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Ecological Health Index: A Short Term Monitoring Method for Land Managers to Assess Grazing Lands Ecological Health

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Abstract: Grazing lands should be monitored to ensure their productivity and the preservation of ecosystem services. The study objective was to investigate the effectiveness of an Ecological Health Index (EHI) for assessing ecosystem ecological health in grazing lands. The EHI was developed by synthesizing existing vegetation and soil cover indicators. We implemented long-term transects at 44 farms from two ecological regions in Patagonia, the Humid Magellan Steppe (HMS) (n = 24) and Subandean Grasslands (SG) (n = 20), to collect data on established quantifiable vegetative and soil measurements and the EHI. Using known quantifiable measures, the HMS had numerically greater species richness compared to SG. Similarly, the average percentage of total live vegetation was more favorable in HMS. Correlating the EHI with these known quantifiable measures demonstrated positive correlations with species richness, the percentage of total live vegetation and carrying capacity and was negatively correlations with bare ground. These results suggest that EHI could be a useful method to detect the ecological health and productivity in grazing lands. Overall, we conclude that EHI is an effective short-term monitoring approach that ranchers could implement annually to monitor grazing lands and determine the impacts of ranch decision-making on important ecosystem indicators.

Keywords: grazing; ecological health; ecosystem indexes; Patagonia; grasslands; sustainability

1. Introduction

Grazing lands are necessary ecosystems to human life and occupy 3.6 billion ha or about one third of global land area [1]. Grazing lands provide a range of provisioning ecosystem services such as food, fiber and energy in addition to numerous regulating, cultural and supporting ecosystem services. Because of population growth, urban sprawl and land-conversion, pastoral livestock production systems have and will continue to experience challenges contextually to the natural resource base they rely on, particularly land and water [2]. Hence, existing grazing lands must be managed for their long-term productivity and health. Thus, knowledge and techniques assessing the impact (positive or negative) of management of grazing lands on ecosystem services are critical.

To monitor the ecological health of grazing lands, several methods and techniques are used. These monitoring strategies employ direct field sampling and lab measurement to obtain precise data of specific ecosystem properties such as vegetation composition and soil organic matter [3–6]. However, the ecological processes (water cycle, energy flow and nutrient cycle) and their interrelationships are very complex which make it difficult or expensive to directly measure, particularly by land managers [7]. Moreover, spatial and temporal variability in extensive grazing management systems adds difficulty in detecting changes across landscapes [8]. Other techniques such as satellite remote sensing or modeling are often used to evaluate ecosystem services or processes (vegetation cover, soil erosion, runoff, productivity, rain use efficiency, carbon and nitrogen fluxes, etc.) and their subsequent relationship with climate conditions and land use management [8–14]. These approaches require professional expertise of well-trained scientific researchers and this expertise is not easily transferred to land managers and herders. Another evaluation method demonstrated by the USDA NRCS utilizes 17 indicators to monitor ecosystem health and is easier for land managers to use [7] but this procedure was also developed for use by experienced, rangeland professionals—not land managers. Therefore, it is imperative that inexpensive monitoring approaches that maintain efficacy but are easy to learn and comprehend for farmers and ranchers, continue to be improved upon.

To assess grazing land ecological health, ecosystem processes are often valued through life cycle assessment or environmental footprints, such as carbon, water, energy, nitrogen and biodiversity [15]. To simplify ecosystem function assessment, managers can assess soil and site stability, hydrologic function and biotic integrity by selecting a series of indicators such as bare ground, vegetation composition, litter movement, soil loss, plant functional groups, water flow patterns, plant mortality and invasive plants [16–20]. Further, Mitchell [21] summarized that plant and animal resource indicators (e.g., plant species and communities) productive capacity indicators (e.g., annual primary productivity, number of livestock, wildlife, etc.) or soil quality indicators (e.g., soil organic matter, etc.) are useful to evaluate the sustainability of grazing lands and the supply of ecosystem services. In grazing lands, indicators interconnected between livestock activities and landscape function are particularly useful, such as the vegetation and soil patch attributes [22].

Beginning in 1990 and later published by Borelli and Oliva [23] land monitors began to utilize a generic land-monitoring scorecard representing eight ecological indicators including functional group assessment, however the method included no indicators on mineral cycling and energy flow. Later, the qualitative grazing lands assessment method described by Pyke et al. [16] and Pellant et al. [17] was adopted and interfaced into the original monitoring scheme of Borelli and Oliva [23]. Importantly, Pellant et al.'s [17] method first described a 'reference area' as a monitoring area within an ecoregion which exhibits high-functioning ecosystem processes. Further they provided more indicators relative to live canopy, bare soil and evidence of plant species (desirable, undesirable and rare). Pellant et al. [17] also provided a scaled scoring approach that ranks each indicator on the amount of departure from the reference area (none to slight, slight to moderate, moderate, moderate to extreme and extreme). However, the overall methodology still lacked indicators of mineral cycling, soil erosion and plant vigor. Further as the scoring was relative to the reference area, a monitor could not provide quantitative scoring for how the ecological indicators functioned at the land surface.

Within this manuscript we present an ecological monitoring strategy, the Ecological Health Index (EHI), which has been developed over a 20-year period and practiced on 2 million ha of land in Argentina. The objective of EHI is to provide land users a quick, inexpensive method that uses biological indicators that have predictive value of ecosystem function namely biodiversity, energy flow and the mineral and water cycles. We adopted components of the Landscape Function Analysis (LFA) by Tongway and Hindley [24], along with elements from Pyke et al. [16], Pellant et al. [17] and Borelli and Oliva [23], to provide greater strength in quantifying land use change. Specifically, LFA is a visual assessment procedure employing quickly determined field indicators related to soil properties and ecosystem processes. Importantly, the method allows for greater assessment of litter composition and for landscape function indices derived from indicator scoring to be grouped by ecosystem process. The LFA has been used to assess soil function under grazing management, ecological restoration or rehabilitation and has been shown to be an effective monitoring tool [25–27]. One challenge to the monitoring strategy is the use of Canfield lines [28], a line interception method that requires measuring of plant distance to an intercept among other calculations which can be time consuming.

