpinning decision support tools for woodland management, and for predicting the effects of global change. As with remote sensing, there is a complementary relationship between the field data collection in SEOSAW and related modeling efforts.

First, nearly all types of models need to be calibrated and validated using field data. For instance, PSP data can be used to set the initial conditions for models (e.g., the size of the woody carbon pool, or the age structure of the woodland), and to constrain model parameters (such as mortality rates or carbon residence times). The exact model–data interaction depends on the model structure and state variables. Individual-based models (IBMs; Desanker, 1996; Friend et al., 1993; Holdo, 2007; Ryan & Williams, 2011), cohort/demographic models (Higgins et al., 2000; Scheiter & Higgins, 2009; Sitch et al., 2003), and biogeochemical (BGC) models (e.g., Clark et al., 2011) represent savannas in different ways, and thus contain different state variables for initialization and parameters representing different processes. An IBM simulates tree demographics, including processes of germination, growth, and mortality at stem level, with competition among stems for resources. A BGC model represents a forest as a collection of carbon pools, and includes bulk processes of carbon allocation from photosynthesis, and carbon residence times, with no simulation of competition. Cohort models aim to combine both pool dynamics and forest demography in a simplified manner.

Second, modeling outputs can guide field data collection. At a global scale, the fact that dynamic global vegetation models predict a large and rapidly growing carbon sink in the woodlands (Higgins & Scheiter, 2012; Sitch et al., 2015) provides a clear hypothesis for the whole SEOSAW network to test. At finer scales, models can highlight which aspects of ecosystem function are critical to responses to global change, guiding data collection. An example is the discovery from modeling that carbon residence times (which are closely related to mortality rates) are critical to correctly modeling the changing carbon stocks of the Amazon (Johnson et al., 2016). This finding has spurred the development of more detailed representation of stem mortality in some global models (Galbraith et al., 2013) and helps justify the collection of long-term PSP data on mortality rates.

A new development is to use the data from PSPs and other sources in Bayesian model–data fusion analyses of the ecosystem carbon cycle. PSP data are used either to define priors or as a constraint on model parameters (Exbrayat et al., 2018). This approach allows the full information content of the PSP data to be utilized, including not just mean values of key attributes, but the associated variances and cross-correlation between attributes such as phenology, leaf traits, stem growth, and mortality. The advantage here is that strongly constraining some parts of the model with data helps to constrain other, harder to measure parameters and fluxes (Bloom et al., 2016). So, for example, data from PSPs can be used to provide robust constraints on woody biomass pools and their changes. The model can then propagate this information into probabilistic

estimates of ecosystem carbon sequestration, helping to address Question 1 above. Linking biomass stock changes to ecosystem flux estimates is important because flux data are very sparse in the SEOSAW region (Merbold et al., 2008), and little is known about the residence time of carbon in the major pools.

5.3 | Links to herbarium collections

PSPs with tagged trees can help in the effort to complete the species inventory of tropical biomes. PSPs provide an opportunity for taxonomists to identify new species and document the reproductive characteristics and ecology of poorly known species, as tagged trees can be revisited across seasons and years (Baker et al., 2017). For example, vouchers from tagged trees in PSPs in Jenaro Herrera, Peru that were archived in national and international herbaria have led to the subsequent discovery of 26 tree species new to science (Honorio, 2006, unpubl. MSc thesis; Baker et al., 2017). The impressive efforts behind RAINBIO has resulted in a mega-database of taxonomically standardized, harmonized, and georeferenced records for 25,356 vascular plants in continental tropical Africa (Gilles et al., 2016). However, there are still gaps in the database in southern Africa and outside of tropical forest ecosystems: PSP data, backed up by vouchers, can fill these gaps.

Beyond this, vegetation inventory plots, which quantify abundance of taxa and provide measures of sample effort, provide an advantageous means of determining species environmental preferences, distributions and limits, compared to more commonly used, presence-only data from herbaria collections (Gomes et al., 2018). Lastly, PSP data can identify threatened species much sooner than presence/absence data in herbaria, as species decline in abundance before they go extinct (Jew et al., 2016). Thus, inventory plot data that record abundances are well-poised to document meaningful changes in biodiversity, as demonstrated by studies showing shifts in the elevational distribution of tree species in the Andes (Fadrique et al., 2018) and compositional shifts in Amazonian tree communities (Esquivel-Muelbert et al., 2019).

6 | THE WAY FORWARD

Currently the SEOSAW partnership is focused on four main activities, and we welcome new collaborations to advances these, and other aspects of our work.

