

Supplementary Information for “Comparing methods for estimating habitat suitability”

S.1. Habitat conditions

We attempted to find a habitat component that is common in all habitats to use an indicator to estimate habitat suitability. We took what we could gather from the Encyclopedia Britannica regarding the characteristic structures of deciduous, coniferous, and mixed forests, wooded and herbaceous wetlands, shrub lands, grasslands, and bare lands.

Deciduous Forest

Deciduous forests consist of primarily broad-leaf trees with seasonal shedding with a dense canopy allowing little light through with shrubs found in clearings. These forests occur in temperate to arid regions along stream banks and around bodies of water. The trees that can make up a deciduous forest are oak, beech, birch, chestnut, aspen, elm, maple, and basswood trees. The soil consists of gray-brown and brown podzols, is slightly acidic, and has a granular hummus layer (mull) which is a mix of organic material and mineral soil with many invertebrates such as earthworms. The animals that inhabit deciduous are invertebrates such as snails, slugs, insects, and arachnids, amphibians such as salamanders and frogs, reptiles such as lizards and snakes, a large variety of birds including warblers, flycatchers, vireos, thrushes, woodpeckers, hawks, and owls, and mammals like moles, chipmunks, squirrels, rabbits, bears, and deer [1].

Coniferous Forest

Coniferous forests, also called evergreen forests, consists primarily of cone-bearing needle-leaved or scale-leaved trees such as pines, spruces, firs, cedar, and larches. These forests exist in regions with long winters and high annual precipitation. The soil therein is light-colored acidic podzol with a compacted hummus layer (mor) that contains many fungi. It is also low in mineral content, organic material, and number of invertebrates like earthworms. Animals present are mosquitoes, flies, few cold-blooded vertebrates, birds (woodpeckers, crossbills, warblers, kinglets, nuthatchers, waxwings, grouse, hawks, and owls), shrews, voles, squirrels, martens, moose, reindeer, lynx, and wolves [2].

Mixed Forest

Mixed forests are described as a forest with both deciduous and coniferous trees. It may also describe forest with two or more dominant tree species. Common tree species include spruce, oak, maple, and beech. The understory is made up of shrubs, grasses, and ferns. These habitats are commonly found in humid temperate climate regions [3, 4].

Wetlands

Wetlands are complex ecosystems characterized by flooding or saturation of the soil, which creates low-oxygen environments. They are usually classified by soil and plant type. They exist in all climates from temperate to arctic. The soil is either organic or mineral soils. Organic wetland soils, such as peatland soils, contain at least 12 % organic matter and are typically acidic and possess a high water-holding capacity and low nutrient availability. Mineral wetland soils have less than 12 % organic matter, and they often exhibit gleying, where ferric iron (Fe^{3+}) and manganese are reduced in the soil by anaerobic bacteria that thrive in oxygen depleted conditions [5]. Fish, amphibians, reptiles, birds, and mammals can be found in wetlands [6]. Different types of wetlands include bogs, marshes, and swamps.

- **Bogs** are characterized by wet, spongy, poorly drained peaty soil which is moderately acidic to highly acidic. Bogs are categorized into typical bogs, fens, and tropical bogs. Typical bogs are dominated by mosses and heath trees. Fens are dominated by grass-like plants, grasses, sedges, and reeds. Finally, tropical bogs have soils where the peat is formed entirely by tree remains.
- **Marshes** are characterized by poorly drained mineral soils and by plant life dominated by grasses as well as grass-like sedges, reeds, and wild rice.
- **Swamps** are characterized by mineral soils with poor drainage and by plant life dominated by trees such as red maple, white cedar, cypress, mangroves, and tupelo trees.

Shrub Land

Shrub lands, also known as scrublands, are dominated by woody plants shorter than 5 meters in height if it has a single main stem, or 8 meters if it is multi-stemmed. Many shrubs in all regions are thorny with foliage that lacks nutritive value and contains off-putting substances that discourage browsing. Shrub lands appear in warm temperate climates, with mild, wet winters and long, dry summers. Mainly between 20° and 40° latitude in both hemispheres. Common plants are heath, bean, and daisy shrubs as well as sedges, lilies, irises, grasses, and orchids. These landscapes commonly have high plant diversity. For example, there are 8,500 species in Cape flora, a shrub land region in South Africa. The soil is nutrient poor and the animals common there are butterflies, nectar eating birds, and small mammals [7].

