A topographic framework for estimating spatial variation in hill country grasslands

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Abstract

Livestock graze hill country regions worldwide where grassland biomass or structure is important both economically as forage and enviromentally as habitat for wildlife. Manual measurements of biomass in remote and expansive hill country landscapes are time consuming, expensive, and difficult to estimate due to spatiotemporal variability. Pasture areas where livestock utilisation or grassland biomass is exceptionally high or low could be mapped within a topographic framework. A model was developed that integrates several data sources (elevation, spectra and field data) to estimate hill-country biomass. Topographic data were modelled and used to classify biomass, which ranged from low at summits (1493 kg/ha) to high at toe-slopes (2876 kg/ha). These estimates were compared with the current plant height-based model, which ranged from low (2014 kg/ha) to high (3032 kg/ha). This paper demonstrates how expansive, heterogeneous grassland landscapes can be assessed seasonally using topographic markers within an integrated spatial data framework.

Keywords: Remote sensing, DEM, structure, Landsat 8, forage utilisation, graziers

Key messages

- Topographic and height-based indicators of grassland structure are comparable
- New model developed for the Unite States hill country is applicable to New Zealand
- Grazing can be finely tuned with low-cost, seasonal maps indicating utilisation.

Introduction

Hill country landscapes worldwide support multiple uses such as forage for livestock, wildlife habitat and recreational hunting. The need to collect and map grassland heterogeneity has been demonstrated by researchers in both the North and South Islands of New Zealand and other areas of the world (Radcliffe 1982; Schellberg *et al.* 2008; Vartha *et al.* 1982). However, data maps representing grassland total standing crop (TSC) or structure for these expansive hill country landscapes are currently not available. Intensification of agriculture in New Zealand has raised new questions about the capacity of hill country grasslands to sustainably produce more forage without compromising other ecosystem services, such as structure for wildlife cover. Data maps indicating the full range of spatial variation in grassland stocks across the landscape could indicate how livestock utilisation effects pasture production under variable climates. These technologies are available, but data costs and processing (acquisition, ortho-rectification, calibration, and analysis) expenses can be prohibitively high, particularly when data are collected on aerial or drone platforms. Low-cost, spatially explicit approaches for assessing locations where forage may be over- or under-utilised are needed as greater pressure is placed on hill country pastures to support the world demand for food production.

Field-based measures of canopy height (Sjursen 2009; Svingen 2009; Uresk & Juntti 2008) and spectral-based measurements of canopy reflectance (Chen 1996; Washington-Allen *et al.* 2006) are common grassland assessment metrics. When height and TSC are highly correlated, the regression model is considered an estimate of grassland structure (Robel *et al.* 1969; Uresk & Benzon 2007; Uresk & Juntti 2008; Vermiere & Gillen 2001; Vermiere *et al.* 2002). These regression models change with a number of factors, such as species composition (Phillips 2014). Practitioners rarely measure both height and TSC; both are commonly used as proxies for structure (Robel *et al.* 1969). Spectral data are often applied to estimate TSC, but spectral indices are also influenced by a number of factors, such as plant water content, species composition and soil background (Phillips *et al.* 2006). Hill country grasslands present a unique set of challenges for large-scale assessment mapping (Schellberg *et al.* 2008). Application of simple models or a spectral index cannot adequately represent expansive, heterogeneous hill country landscapes.

Spectral data acquired using sensors on-board aircraft and satellites can be modelled to estimate plant chemical and structural characteristics, and optimum models for estimating variables such as TSC or nitrogen content vary seasonally (Chen 1996; Phillips *et al.* 2012; Phillips *et al.* 2013; Washington-Allen *et al.* 2006). In many of these cases, aerial hyperspectral data are collected in conjunction with intensive field campaigns, and results indicate some plant canopy

ISSN 0110-8581 (Print) ISSN 2463-4751 (Online)

characteristics can be effectively mapped (Beeri *et al.* 2007; Haboudane *et al.* 2004; Phillips *et al.* 2012; Phillips *et al.* 2013; Pullanagari *et al.* 2013). Another approach, which provides a greater spatial extent at lower cost, is to correlate multispectral data acquired from satellite-based sensors with field data (Phillips *et al.* 2006; Phillips *et al.* 2012). Choices regarding the type of spectral data (multispectral or hyperspectral) and platform (satellite, aircraft, drone) affect the spatial coverage, cost and accuracy. The expansive nature and physiography of grasslands in hill country are particularly suited to application of satellite-based, spectral data when used in conjunction with topographic and field data (Phillips *et al.* 2012; Phillips *et al.* 2013; Phillips 2014). Additional work is needed to evaluate application of topographic position as a metric for defining low, medium and high TSC biomass relative to the current field metric of canopy height.