Therefore, integrating the work of Pyke et al. [16], Pellant et al. [17], Borelli and Oliva [23] and Tongway and Hindley [24], the EHI is a visual assessment method encompassing field indicators which are closely related to ecosystem processes and can also be quickly measured (requiring about five minutes per checkpoint). Moreover, the selected indicators for EHI, such as the species richness (the number of species in the checkpoint), are simple in scope and thus hopefully more apt to be adopted by farmers and managers.

Another component to our ecosystem indicator selection was the fact that those primarily involved in its development are also accredited educators for holistic management which teaches the evaluation of four ecosystem processes (water cycle, mineral cycle, energy flow and community dynamics) at the landscape surface. Thus, we also worked to use language and variables that existing holistic management practitioners associate with.

Before applying a new land monitoring strategy, it is essential to test its feasibility and reliability by comparing the index score to other quantifiable measurements (QM) that are known ecological indicators. For example, LFA indices (e.g., stability, infiltration and nutrient cycling index) have been shown to positively correlate with soil properties (e.g., aggregate stability, water infiltration and soil respiration) [24,25]. Therefore, our objective was to determine the effectiveness of EHI on assessing the ecological health of grazing lands. To do this, we compared EHI and known QM in the literature, resulting in ecological health comparisons between two ecoregions encompassing 44 grazing farms across 398,949 ha. We also assessed the correlation between EHI, QM and carrying capacity for insight into EHI effectiveness. Our hypothesis is the EHI is correlated to QM and carrying capacity and thus can used as an effective method or grazing land monitoring.

2. Materials and Methods

2.1. Experimental Site

The study was conducted between 2011 and 2014 at 44 farms in two ecoregions of Patagonia: the Humid Magellan Steppe (HMS) (n = 24; 279,595 ha) and the Subandean Grasslands (SG) (n = 20; 119,354 ha). During the monitoring period, HMS had an annual average temperature of 5.8 °C and ~300 mm rainfall. The annual average temperature for SG was 7.9 °C and average rainfall ~345 mm (Table 1).

Table 1. Climate and monitoring information of the Humid Magellan Steppe (HMS) and Subandean Grasslands (SG) ecoregions.

Farm Name	Hectarage (Ha)	Monitored Subsidiaries within Farm	Year of Monitoring	Average Rainfall (mm)	Temperature (°C)
HMS					
Monte Dinero	8000	1	2011	270	6.5
Morro Chico	26,025	2	2012	300	5.5
Namuncura	22,135	4	2012	250	5
Rupai Pacha	25,000	2	2012	200	5
Viamonte	40,600	1	2012	400	5
Punta Delgada	93,000	6	2013	250	6.5
Teraike	29,605	3	2013	400	6
Pamela Christian	9018	3	2013	400	6
Armonia	8000	2	2014	350	6
SG					
La Paulina	4306	2	2012	250	8
Numancia	23,000	5	2012	400–600	8
Bajada de los Orientales	56,000	3	2012	200	7
El Amanecer	4661	1	2012	350	8
El Cronometro	4746	2	2012	350	8
La Legua	2500	1	2012	250	8
Montoso	2500	1	2012	250	9
Media Luna	1200	1	2012	350	8
Bajada de los Orientales	58,000	1	2013	180	5.8
Fortin Chacabuco	4382	3	2014	400	8

2.2. Ecological Health Index

In this study, EHI was developed as an adaptation of previous work [17,23,24]. Ecological properties and processes including soil stability, water cycle, nutrient cycle, plant community dynamics and energy flow were evaluated annually using multiple indicators determined by visual assessment (Table 2, Appendix A). Each EHI indicator and the ecosystem processes they influence are referenced in Table 2.

Table 2. Ecological processes and related indicators evaluated for Ecological Health Index (EHI). The Type columns explains if the indicator is evaluated as compared to the reference area or as a stand-alone, absolute indicator. The latter four columns indicate which of the key four ecosystem cycles this is an indicator of (white, not an indicator; gray, an indicator).

#	INDICATOR	UNIT	Source	Type	Water Cycle	Mineral Cycle	Energy Flow	Community Dynamics
1	Live Canopy Abundance	Total green biomass production/Site potential	[24,29]	Ref. Area				
2	Living Organisms	Evidence of microfauna	[24,30]	Absolute				
3	FG 1—Warm Season Grasses	Vigor, reproduction, crown integrity	[24,29,30]	Absolute				
4	FG 2—Cool Season Grasses	Vigor, reproduction, crown integrity	[24,29,30]	Absolute				
5	FG 3—Forbs/Legumes	Vigor, reproduction, crown integrity	[24,29,30]	Absolute				
6	FG 4—Desirable Trees/shrubs	Vigor, reproduction, crown integrity	[24,29,30]	Absolute				
7	Contextually Desirable Rare Species	Frequency	[24]	Ref. Area				
8	Contextually Undesirable Species	Abundance	[24,29,30]	Ref. Area				
9	Litter Abundance	% Cover	[23,24,29–31]	Ref. Area				
10	Litter Incorporation	Litter type, Soil contact	[23,24,29–31]	Absolute				
11	Dung Decomposition	Dung Disappearance rate	[24]	Absolute				
12	Bare Soil	% Bare soil	[23,24,29–31]	Ref. Area				
13	Capping	Soil surface resistance	[23,24,29,31]	Absolute				
14	Wind Erosion	Blowout/Deposition	[23,24,29–31]	Absolute				
		Active pedestals	[23,24,29–31]	Absolute				
15	Water Erosion	Rills/water flows	[23,24,29–31]	Absolute				
		Gullies	[23,24,29–31]	Absolute				

To use the EHI, an evaluation matrix was created for each ecoregion, following the procedures proposed by Pellant et al. [17]. For each ecoregion, we first identified two or more reference areas—the described, best-known expression of biodiversity, site stability and ecosystem function or a site considered most representative of the grazing land's ideal state. The evaluation matrix for reference areas in HMS and SG are presented in Appendix A. A reference area score card was developed according to the ecoregion evaluation matrix. At each participating farm, scores were assigned to each indicator using the score card. The EHI is the cumulative score of for all indicators ranging from −130 to +110. Higher EHI indicates greater ecosystem function while low values suggest that the ecosystem is a low-functioning landscape with considerable negative departure from the reference area in that Ecological Region.