Grassland

These areas are dominated by a nearly continuous cover of grasses. Other plants that occur there are sedges, rushes, clovers, and herbs. Grasslands can be found in tropical, temperate, desert, and tundra climates. The soil has low fertility and nutrient levels. They are inhabited by large mammals (jaguar, rhino, elephant, bison, etc.), small mammals (prairie dogs, rodents, etc.), insects, reptiles, and birds. Meadows, steppes, and savannas are considered grasslands [8, 9].

- **Meadows** are an open habitat, or field, vegetated by grass, herbs and other non-woody plants. They are subject to harsh climate conditions and low soil fertility. Meadows are inhabited by large grazing mammals and pollinating insects.
- **Steppes** are characterized by grassland plains without trees apart from those near rivers and lakes. They exist in both hot and cold semi-arid climates. Steppes have chernozem soil which is a black-colored very fertile soil with high percentage of humus, phosphoric acids, phosphorus, and ammonia. These habitats are home to rodents, antelopes, foxes, horses, bison, elk, and deer.
- **Savannahs** are characterized by an open tree canopy (i.e., scattered trees, typically deciduous) above a continuous tall grass understory. They are found in hot, seasonally dry climates. The soil is sandy or stony with low fertility. Common animals are large grazing mammals, grasshoppers, caterpillars, and termites.

Bare Land

Bare lands are areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover [10]. Bare lands are found in arid, semi-arid, polar and tundra climates. They can also be found in milder, temperate, and/or humid climates. The vegetation is typically made up of scarce scrubby plants and lichens. The soil is made up of rock, sand, and/or clay and is toxic or infertile. Bare lands are home to small mammals (woodrat, beach mice), amphibians, birds (swallows, sparrows, vultures), reptiles, and arthropods (insects and arachnids) [11].

S.2. Habitat Comparisons

To compare the various habitats, we arranged characteristics of each habitat into Venn diagrams. Figure S1 is a comparison of deciduous forests, coniferous forests (evergreen), and wetlands. Figure S2 compares shrub lands, grasslands, and bare lands. Plants and animals were common across all six habitats. There was no single plant or animal species that can be found in every habitat, though. This is what lead to the selection of the biodiversity approach.

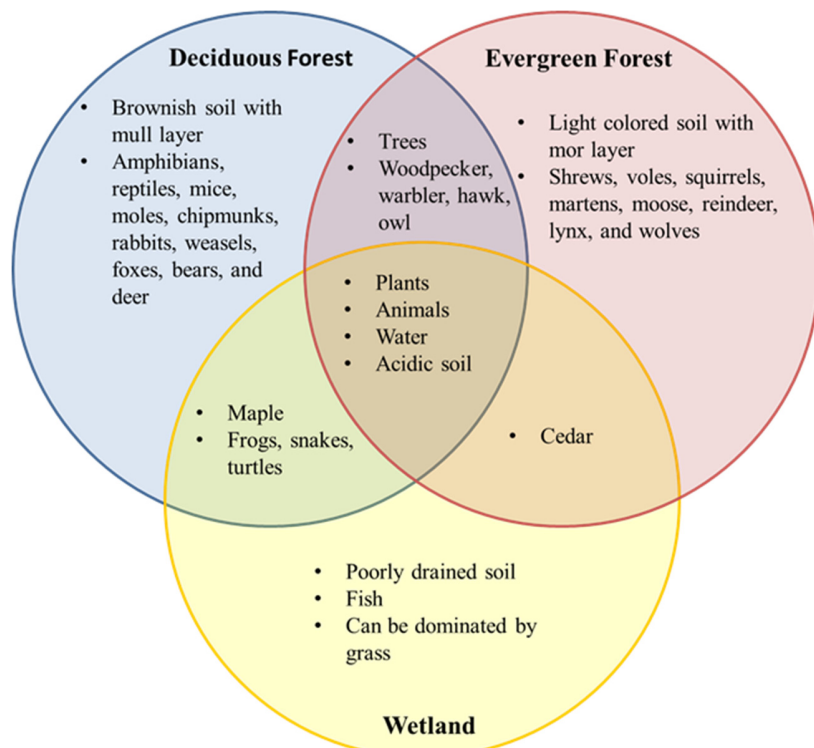


Figure S1. Venn diagram that compares deciduous forest, evergreen forest, and wetland habitats