Here, we aimed to evaluate a hill-country assessment framework that applies known variation in topographic position (Phillips *et al.* 2012; Phillips *et al.* 2013; Radcliffe 1982) to classify thresholds in total standing crop biomass (TSC-Topo) relative to the current canopy height-biomass (TSC-Height) model. This case study was performed in the northern mixed-grass prairie region of the USA, where elevation changes and plant functional groups are comparable to New Zealand hill country regions (Dalton & Ackerley 1974; Phillips *et al.* 2012; Phillips *et al.* 2013; Radcliffe 1982; Vartha *et al.* 1982). The goal was to evaluate total standing crop biomass according to: (1) the TSC-Height model (where low biomass is defined as height <9 cm); and (2) the TSC-Topo model (where low biomass is defined by summits). A comparison of these approaches would demonstrate (1) how field data could be modelled to provide a spatially explicit map of TSC biomass for expansive hill-country landscapes and (2) how extrapolation from field to landscape scales in heterogeneous grasslands is facilitated by spatial data integration.

Methods

The 30 385 ha area-of-interest (AOI) used to develop and test this framework is located in northwestern South Dakota, USA. The AOI is comprised of multiple grazing allotments that are leased for grazing by the United States Forest Service from May to September each year. This landscape was classified into summit (4.4%), mid-slope (61.1%) and toe-slope (34.5%) polygons (Phillips *et al.* 2012). Previously established plots within the AOI were re-visited for plant data collection in July and September 2014. These 24 plots were split into summit, mid-slope, and toe-slope positions. Each topographic position within a plot is referred to as a field site, with a total of 72 field sites. In July 2014, Daubenmire plots were used to identify the top five species at each site, based on data collected in four cardinal directions (Phillips *et al.* 2012). In September 2014, TSC biomass was determined with Daubenmire plots in four cardinal directions and plant height according to established procedures (Phillips *et al.* 2012; Phillips *et al.* 2013). Samples were separated into green and senescent vegetation, and then oven-dried at 60 °C. The relationship between TSC and plant height was determined to estimate TSC thresholds associated with low (< 9 cm), medium-low (9–12 cm), medium-high (12–18 cm), and high (>18 cm) structure (Phillips *et al.* 2012).

All TSC data are reported on a dry matter basis (kg/ha). A cloud-free Landsat Operational Land Imager (OLI) image was acquired from the Landsat 8 platform on 14 September 2014. The image was downloaded from the Land Processes Distributed Active Archive center (http://glovis.usgs.gov). The raw radiometric

Table 1 Spectral bands Landsat 8 (USGS 2014).

Band	Description	Symbol	Wavelength (nm)	Resolution (m)
1	Coastal/Aerosol	P_{CA}	430–450	30
2	Blue	P_{Blue}	4450–510	30
3	Green	P_{Green}	4530–590	30
4	Red	P_{Red}	4640–670	30
5	Near-Infrared	P_{NIR}	4850–880	30
6	Short-wave Infrared 1	P_{SWIR1}	41570–1650	30
7	Short-wave Infrared 2	P_{SWIR2}	42110–2290	30
8	Panchromatic	P_{Pan}	4500–680	15
9	Cirrus	P_{Cirrus}	41360–1380	30
10	Thermal Infrared Sensor 1	S_{TIR1}	410600–11190	100(30)[a]
11	Thermal Infrared Sensor 2	S_{TIR2}	411500–12510	100(30)[a]

[a]Bands are acquired at 100 meter resolution but delivered at 30 m resolution

data were corrected by applying date-specific instrument calibration parameter files, which converted 12-bit satellite-quantized digital numbers (DN) to at-sensor radiance (USGS 2015). The image was clipped to the AOI containing the 72 field sites. Atmospheric correction to at-surface reflectance was performed in ENVI 5.3 (Exelis Inc., Tysons Corner, VA) using QUAC (QUick Atmospheric Correction). Pixel values at the 72 field sites were extracted for bands 2–7 (Table 1) and used to calculate spectral indices (Table 2).