Besides EHI, the functional indexes including Soil Stability Index (SSI), Water Cycle Index (WCI), Nutrient Cycle Index (NCI), Plant Community Dynamics Index (CDI), Energy Flow Index (EFI) were calculated using related indicators (Table 2) from the following equation adapted from Tongway and Hindley [24]:

$$I = 1 - (M - i)/D$$

where

I = Index value (SSI, WCI, NCI, CDI or EFI),
M = Max possible value of the total scores of related indicators,
i = total scores of related indicators,
D = Difference between max and min possible values of the total scores of related indicator.

The value of each functional index reflects the ecosystem cycle function observed at the monitored site in comparison to the ideal condition of the reference area. For example, if the WCI value is 100%, this indicates the assessed water cycle is similar to the best expected condition for water in the monitored area.

2.3. Long Term Fixed Transects

The methodology for long term fixed transects was adapted from Oliva et al. [32] for assessing grazing lands in Patagonia [32]. Transects can be used for long-term monitoring (every 4 to 5 years). The aim is to track the change in ecosystem process functionality over time using QM, an addition to the short-term attributes measured with EHI. In this study, the long-term fixed transects were used to assess QM and EHI in the same years, so as to compare these two monitoring methods. At each monitoring farm a fixed transect was installed (Figure 1) and measures were taken to assess QM including species richness, the Shannon-Wiener Index, percentage area of bare ground, litter, standing dead (dead material not in contact with the land surface), evidence of cryptogams or ephemeral species and total live vegetation abundance. These QM aimed to reflect the soil surface and vegetation composition as ecosystem function indicators. Specifically, the basal cover and plant biodiversity was read using a Point and Flexible Area Method (PAF) [33]. This method is used for rapid inventories of ecological function status combines classical methods of line point intercepts with quadrat sampling areas. As indicated in Figure 1, two-line point transects (transect 1 and 2) of 25 m long, points spaced every 0.25 m (100 points in each transect, total 200 points) were used to do quantifiable assessment of plant species. At each point, a pin was pointed to the ground and the plant species touched by the pin were recorded. Also, a variable area on each side of T2 (flexible quadrat) was used to check for rarer species. All species not recorded by pin hits included in the area between T1 and T3 were recorded, with their basal area and distance to T2. A complete species list with quantifiable cover estimates was then obtained. Species litter or bare ground observed from the 200 points were recorded. This procedure gives an estimate of biodiversity indicators (species richness and Shannon-Wiener Index) and describes canopy cover by species and functional groups. The T3 was used for observation in ten 50 × 50 cm quadrats, spaced every 2 m and the EHI was evaluated and recorded. Each participating farm was surveyed to assess their carrying capacity. The carrying capacity data corresponds to paddock average, was defined as sheep animal days/hectare and was compared with EHI.

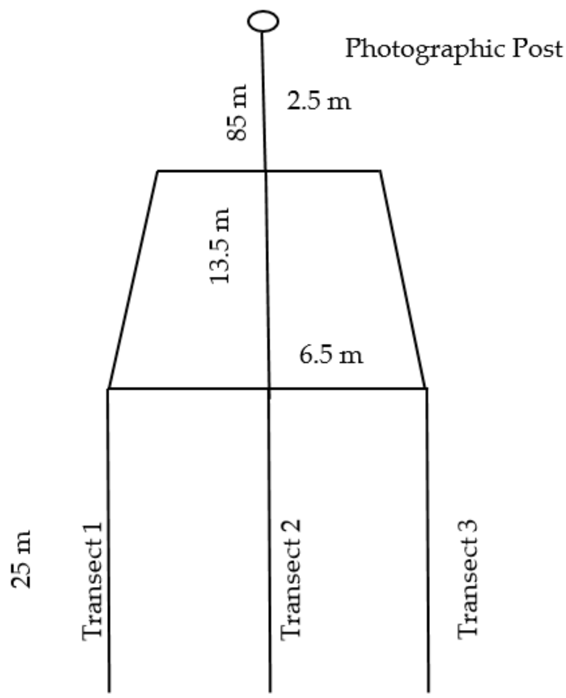

Figure 1. Long-term monitoring transects.

2.4. Statistical Analysis

Linear correlation between EHI, QM and carrying capacity and between functional indexes (SSI, WCI, CDI and EFI) and QM was conducted using SAS PROC CORR procedure (SAS 9.4, 2013). The linear regression analysis was conducted using SAS PROC REG procedure with EHI as the independent variable and QM as the dependent variable.

3. Results

3.1. Ecological Health Index and Quantifiable Measurements

Both HMS and SG had 2 farms with EHI values greater than 40, indicating they are ecologically high functioning. However, 11 farms in SG (55% of 20 farms) and 6 farms in HMS (25% of 24 farms) had negative EHI (<0), suggesting a low ecosystem function.