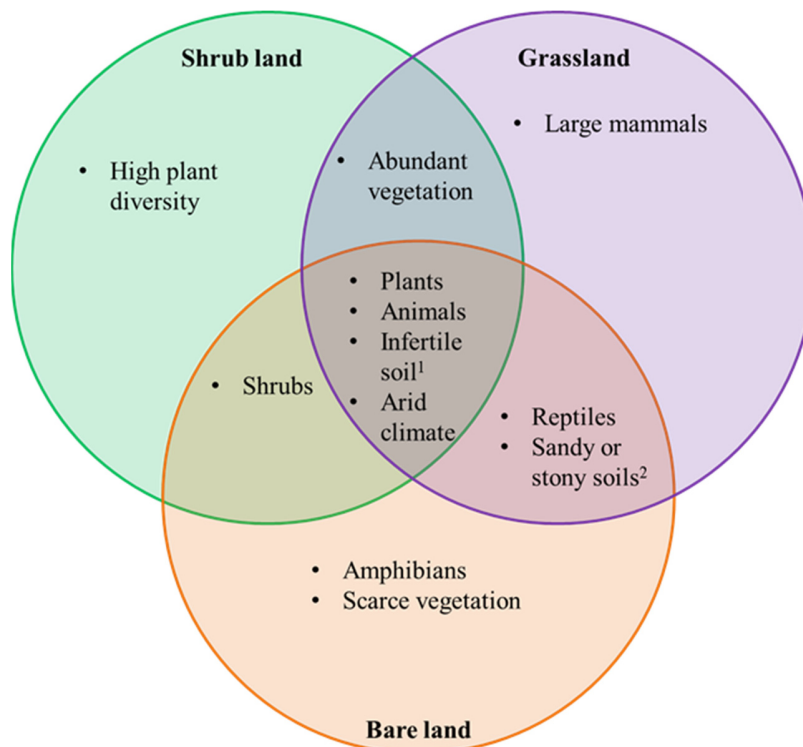


Figure S2. Venn diagram that compares shrub land, grassland, and bare land habitats. ¹Steppe grasslands have very fertile soils. ²Savannah grasslands have sandy/stony soil

Table S1 lists the potential habitat conditions (climate and soil) and biotic components (plants and animals). Habitats that potentially display each condition and component are listed as superscripts. It is important to note that structural components such as topography, amount of water, and tree height are not present in the table. This is because these characteristics vary among individual habitats. Topography and water bodies are more so based on geography rather than habitat and tree height only applies to wooded landscapes.

Table S1. Potential Habitat Conditions and Components: A – all; B – bare land; D – deciduous forests; E – evergreen forests; G – grassland; S – shrub lands; W - wetlands

Climate	Soil Conditions	Plants	Animals
Wet ^{B,D,E,W}	Wet ^W	Moss ^{B,E}	Fish ^W
Dry ^{B,D,G,S}	Dry ^B	Grass ^{G,S,W}	Amphibians ^{B,D,W}
Tropical ^{G,W}	Organic ^{D,E,W}	Herbs ^{G,D,W}	Reptiles ^{B,D,G,W}
Sub-tropical ^{G,W}	Mineral ^{B,D,E,W}	Shrubs ^{B,D,E,S}	Birds ^A
Temperate ^A	High Nutrients ^{D,E}	Deciduous Trees ^{D,G,W}	Small Mammals ^A
Tundra ^{B,E,G,S,W}	Low Nutrients ^{B,G,S,W}	Coniferous Trees ^{E,W}	Large Mammals ^{D,E,G}
	Acidic ^{D,E,W}		Arthropods ^A

Figure S3 displays a comparison of the average total species richness values for each habitat. Species richness was related to LULC class. The values of grid cells in the Choctawhatchee Watershed, Southeastern Plains ecoregion, Eastern Temperate Forest ecoregion, and the entire contiguous USA were averaged. The Choctawhatchee River Watershed had higher values than at broader levels (Level III ecoregion, Level I ecoregion, and national level). This can be due to (1) the watershed was more diverse than average or (2) there was a smaller sample size which resulted in higher average values.