1. Building consensus around core methods which will enable cross-site comparison within the region and between SEOSAW and other plot networks. This paper and the associated field manuals on https://seosaw.github.io mark the first step in this direction, and the manuals will be regularly updated.
2. Collating existing data from permanent and one-off plots and making the data available for cross-site analysis. The current version of the SEOSAW database holds data on > 8,000 one-off plots
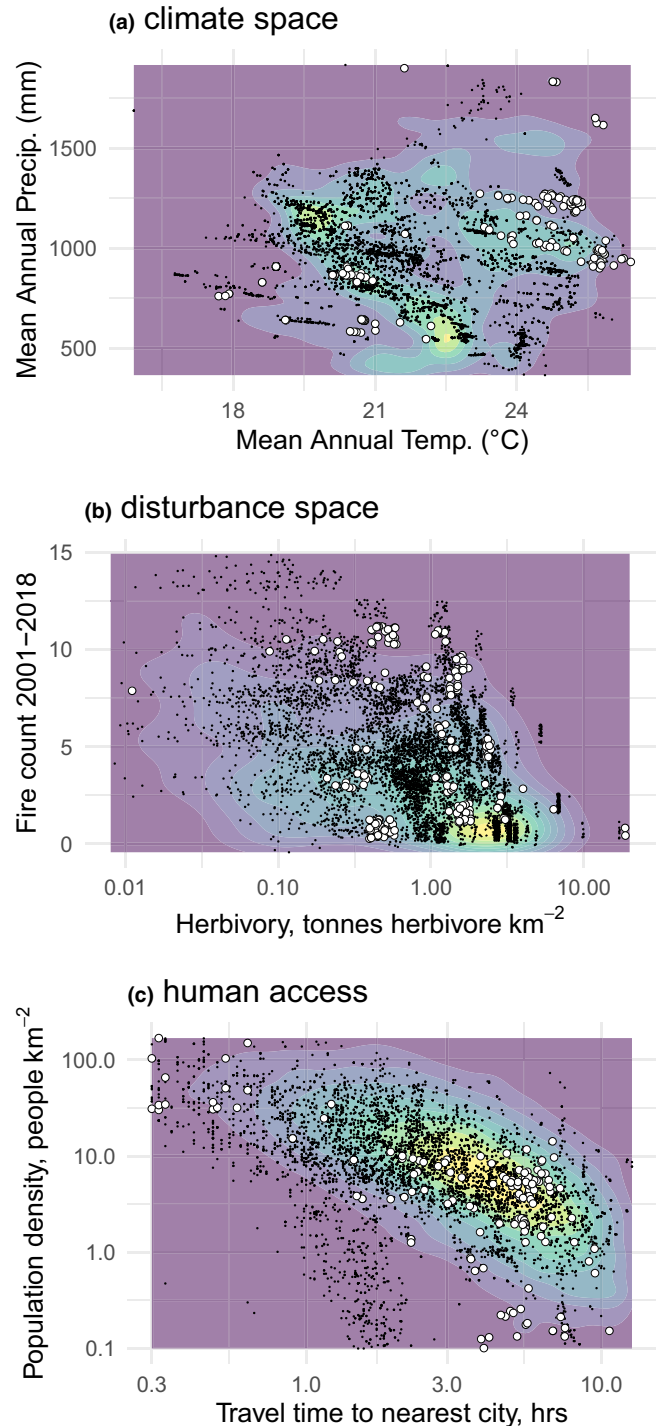

FIGURE 4 (a) The location of the SEOSAW plots in the climate space of the region (geographically defined as the area in dark green in Figure 1: woodlands, woodland transitions, bushlands and thicket, and forest transitions). White circles = PSPs, suitable for repeat measurement of individual stems, black dots = one-off plots (where trees are not tagged or otherwise easily remeasured). Purple to yellow contours show the density of pixels in the SEOSAW region. (b) as (a) but for disturbance space, considering current herbivory (Hempson et al., 2017) and burned area (Giglio et al., 2018). (c) Plot locations in terms of human population density (WorldPop, 2018) and travel time to cities (Weiss et al., 2018). Online versions of these plots, along with a detailed description of the current SEOSAW dataset can be found at https://seosaw.github.io/description

and > 200 PSPs. We are currently working to integrate other existing datasets into the SEOSAW framework and analyze regional patterns of diversity and function.

3. Expanding the network into new areas. Major geographical gaps remain to be filled, particularly in the mopane and Baikiaea woodlands, and in the west and central parts of the region. Additionally, the PSP network does not yet cover the extremes of climate space (Figure 4a), and given projections of rising temperatures, increased rainfall seasonality and declining frost (Ryan et al., 2016), locating plots at these current climatic limits is a priority for understanding responses to climate change. The current network covers "disturbance space" reasonably well (Figure 4b), but there are gaps in low herbivory-low fire systems. Many of the existing PSPs are located in remote and sparsely populated areas (Figure 4c), so the network will need to expand into more human-dominated landscapes nearer to cities to increase its representativeness.

4. Remeasuring PSPs and expanding the information to cover soils and grasses. We have started a programme of remeasuring the PSPs, generating a new regional dataset describing tree demography. An even greater challenge in terms of resources and expertise is to generate new data on the understory and soils of the PSPs, which will require a higher degree of funding and collaboration to achieve consistent datasets across the region.

In the next phase of SEOSAW, we will also continue our capacity building efforts, together with the Miombo Network. We have also started a program of work to better understand the social context of the PSPs, as this is currently rather limited. The next stage of SEOSAW involves further outreach and we welcome new partnerships with interested researchers and practitioners.

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The following authors contributed ideas to this paper via the SEOSAW discussion meetings, by commenting on the manuscript, or by contributing data used in the analysis:

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[Correction added on 29 January 2021, after first online publication: Reference section has been modified.]