In order to assess EHI efficacy, we compared the EHI farm score to multiple QM in each ecoregion and analyzed the correlation between EHI and selected QM. The QM included species richness, the Shannon-Wiener Index (which refers to the diversity and evenness of plant species) and the percentage area of bare ground, litter, standing dead, cryptogams, ephemeral species and total live vegetation. In each ecoregion, EHI was positively correlated with species richness (R = 0.61, P = 0.0022 for HMS, Figure 2; R = 0.67, P = 0.0022 for SG, Figure 3).

No significant correlations were detected between EHI and the Shannon-Wiener Index (data not shown). The Shannon Wiener Index was 1.6 to 2.5 for HMS and 0.6 to 2.4 for SG, respectively. The HMS and SG had 0 to 11.7% and 0 to 19.5% standing dead respectively and 0 to 9.5% and 0 to 3.5% cryptogams respectively, none of which was correlated with EHI. The percentage of ephemeral (short-lived, non-perennial) species was lower than 6% and no correlations with EHI were detected. Perennial species play an important role on regulating ecosystem services, even on annual dominated ecosystems [34]. In this study, the percentage of cryptogams and ephemeral species are relatively low so both ecoregions were dominated by perennial grasses.

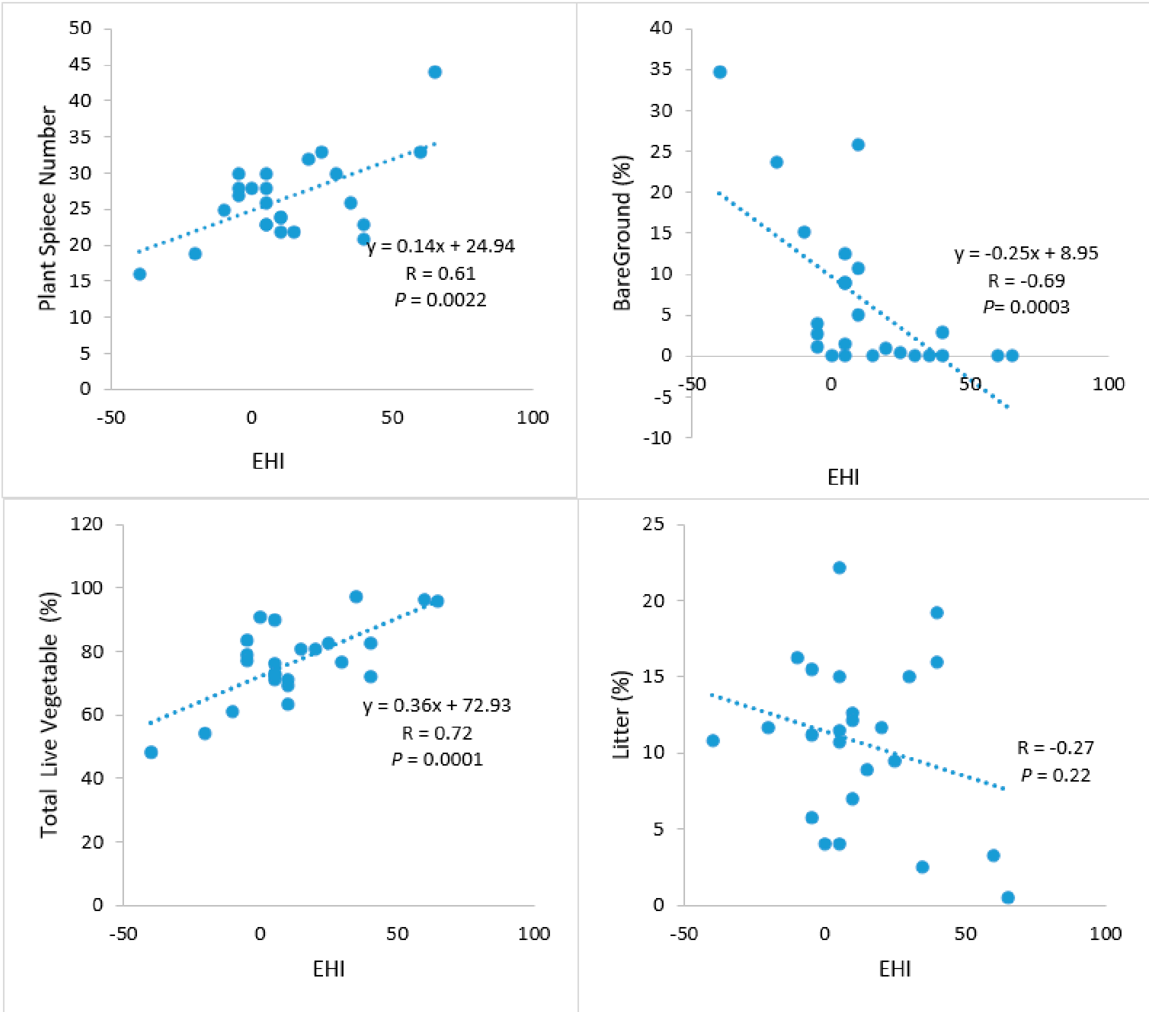

Figure 2. Linear regression for HMS between EHI and QMs species richness (R = 0.61), cover percentage of total live vegetation percentage (R = −0.69), bare ground (R = 0.72) and litter (R = −0.27).

To further confirm the effectiveness of EHI, we calculated functional indices (SSI, WCI, NCI CDI and EFI) by selecting indicators used for EHI associated with soil stability, water cycle, nutrient cycle, plant community dynamics and energy flow (see Table 2). The correlation analysis between the functional indices and QM are indicated in Table 3. Similar to EHI, the SSI, WCI, CDI and EFI were generally positively correlated to species richness and the percentage of total live vegetation and negatively correlated with percentage of bare ground, at both ecoregions. Specifically, SSI, WCI and EFI were highly correlated with the percentage of total live vegetation (R = 0.69 to 0.85) and bare ground (R = −0.74 to −0.93), indicating soil stability, water cycle and energy flow are potentially effective indicators for ecological function.