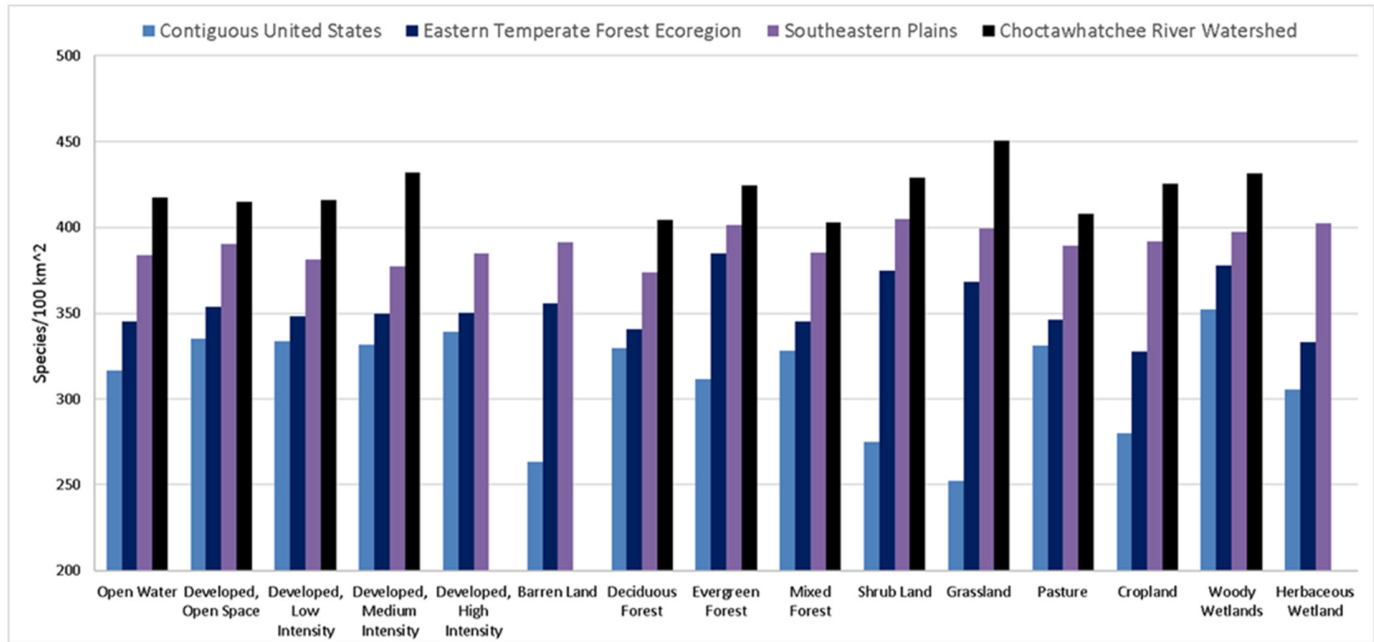


Figure S3. Average terrestrial species richness for each LULC class.

S.3 Other HS Methods Found in Literature

The U.S. Fish and Wildlife Service’s Habitat Evaluation Procedures Handbook describes the process of calculating a habitat suitability index (HSI) in general. The HSI index value is the ratio of the study area’s habitat conditions divided by the optimum habitat conditions, yielding a value between 0 and 1 (Eq. 1). A value of 0 means the habitat is completely unsuitable and a value of 1 represents optimum conditions. The handbook also provides index calculation methods based on outputs from existing models as seen in Eq. 2. A model’s output can be converted to HSI by dividing the model output by an established standard of comparison. This standard of comparison can be an assigned numerical value that corresponds with qualitative rankings (excellent=4, average=2, etc.). The standard can also be the maximum regional value for models that use defined units (productivity, population density, etc.) or the maximum rank for models that classify habitats hierarchically [12]. The denominators in all these methods are related to the optimum habitat conditions. Factors affecting optimum habitat conditions can be biotic or abiotic.