Stepwise regression analysis was used (Phillips *et al.* 2013) to select the spectral index (Table 2) most predictive of TSC. The data were randomly partitioned into training (0.66) and test datasets (0.33), so the Root Mean Square Error (RMSE) could be reported based on the separate test or validation data set. Resulting equations were used to estimate TSC for each pixel in the AOI. Modelled TSC by pixel was averaged by polygon and mapped. The data were then classified into low, medium-low, medium-high, and high TSC biomass using (a) the linear relationship between TSC and canopy height at the 72 field sites (TSC-Height) and (b) average modelled TSC for summit, mid-slope and toe-slope for the entire AOI (TSC-Topo). The proportion of the AOI in each class was calculated, based on each approach and used as a basis of comparison.

Results

Field data

Species data collected in July at the 72 field sites are given in Table 3. Summit plant cover was dominated by shortgrass species. Mid-slopes and toe-slopes, on the other hand, were dominated by mid-grass species and tall sweet clover (*Melilotus officinalis*). In September, most of the vegetative material was senescent. Green material (photosynthetically active vegetation) ranged from 37 to 42% at all topographic positions. Average (std. error) canopy height for summit, mid-slope and toe-slope positions at the field sites were 7 (1) cm, 12 (1) cm, and 12 (1) cm, respectively. Average TSC (both green and senescent vegetation) was 1195 (96), 2518 (212), and 3091 (273) kg/ha, at summit, mid-slope and toe-slope positions, respectively. Figure 1 and Equation 1 demonstrate the relationship between canopy height and TSC at the 72 field sites.

$$TSC = 484 + 170 * \text{height};\ r^2 = 0.61 \qquad (1)$$

Plant height at 37 of the 72 field sites was <9 cm; 21 of the 37 field sites below 9 cm were located at summits, as shown in Figure 1. The remaining 16 field sites below 9 cm were located at mid-slope and toe-slope positions. The TSC-height model (Figure 1; Equation 1) indicated low structure (< 9 cm height) corresponded to TSC values <2014 kg/ha. Medium-low structure (9-12 cm height) corresponded to TSC ranging from 2 014-2524 kg/ha; medium-high structure (12-15 cm) to TSC ranging from 2524-3034 kg/ha; high structure (> 15 cm) to TSC >3034 kg/ha.

Modelled TSC

The statistical model selected topographic position and the Modified Triangular Vegetation Index 1 (MTVI1) as the spectral index (Haboudane *et al.* 2004) most predictive of TSC. Equations for estimating TSC at each topographic position are given below.

$$TSC_{Summit} = 863 + (0.87 * MTVI1) - 982 \qquad (2)$$

$$TSC_{Mid\text{-}slope} = 863 + (0.87 * MTVI1) \qquad (3)$$

$$TSC_{Toe\text{-}slope} = 863 + (0.87 * MTVI1) \qquad (4)$$

The RMSE for modelled TSC at all topographic positions, based on hold-out (test) samples, was 940 kg/ha.

Table 2 Spectral vegetation indices tested in the field-calibrated model.

Index	Equation
NDVI	$(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$
EVI	$2.5 * (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + 6 * \rho_{Red} - 7.5 * \rho_{Blue} + 1)$
SR71	ρ_{SWIR1}/ρ_{Blue}
ND53	$(\rho_{SWIR1} - \rho_{Red})/(\rho_{SWIR1} + \rho_{Red})$
NDSVI	$(\rho_{SWIR2} - \rho_{Red})/(\rho_{SWIR2} + \rho_{Red})$
SWIR3/SWIR2	$\rho_{SWIR2}/\rho_{SWIR1}$
MTVI1	$1.2[1.2(\rho_{NIR} - \rho_{Green}) - 2.5(\rho_{Red} - \rho_{Green})]$
MTVI2	$1.5[\frac{(1.2(\rho_{NIR} - \rho_{Green}) - 2.5(\rho_{Red} - \rho_{Green}))}{((\sqrt{(2 * \rho_{NIR} + 1)^2}) - (6 * \rho_{NIR} - 5 * \sqrt{\rho_{Red}} - 0.5))}]$
NDWI	$(\rho_{SWIR1} - \rho_{NIR})/(\rho_{SWIR1} + \rho_{NIR})$
ND71	$(\rho_{SWIR2} - \rho_{Blue})/(\rho_{SWIR2} + \rho_{Blue})$
SWIRDVI	$(\rho_{SWIR2} - \rho_{SWIR1})/(\rho_{SWIR2} + \rho_{SWIR1})$
SATVI	$[(\rho_{SWIR2} - \rho_{Red})/(\rho_{SWIR2} + \rho_{Red} + 0.5) * 1.5] - (\rho_{SWIR2}/2)$
NDII	$(\rho_{SWIR1} - \rho_{NIR})/(\rho_{SWIR1} + \rho_{NIR})$
MSI	ρ_{SWIR2}/ρ_{NIR}