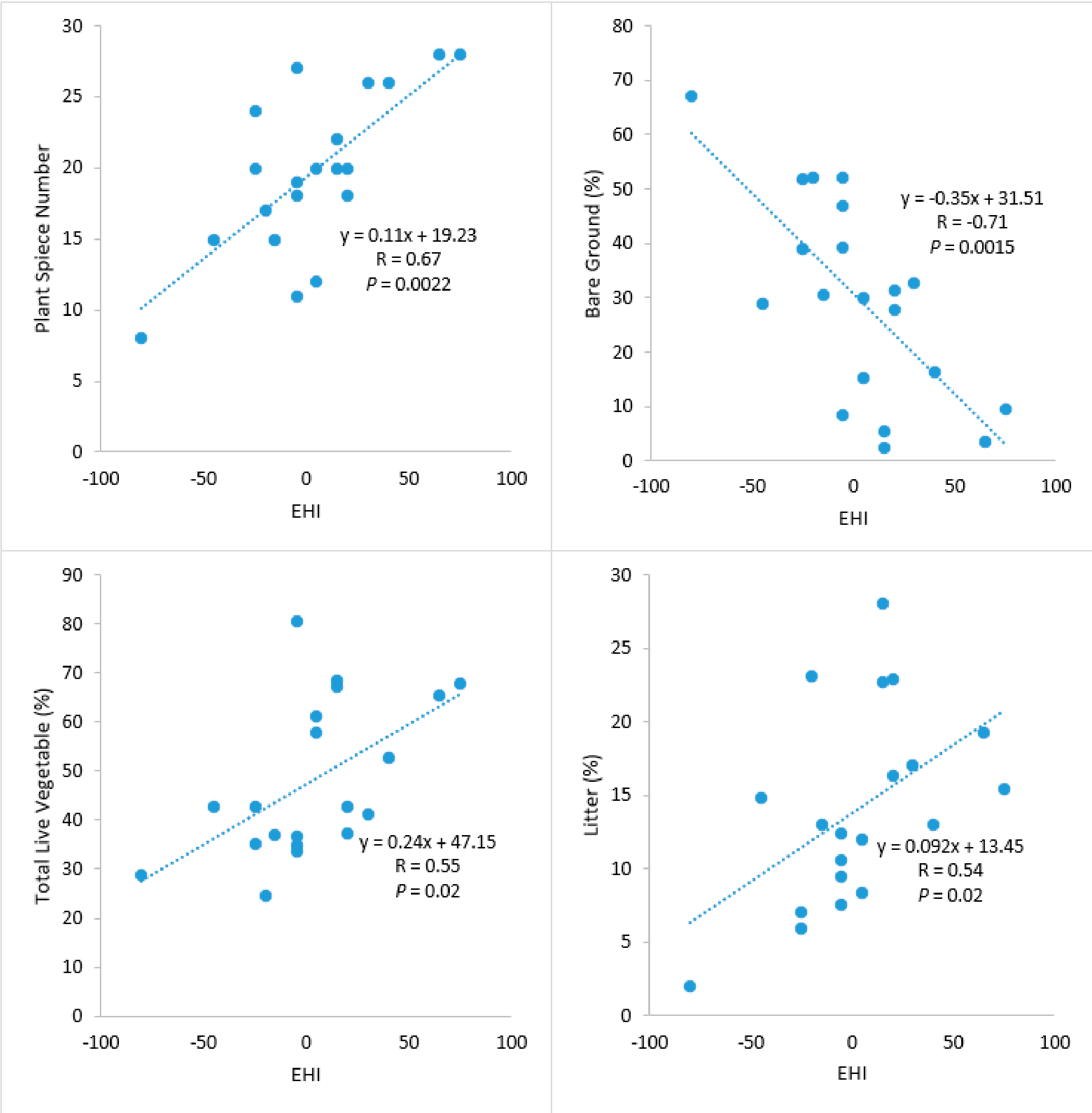

Figure 3. Linear regression for SG between EHI and QMs species richness, cover percentage of total live vegetation, bare ground and litter.

Table 3. The correlation analysis between functional indexes (SSI, WCI, CDI and EFI) and quantifiable measurements (QM) in Humid Magellan Steppe (HMS) and Subandean Grasslands (SG).

	Species Richness	**Litter**	**Standing Dead**	**Cryptogams**	**Ephemeral**	**Total Live Vegetation**	**Bare Ground**
				SSI §			
HMS							
R	0.44	−0.10	−0.43	0.29	−0.41	0.80	−0.92
R^2	0.19	0.01	0.19	0.09	0.17	0.64	0.84
P	0.04	0.67	0.04	0.18	0.05	<0.0001	<0.0001
SG							
R	0.51	0.37	0.06	0.27	0.22	0.77	−0.83
R^2	0.26	0.13	0.003	0.07	0.05	0.59	0.70
P	0.02	0.11	0.82	0.25	0.36	<0.0001	<0.0001

Table 3. *Cont.*

	Species Richness	Litter	Standing Dead	Cryptogams	Ephemeral	Total Live Vegetation	Bare Ground
WCI							
HMS							
R	0.53	−0.16	−0.43	0.28	−0.42	0.84	−0.93
R^2	0.28	0.02	0.19	0.08	0.18	0.71	0.86
P	0.01	0.49	0.05	0.21	0.05	<0.0001	<0.0001
SG							
R	0.58	0.48	0.13	0.28	0.17	0.69	−0.82
R^2	0.34	0.23	0.02	0.08	0.03	0.47	0.68
P	0.01	0.03	0.58	0.24	0.48	0.001	<0.0001
CDI							
HMS							
R	0.49	−0.36	−0.13	−0.23	−0.10	0.49	−0.29
R^2	0.24	0.13	0.02	0.05	0.01	0.24	0.08
P	0.02	0.10	0.56	0.30	0.65	0.02	0.19
SG							
R	0.66	0.37	0.06	0.52	−0.11	0.45	−0.54
R^2	0.44	0.13	0.004	0.27	0.01	0.20	0.30
P	0.002	0.11	0.79	0.02	0.64	0.05	0.01
EFI							
HMS							
R	0.68	−0.25	−0.34	0.06	−0.29	0.76	−0.74
R^2	0.46	0.06	0.12	0.003	0.09	0.58	0.55
P	0.001	0.27	0.12	0.81	0.19	<0.0001	<0.0001
SG							
R	0.27	0.26	0.02	0.37	0.24	0.85	−0.85
R^2	0.07	0.07	0.0004	0.14	0.06	0.73	0.73
P	0.25	0.27	0.93	0.11	0.31	<0.0001	<0.0001