$$HSI = \frac{\text{Study Area Habitat Conditions}}{\text{Optimum Habitat Conditions}} \quad (1)$$

$$HSI = \frac{\text{Existing Model Output for Area of Interest}}{\text{Defined Standard of Comparison}} \quad (2)$$

S.3.1 Species-focused Approach to Estimating HS

One approach to habitat suitability modeling is to estimate suitability based on individual species or species group. Estimates are based on niche characteristics, niche interactions, multi-species studies, and/or niche evolution. Niche characteristic models focus on environmental variable selection, species fitness, and interactions between variables. Niche interaction models relate biotic interactions such as competition, predation, parasitism, and mutualism to species fitness and behavior. Multi-species studies are of global characteristics and spatial patterns of species over large areas like biodiversity or species abundance. Finally, niche evolution models are used to study how species maintain their role when separated geographically for long periods of time [13].

Optimum habitat conditions are also estimated for specific species. The factors that determine the optimum conditions differ depending on species. For example, the woodland species *Gagea spathacea* requires a specific soil moisture content, percentage of available light, water pH, percent carbon concentration, percent nitrogen concentration, and cation exchange capacity [14]. Table S2 lists the optimum habitat conditions for cattle, a type of wetland reed, and a type of sea cucumber. It is evident when looking at the factors that determine optimum conditions for each species that conditions that are ideal for one species are not necessarily ideal for others.

Table S2. Optimum habitat conditions

Species	Optimum conditions	Reference
Livestock/Cattle	<u>Abiotic</u> Water: Areas within 1.6-3.2 km of water in gentle terrain; Areas within 200 m of water for rough terrain Slope: <20% Thermoregulation: Need shaded areas for sunny days, Sandy soils to dissipate heat. <u>Biotic</u> Forage Quantity and Quality: Pastures with standing crops of 382 to 720 kg*ha ⁻¹ . Standing nitrogen of 5 to 16.5 kg N*ha ⁻¹ . Riparian and meadows provide 1.5-6 times more forage than uplands. Heterogeneity of Forage: Variety allows cows to be selective but can reduce the uniformity of grazing.	[15]
Germination of Phragmites australis in coastal wetlands	Salinity: <2.5% Water depth: 0 – 5 cm O2 concentration: 2.5%	[16]

	Temperature: 10 - 25 C	
Sea cucumber <i>Stichopus japonicus</i>	Temperature (C): 6 – 17 Salinity (psu): 33.2 - 34.3 Dissolved oxygen (mg/L): >5.0 pH: 8.3 - 8.8 Water depth (m): 3.8 – 10 Water flow velocity (m/s): 0.2 - 0.4 Bottom composition: Rocks, boulder stone, sands, and retiring place and rich source of food	[17]

S.3.2 Habitat-focused Approach to Estimating HS

Another approach is to estimate HS for specific habitats. For instance, a Forest Productivity Index (FPI) can be used to estimate the suitability of a forest habitat. The idea is that the productivity of a forest, or the potential revenue that can be gained by a forest, is indicative of a forest's ability to support life [18]. In other words, FPI is an index that evaluates how much timber a forest can produce. If a forest can support more trees, there will be more timber that can be gained from that forest. Another index to estimate HS is the Floristic Quality Index (FQI). Various versions of the FQI have been used to assess the condition of vegetation across ecosystems. Modified FQI equations take both endemic and invasive species into account. These equations relate the percent cover of a species at a specific time and the coefficient of conservation for that species to the floristic quality of an ecosystem. The equation is expressed as:

$$FQI_{mod\ t} = \left(\frac{\sum(COVER_{it} \times CC_i)}{100} \right) \times 10 \quad (3)$$

Where $COVER_{it}$ is the percent cover of species i at time t and CC_i is the Coefficient of Conservation for species i . If the total number of species within an area at a given time exceeds 100, you would use the total species cover as the denominator as shown in the following equation:

$$FQI_{mod\ t} = \left(\frac{\sum(COVER_{it} \times CC_i)}{\sum Total\ COVER_t} \right) \times 10 \quad (4)$$

The FQI is used to measure wetland ecological condition by providing a quick assessment that is standardized, repeatable, and useable for different vegetation and community types [19, 20].