Table 3 Dominant plant species observed at the 72 field sites July 2014.

Functional Group	Scientific Name	Summit	Mid -slope	Toe -slope
Mid	*Agropyron cristatum*			X
Short	*Bouteloua gracilis*	X		
Short	*Carex* sp.	X	X	
Mid	*Hesperostipa comata*	X	X	
Short	*Koeleria macrantha*	X		
Forb	*Melilotus officinalis*		X	X
Mid	*Nassella viridula*		X	X
Mid	*Pascopyrum smithii*	X	X	X
Mid	*Poa pratensis*			X

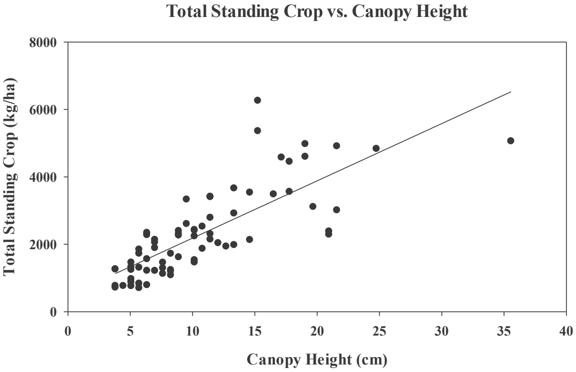

Figure 1 Regression of total standing crop (TSC) on canopy height measured at the 72 field sites 15 September 2014.

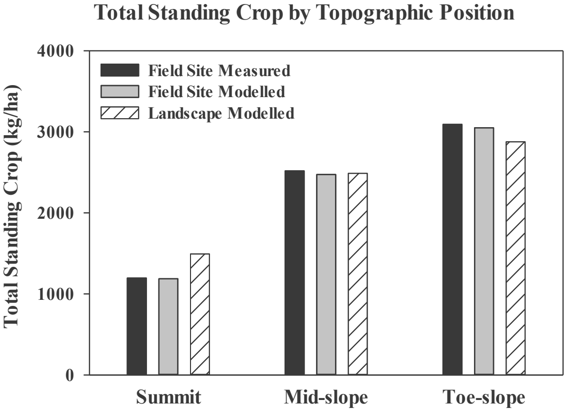

Figure 2 Average (std. error) total standing crop (TSC) measured and modelled at the 72 field sites by topographic position. The hatched bars represent average modelled TSC by topographic position for the entire grassland landscape on 14 September 2014.

A comparison of measured and modelled TSC topographic position is depicted in Figure 2. The first and second bars at each topographic position in Figure 2 indicate TSC measured and modelled, respectively, at the 72 field sites. The third bar in Figure 2 indicates model-based TSC at summits, mid-slopes and toe-slopes for the entire AOI. All three estimates of TSC indicated summit TSC were consistently lower than mid-slopes and toe-slopes. This result provided the basis upon which summit data could be used as indicators of low TSC. Field-site measured and modelled TSC by topographic position were more closely aligned than TSC estimated by topographic position for the entire AOI.

Trends in TSC by topographic position modelled for the entire landscape were similar to trends at the 72 field sites (Figure 2). The proportion of the landscape classified as low, medium-low, medium-high, and high TSC according to landscape-wide average summit, mid-slope and toe-slope data are given in Table 4. Table 4 demonstrates the proportion of the AOI within each of these classes, based on the three distinct metrics for identification of grassland structure. Based on the relationship between plant height and TSC, low structure would account for 4.5% of the grassland landscape, and based on average TSC at summits, low structure would account for 2.8% of the landscape, for a difference of 519 ha.