§ Functional indexes: Soil Stability Index (SSI), Water Cycle Index (WCI), Plant Community Dynamics Index (CDI), Nutrient Cycle Index (NCI), Energy Flow Index (EFI).

3.2. Carrying Capacity

Participating managers were surveyed on the overall carrying capacity of their managed landscapes. The average carrying capacity was 123 (ranging from 23 to 503) and 35 (ranging from 0 to 84) sheep animal days per hectare in HMS and SG, respectively (data not shown). The EHI was positively and significantly correlated with carrying capacity (R = 0.72, *P* = 0.0003 for HMS and R = 0.57, *P* = 0.02 for SG (Table 4).

Table 4. Ecological health indicator (EHI) and quantifiable measurements (QM) correlated with carrying capacity in Humid Magellan Steppe (HMS) and Subandean Grasslands (SG).

	EHI	Species Richness	Litter	Total Live Vegetation	Bare Ground
HMS					
R	0.72	0.62	−0.63	0.54	−0.37
R^2	0.51	0.39	0.40	0.30	0.14
P	0.0003	0.0025	0.0021	0.01	0.08
SG					
R	0.57	0.40	0.41	0.48	−0.36
R^2	0.33	0.16	0.17	0.23	0.13
P	0.02	0.11	0.10	0.05	0.12

4. Discussion

4.1. Ecological Health Index and Quantifiable Measurements

Species richness, an indicator of plant diversity, is a useful metric for landscape health as it can influence ecosystem multifunctionality and stability [35–39]. The consistent correlation between species richness in our pilot locations and EHI suggest that EHI could be an effective assessment of grazing land ecological health. Vegetation cover and bare ground percentage is likewise an important ecological indicator as greater bare ground results in increased runoff and sediment loss [25]. In this study, mean live vegetation percentage was positively correlated with EHI at both ecoregions (Figure 2; Figure 3). Martin et al. studied the impacts of precipitation pattern on grazing lands and reported that decreased rainfall can be detrimental to net primary productivity while increased precipitation variability may have negative, none or positive effects [11]. We did detect numerically different vegetation cover and plant species between HMS and SG and assess this was partly attributed to the increased precipitation and generally milder growing conditions in HMS. Conversely to vegetation cover, the percentage of bare ground was negatively correlated with EHI in both ecoregions.

An Australian rangeland study by Bartley et al. [25] reported a consistency in evaluating ecological health by using vegetation cover percentage and the soil surface condition (SSC) index derived from the LFA method [24]. The authors reported that both vegetation cover percentage and the SSC index were highly correlated with infiltration rate. We offer that EHI can be used in a similar fashion to assess water cycle function. Moreover, the correlation between EHI and QM further confirm the effectiveness of EHI. Besides plant composition and bare ground percentage, litter amount is also an ecological health indicator and the percentage of litter cover can be influenced by grazing management [40,41]. Litter percentage had a low correlation with EHI only in SG (but not HMS). The small live plant percentage and lower species richness in SG may lead to less root biomass and diversity when compared to other regions with more favorable growing conditions. Since root residues and exudates determine the labile C input, litter may be more important to sustain ecosystem function in drier areas such as SG and to a lesser degree HMS, to provide C input and a food source for soil microbes [42]. Moreover, the litter cover can protect soil from erosion, which is critical in regions such as SG with less vegetation cover and less precipitation [43]. Conversely, HMS has relatively higher precipitation which favors litter decomposition, so the litter amount is not necessarily correlated to ecosystem functions.

The absolute values of correlation coefficients (R) between EHI and species richness, percentage of total live vegetation and bare ground were between 0.55 and 0.72 ($P < 0.05$). Similar to our study, Kosmas et al. reported a correlation (R = 0.57) between the desertification risk index and soil organic matter content from a land degradation study attributing the causes of this correlation to other factors such as land management, climate conditions or soil characteristics [14]. Similarly, a Colorado study indicated correlation coefficients between qualitative indicators and other quantitative measures between 0.31 and 0.69 [44]. Tongway and Hindley also analyzed the relationship between the LFA-derived indexes and different QM and they indicated a high correlation between nutrient cycling index and respiration (R > 0.9) and between infiltration index and infiltration (R > 0.8) [24]. Likewise, the infiltration index and measured infiltration rate was highly correlated (R > 0.9) in the study of Bartley et al. [25]. The higher correlation detected from these studies, however, were between the functional index and its related processes (nutrient cycling index vs. respiration, infiltration index vs. infiltration, invasive plant indicator vs. invasive plant foliar cover, bare ground indicator vs. basal gap percentage, etc.). Conversely, in our study, EHI is an integrated index encompassing soil stability, water cycle, nutrient cycle, plant community dynamics and energy flow, aiming to detect the whole ecological status of a grazing land ecosystem.