A similar method for grassland landscapes is Grassland Quality evaluation. This measure is based on floristic analysis for individual dominant species groups. These species groups include grasses, sedges and rushes, legumes, mosses, etc. This is represented by the following equation:

$$E_{GQ} = \frac{\sum(D, FV)}{8} \quad (5)$$

Where E_{GQ} is the evaluation of grassland quality, D is the predominance of a species in %, and FV is the forage value of that species. FV ranges from -4 for toxic species to 8 for valuable species. The denominator is the maximum FV [21].

S.4 Other Biodiversity Indicators for Estimating HS for Conservation

To determine an indicator that could be used to model suitability across all landscapes, the characteristics of each landscape were studied. This included the biotic and abiotic components of deciduous forests [1], evergreen forests [2], mixed forests [3, 4], wetlands [5, 6], shrub lands [7], grasslands [8, 9], and bare lands [10, 11]. These seven natural habitats were compared based on climate, soil characteristics, plant life, and wildlife. In failing to find a specific characteristic or component to use as a general indicator for suitability, it was decided to use biodiversity as an indicator. This was because the only thing these habitats had in common was the presence of living things. An in-depth comparison can be found in the Supplementary Information.

Polasky et al. 2011 estimated habitat suitability for general terrestrial biodiversity by assigning HS values for each LULC based on each species group. The values seemed to be values estimated based on what was known about each species' requirements due to the HS values being multiples of 5 (0.2, 0.35, 0.5, etc). However, a score of zero was given to landscapes such as bare land even though species could be found living there.

Each of the equations listed in Table S3 relates biodiversity to species richness, which is symbolized by the variable S , the number of species. The number of species affected the biodiversity index value differently depending on the chosen equation. The number of species had a linear relationship with the index in Margalef's and Menhinick's Diversity Indices when absolute values were used, which changed when density values were used. One study found there was an almost perfect linear relationship between the Margalef index and species richness with the exception of species richness between 20 and 40 [22].

Margalef's and Menhinick's indices were both limited to sampling effort as they were based on what was observed. Instead of the basic biodiversity index formula, $D=S/N$, Margalef and Menhinick used the natural log of N and the square root of N , respectively. This was an attempt to correct for sampling size. The Brillouin and Shannon-Wiener indices were usually used to measure the uncertainty of information found in a code or message. The Brillouin index was used when randomness cannot be guaranteed. An example of this was when a specific species was being sampled more than others in the region. The Shannon-Wiener index assumed species were being randomly sampled. Hurlbert's index measured the probability of inter-specific encounters (PIE) and incorporated both species richness and evenness components [23].

Table S3. Biodiversity Index Equations

Index	Equation	Description	Reference
Margalef's Index	$d = \frac{S - 1}{\ln N}$	S - number of species N - number of individuals	[24]
Brillouin Index	$H = \frac{1}{N} [\ln(N!) - \sum_{i=1}^S \ln n_i!]$	n_i – number of i^{th} species N – total population S - number of species	[25]
Menhinick's Index	$d = \frac{S}{\sqrt{N}}$	S - number of species N - number of individuals	[26]
Shannon-Wiener Index (H') and Hurlbert Encounter Index (PIE)	$H'_n = - \sum_{i=1}^s \frac{n_i}{n} \ln \frac{n_i}{n}$ $H'_\omega = - \sum_{i=1}^s \frac{b_i}{b} \ln \frac{b_i}{b}$ $\text{PIE} = \frac{n}{n-1} [1 - \sum_{i=1}^s (\frac{n_i}{n})^2]$	n_i – number of i^{th} species b_i – biomass of i^{th} species n – total population of all species b – total biomass s – total number of species	[27]
Species Diversity Index /Shannon-Wiener Index	$H = - \sum_{i=1}^S P_i \ln P_i$ $P_i = \frac{n_i}{N}$	P_i – proportion of individuals belonging to i^{th} species n_i – number of i^{th} species N – total population S – number of species	[28]

A Venn diagram comparing the Shannon-Wiener, Brillouin, and Hurlbert Encounter Index equations is shown in Figure S4. The equations, explanation of variables, and scenario where each equation is appropriate is listed. One thing the three equations had in common was that they incorporated both species richness and evenness. Species richness is symbolized by the variable S in the equations. Evenness describes how evenly the species are distributed in an area.