Table 4 Grand River National Grassland percentage and hectares within each threshold group by modelling type.

	TSC-Height Threshold		
	cm	ha	%
Low	<9	1351	4.5
Med-Low	9-12	3316	10.9
Med-High	12-15	13921	45.8
High	>15	11797	38.8
		30385	
	TSC-Topo Threshold		
	kg/ha	ha	%
Low	<1493	832	2.8
Med-Low	1493-2487	3141	10.3
Med-High	2487-2876	11940	39.3
High	>2876	14472	47.6
		30385	

Figures 3 and 4 depict maps of structure classes based on the TSC-Height and TSC-Topo models, respectively. There is a high degree of similarity between the two maps, with low structure areas mapped in Figure 3 also mapped in Figure 4.

Discussion

Both height and topographic position classifications indicated TSC for most of the landscape (between 85-87%) was medium-high or high. The proportion of the AOI considered low was 4.5% based on height and 2.8% based on topography (Table 4). A greater proportion of the landscape was low using the TSC-Height model because a low threshold of 9 cm corresponded to 2014 kg/ha. The TSC-Topo model corresponded, on the other hand, to 1493 kg/ha (Table 4). It is important to note that TSC needed to be modelled for the entire landscape to make these determinations. Extrapolation of the field estimates of plant height at the 48 non-summit locations only, meant 33% of the landscape would have been classified as low (Figure 1).

Our integrative approach that includes Landsat, DEM and field data provides a framework for field data extrapolation and adaptive management. Livestock

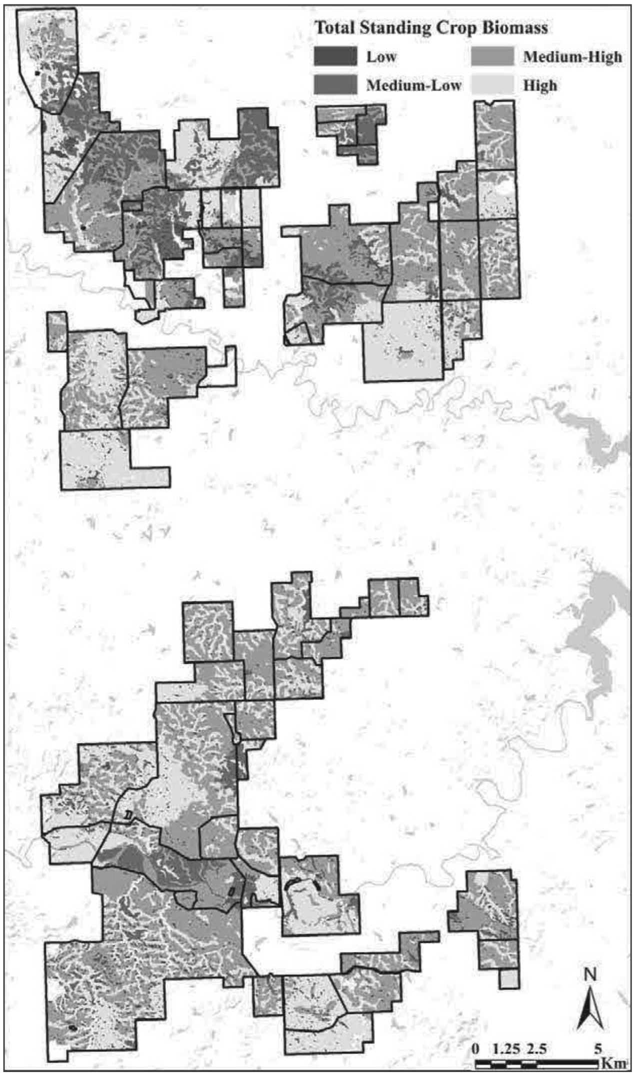

Figure 3 Proportion of landscape that was high, medium-high, medium-low, and low structure in September 2014 according to the TSC-height model thresholds.