4.2. EHI and Carrying Capacity

At both ecological sites, carrying capacity was positively correlated with the percentage of total live vegetation. Similarly, other studies also indicate that carrying capacity can be improved by promoting plant production [45]. Conversely, lower plant productivity, which may result in or attribute to a greater area of bare ground or erosion pavement, may be detrimental to carrying capacity. In each location, bare ground was negatively correlated with carrying capacity. The consistency of EHI and QM on their relationship with carrying capacity further suggest that EHI can be a useful method to evaluate ecological function. Importantly, while a relationship between EHI and SG carrying capacity is positive, in this brittle environment there could be risk for conflating a positive correlation with an overstocked landscape. However, this would only be in a short-term situation and overtime, the two metrics, if actually related, would become more correlated.

The relationship between plant diversity and ecosystem function is not very well understood and more studies are needed to determine the impacts of species richness on animal production [46]. In this study, data indicate that the carrying capacity was positively correlated to species richness in HMS (P = 0.0025) suggesting a potential advantage of biodiversity in supporting greater animal productivity with high vegetation cover.

Overall, the strongest correlations we detected were between EHI and carrying capacity. This correlation would indicate that EHI can be a useful indicator in overall landscape productivity. So, while EHI was not closely aligned with every indicator we monitored, from a holistic sense the aggregated monitoring approach effectively aligned with a high indicator of overall land productivity. Ultimately, land with a greater EHI could effectively sustain a greater carrying capacity with improved ecosystem function.

5. Conclusions

The EHI is a monitoring protocol that utilizes tools from multiple land assessment approaches. By measuring both EHI and QM and conducting correlation analysis between the two, our data indicate that EHI increased with species richness, percentage of total live vegetation and decreased with percentage of bare ground. However, we did not detect relationships between the Shannon Wiener Index and EHI. While there were positive and significant relationships between EHI and carrying capacity. Thus, EHI can be useful to inform decision makers about ecological attributes associated with positive landscape function. Regular monitoring of such attributes leads to a greater understanding of the relationship between management and ecosystem services in agricultural ecosystems and provides information on how to improve subsequent management. We suggest that a combination of frequent EHI monitoring with long-term QM, as proposed by Borrelli et al., can provide a cost-effective assessment of ecosystem health in grazing lands [31].

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Appendix A

The evaluation matrix for reference areas in HMS (Table A1) and SG (Table A2).

Table A1. Evaluation Matrix (Humid Magellan Steppe Descriptors).

				Departure from Reference Sheet				
Num.	**Atribute**	**Process Indicator**	**Score**	**N-S**	**S-M**	**M**	**M-E**	**E-T**
1	Vegetation cover	% Vegetation cover	−10 to +10	Total perennial vegetation cover exceeds 95%	Total perennial vegetation between 90–95%	Total perennial vegetation between 80–90%	Total perennial vegetation between 70–80%	Total perennial vegetation less than 70%
				10	5	0	−5	−10
2	Capping	Surface soil resistance	−10 to +10	Loose soil or light capping that breaks easily with finger tip	Loose soil or light capping that breaks easily with finger tip	Loose soil or light capping that breaks easily with finger tip	Moderately hard capping requires pressure to break	Very hard capping requires metallic tool to break
				10	5	0	−5	−10
3	Wind erosion	Active blowout/ deposition processes	0 to −20	Not present	Not present	Slight soil movement	Blowout/deposition areas cover 10–25% of the area	Blowout/deposition areas >25% of the area
		Active pedestals		Not present	Not present	Few active active pedestals, hard to find	Active pedestals 5–10 cm deep	Pedestals abundant and active, more than 10 cm deep
		Total		0	0	0	−10	−20
4	Water erosion	Active rills	0 to −20	Not present	Not present	Not present	Laminar erosion or active rills evident and well defined	Rill formation is severe and well defined throughout the site
		Active water flows		Not present	Not present	Not present	Visible waterflows width < than 2 cm	Visible water flows, width > 2 cm
		Active gullies		Not present	Not present	Not present	Active gullies present, low frequency	Active gullies frequent
		Total		0	0	0	−10	−20
5	Litter incorporation	Litter/soil contact	10	More than 50% of the area with low incorporation	20 to 50% of the area with low incorporation	Incorporation null	Incorporation null	Incorporation null
				10	5	0	0	0
6	Living organisms	Evidence of microfauna	10	Abundant presence of dung beetles, aunts, spiders and other species	Moderate presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species
				10	5	0	0	0
7	Dung decomposition	Dung age structure	10	Only fresh dung is present. Fast cycling	Fresh and old dung mixed	Most of dung patches are more than 1 year old (mummified)	Most of dung patches are more than 1 year old (mummified)	Most of dung patches are more than 1 year old (mummified)
				10	5	0	0	0
8	Tussock	Tussock in good condition	−10 to 10	>30%	20–30%	10–20%	<10%	0
		Decadent tussock		<20%	20–30%	30–40%	40–50%	>50%
		Total		10	5	0	−5	−10

Table A1. *Cont.*

				Departure from Reference Sheet				
Num.	**Atribute**	**Process Indicator**	**Score**	**N-S**	**S-M**	**M**	**M-E**	**E-T**
9	Decreasers	Frequency	10	>10 plants/m^2	1–10 plants/m^2	<1 plant/m^2	Decreaser species absent	Decreaser species absent
				10	5	0	0	0
10	Key species	Plants in good condition	−20 to 20	>50%	30–50%	10–30%	<10%	<10%
		Decadent plants		<10%	10–30%	30–50%	50–70%	>70%
				20	10	0	−10	−20
11	Shrubs	Plants in good condition	−10 to 10	>50%	30–50%	10–30%	<10%	Not observed
		Decadent plants		<10%	10–20%	20–30%	30–50%	>50%
				10	5	0	−5	−10
12	Invaders	Abundance		Not observed	Not observed	Not observed	Moderate presence of young plants of Empetrum rubrum, Azzorella or Hieracium pilosella	Abundant presence of young plants of Empetrum rubrum, Azzorella or Hieracium pilosella
				0	0	0	−10	−20
13	Total production	% of Reference area	−10 to 10	More than 75% of reference area	60–75% of reference area	50–60% of reference area	25–50% of reference area	<25% of reference area
				10	5	0	−5	−10
				110	55	0	−65	−130
N-S	Nil to slight							
S-M	Slight to moderate							
M	Moderate							
M-E	Moderate to extreme							
E-T	Extreme to total							
FUNCTIONAL GROUPS								
TUSSOCK	Tall, rough bunchgrasses—Provide structure, produce litter and have deep roots							
Decreasers	Plants that disappear under continuous grazing. Usually broad leaved, more mesic grasses and native legumes							
Key Species	Abundant, preferred species. Determine most of the high quality forage							
Shrubs	Woody plants that create niches and provide forage in winter time							
Invaders	(old term for contextually undesirable species). Plants that are emblematic of an undesired transition. Mostly exotic or unpalatable native woody plants							