This is represented by the probability to encounter each species, or the number of a specific species divided by the total population (n_i/n). The Brillouin Diversity Index uses $n!$ to model evenness as it assumes the factorial is the number of equivalent distinct permutations [25, 27].

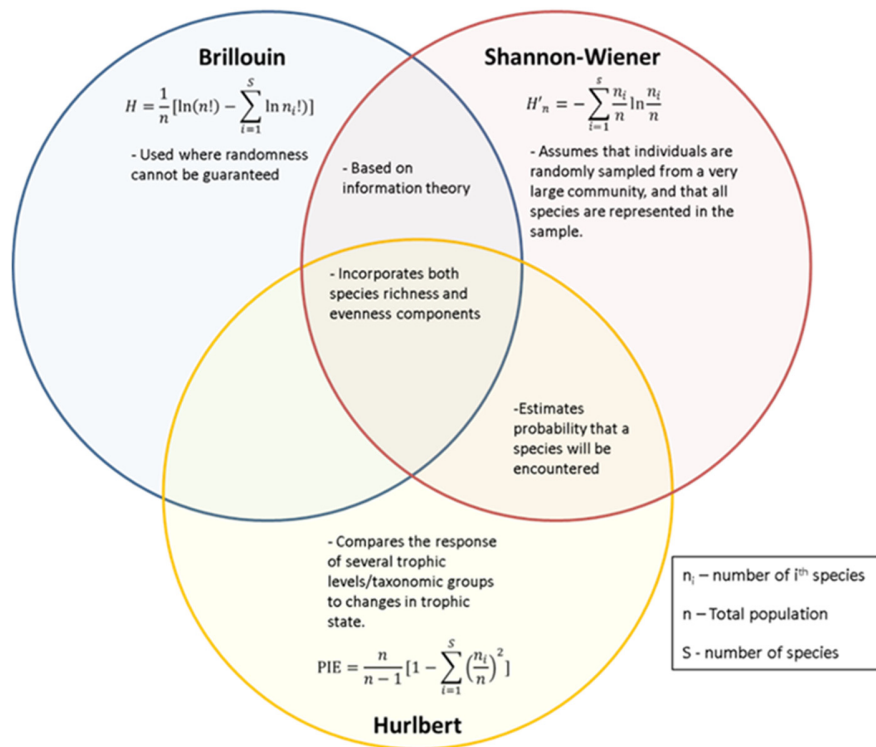


Figure S4. A Venn diagram that compares the Brillouin, Shannon-Wiener, and Hurlbert biodiversity index equations.

The equations used to estimate biodiversity all have similarities and differences. The models are all sensitive to observations. The measures that must be known to use any of the equations are the total population and number of species. The total population is not a value that can be easily found so an alternative method must be formulated. Species richness, which is the number of species per given area, is a simple estimation of biodiversity as biodiversity increases when species richness increases. Richness was used to estimate biodiversity for this reason. Habitat suitability was then calculated as an index of richness. The species richness spatial dataset defines priority areas and estimates both total and endemic species richness for vertebrate and tree species [29, 30]. The difficulty with using this data was that the estimations were for 100 square kilometer grids which were much larger than the 900 square meter grids used in the National Land Cover Database [31]. Before relating species richness to landscape type, the land cover data needed to be resampled so that the grid cell size matched the richness data. The majority land use within each 100 km² area became the land use of the resampled grid. This could possibly result in some inaccuracies. For instance, if a third of a 100 km² area was made up of forest grid cells, but most of the area was made up of agriculture cells then the resampled grid cell was visualized as an agriculture grid. The corresponding species richness grid cell value

was attributed to agriculture land use even though it was unknown how much of the richness was due to the forested area. The assumption was then made that the species within each grid was evenly distributed.

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