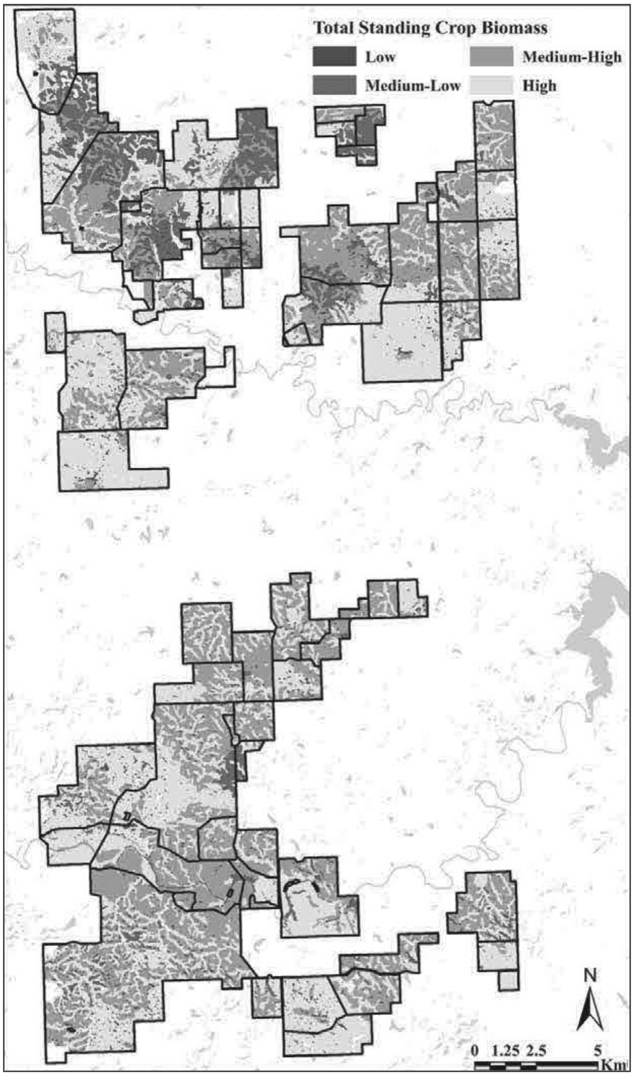

Figure 4 Proportion of landscape that was high, medium-high, medium-low, and low structure in September 2014 according to the TSC-Topo model thresholds.

need to graze grasslands each year, regardless of conditions, and management thresholds should be adaptable (Hunt *et al.* 2003; Schellberg *et al.* 2008). Repeated images and model runs would show how the landscape changes as a result of management and climate. Topographic variation in species, production, soil, canopy height, leaf area, and spectra at field sites over time (Phillips *et al.* 2012; Phillips 2014) in the United States and New Zealand hill country (Dodd *et al.* 2004; Leathwick & Rogers 1996; Radcliffe 1982; Vartha *et al.* 1982) can guide managers to areas of over- or under-utilised pasture and increase understanding of management effects on environment.

Costs associated with this framework will vary with the size and spatial variation of the landscape and the assessment/monitoring goals. Initial set up requirements are detailed in Phillips *et al.* (2012); this is where the bulk of the costs are incurred. Spatial data are freely available online and processing is automated, so after initial set-up, regular assessment costs could be < United States $1/ha. This cost is an order of magnitude lower than costs associated with collection and processing of hyperspectral aerial data.

Results indicate this framework may be useful for (1) targeting pasture areas under- or over-utilised by livestock and (2) extrapolating field vegetation data in a spatially explicit manner. Relative TSC differences in summit, mid-slope, and toe-slope positions can serve as benchmarks that, when joined with field data, provide natural indicators of variables associated with grassland structure.

Conclusions

Seasonal and annual changes in grassland canopy attributes require an assessment framework that can be flexible enough to account for variation in primary production. The spatially-integrated framework presented here is based on the premise that relative differences in summits, mid-slopes, and toe-slopes can provide meaningful benchmarks for managing seasonal variation in the whole-farm resource in hill-country landscapes at minimal expense.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Allen Will, Dan Svingen, Dennis Neitzke, and Karen Dunlap. We sincerely thank Reddy Pullanagari, Errol Thorn, and anonymous reviewers for their comments. This work was supported by USFS agreement 15-CS-11011800-014 and New Zealand Ecosystems and Global Change Fund.

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