Table A2. Evaluation Matrix (Subandean Grassland Descriptions).

				Departure from Reference Sheet				
Num.	**Atribute**	**Process Indicator**	**Score**	**N-S**	**S-M**	**M**	**M-E**	**E-T**
1	Litter	%Cover	0 to 10	Grade 3 litter or more, more than 15% cover	Grade 3 Litter: 10–15% cover	Grade 2 Litter: 1–10% cover	Grade 1 Litter: <1% cover	Grade 1 Litter: <1% cover
				10	5	0	0	0
2	Vegetation cover	% Vegetation cover	−10 to +10	Perennial Vegetation cover exceeds 60% Bare ground less than 20%	Perennial Vegetation cover 55–60%. Bare Ground 20–25%	Perennial Vegetation cover 55–60%. Bare Ground 25–35%	Perennial Vegetation cover 40–55%. Bare Ground 35–50%	Perennial Vegetation cover <40%. Bare Ground >50%
				10	5	0	−5	−10
3	Capping	Surface soil resistance	−10 to +10	Loose soil or light capping that breaks easily with finger tip	Loose soil or light capping that breaks easily with finger tip	Loose soil or light capping that breaks easily with finger tip	Moderately hard capping requires pressure to break	Very hard capping requires metallic tool to break
				0	0	0	−5	−10
4	Wind erosion	Active blowout/ deposition processes	20 to −20	Not present (Grade 4)	Grade 4 predominant, less than 30% Grade 3	Grade 3 predominant	Blowout/deposition areas cover 10–25% of the area	Blowout/deposition areas >25% of the area (Grade 2)
		Active pedestals		Not present (Grade 4)	Not present (Grade 4)	Few active active pedestals, hard to find (Grade 3)	Active pedestals 5–10 cm deep (Grade 2)	Pedestals abundant and active, more than 10 cm deep
		Total		20	10	0	−10	−20
5	Water erosion	Active rills	0 to −20	Not present (Grade 4)	Not present (Grade 4)	Not present (Grade 4)	Laminar erosion or active rills evident and well defined	Rill formation is severe and well defined throughout the site
		Active water flows		Not present (Grade 4)	Not present (Grade 4)	Not present (Grade 4)	Visible waterflows width < than 2 cm (Grade 3)	Visible water flows, width > 2 cm (Grade 2 and 1)
		Active gullies		Not present (Grade 4)	Not present (Grade 4)	Not present (Grade 4)	Active gullies present, low frequency	Active gullies frequent
		Total		0	0	0	−10	−20
6	Biological crust	Cover	0 to 10	>5% (Grade 3)	Between 1–5% (Grade 2)	<1% (Grade1)	Not Present (Grade 0)	Not Present (Grade 0)
				10	5	0	0	0
7	Litter incorporation	Litter/soil contact	0 to 10	More than 50% of the area with low incorporation	20 to 50% of the area with low incorporation	Incorporation null	Incorporation null	Incorporation null
				10	5	0	0	0
8	Living organisms	Evidence of microfauna	−10 to 10	Moderate presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species	Scarce presence of dung beetles, aunts, spiders and other species
				5	0	0	0	0
9	Dung decomposition	Dung age structure	0 to 10	Does not apply	Does not apply	Does not apply	Does not apply	Does not apply
				0	0	0	0	0

Table A2. *Cont.*

				Departure from Reference Sheet				
Num.	**Atribute**	**Process Indicator**	**Score**	**N-S**	**S-M**	**M**	**M-E**	**E-T**
10	Tussock	Tussock in good condition	−10 to 10	>40%	25–40%	10–25%	<10%	Not observed
		Decadent tussock		<10%	10–25%	25–40%	40–60%	>60%
		Total		10	5	0	−5	−10
11	Decreasers	Frequency	0 to 10	Very abundant >10 plants/m^2	1–10 plants per m^2	less than 1 plant/m^2	Decreasers are absent	Decreasers are absent
				10	5	0	0	0
12	Key species	Plants in good condition	−20 to 20	>40%	25–40%	10–25%	<10%	Not observed
		Decadent plants		<10%	10–25%	25–40%	40–60%	>60%
				20	10	0	−10	−20
13	Shrubs	Plants in good condition	−10 to 10	>50%	30–50%	10–30%	<10%	Not observed
		Decadent plants		<10%	10–20%	20–30%	30–50%	>50%
				10	5	0	−5	−10
14	Invaders	Abundance	0 to −20	Not observed	Not observed	Not observed	Rare to moderate presence of young plants of Stipa sp, Nassauvia and Acaena	Frequent presence of young plants of Stipa sp, Nassauvia and Acaena
				0	0	0	−10	−20
15	Total production	% of Reference area		More than 75% of Reference Area	60–75% of Reference Area	50–60% of Reference Area	25–50% of Reference Area	<25% of Reference Area
				10	5	0	−5	−10
				125	60	0	−65	−130

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