A Review of Functional Diversity Metrics focussing on Plants in Agroecosystems and given constraints on Cost, Technology and Time

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Abstract

Diversity is often used to refer to the variety of species in an ecosystem. Recently, a new concept of diversity has emerged known as “functional diversity” (FD) – the range, kind, and relative abundance of functional traits in an ecosystem. FD has a greater effect on ecosystem functioning - productivity, stability, and resource dynamics - than species diversity. The diversity of traits expressed within plant communities can be used to predict ecosystem functioning. Plants with similar traits have a similar effect on functioning and can be grouped together into plant functional types (PFT). Agricultural landscapes are generally dominated by industrialized management techniques (i.e., heavy machinery use, reliance on chemicals, and monocultures), resulting in few PFTs, low FD, and detrimental environmental impacts. Increasing FD by including more PFTs in agroecosystems would increase ecosystem services, allowing for the sustainable management of resources (e.g., soil, water, nutrients, crops). There are many ways to calculate plant FD within agroecosystems; this paper will discuss the relevant sampling and statistical techniques. Assessing measures of FD overtime and between management types will be vital to understanding the effect of diversification on ecosystem services in agroecosystems.

Introduction

In recent years, global losses to biodiversity have become a serious concern. Industrialized agriculture is one facet of modern society which has contributed to this loss (Dudley & Alexander, 2017). Future costs to the environment can be prevented by protecting biodiversity in agroecosystems through the employment of regenerative and restorative farming practices (i.e., farming practices which better emulate natural ecosystems). This being said, how can one be certain that a specific farming practice adequately protects biodiversity? In other words, how can biodiversity be quantified to determine the impacts of a farming practice? To date, there is no standardized way to measure biodiversity in agroecosystems. This is because it is difficult to account for the many different ecosystem types across supply chains whilst conforming to practical limitations including time constrains, cost, and plant identification capacity. The following paper will review methods for measuring biodiversity, in specific functional diversity (FD), and explore whether a metric exists which is both practically and scientifically viable. If a metric exists, this could have large implications for the successful management of agroecosystems which benefit rather than detract from the environment.

Functional Diversity

What is Functional Diversity?

Diversity refers to a variety of things; in an ecological context, the term biodiversity is often used to refer to the variety of species in an ecosystem. Recently, however, a new concept of biodiversity has emerged known as “functional diversity” (FD) (Laureto et al., 2015). FD refers to the variety (i.e., range, kind, and relative abundance) of functional traits (see section below) in an ecosystem (Díaz, Lavorel, Chapin III, et al., 2007; Goswami et al., 2017). It is important to note that the term “function” does not imply an intended purpose, but merely refers to processes undergone within ecosystems (e.g., the acquisition of resources) (Tilman, 2001). FD has become a popular method of representing biodiversity as it has a greater effect on ecosystem functioning than species diversity (Cadotte et al., 2011; Lanta & Lepš, 2006; Tilman et al., 1997). FD represents the interspecific and intraspecific phenotypic variation which occurs as a result of varying genotypes and environmental conditions (Tilman, 2001). In this way, the information which FD contains is richer than that of species diversity which only encapsulates species variation.

When using the term “FD”, semantic confusions arise because of its multiple meanings (Pavoine & Bonsall, 2011). For instance, FD can refer to functional richness (the number of functional traits/groups), functional evenness (how similarly abundant functional traits/groups are), and functional divergence (the degree of distribution of functional traits/groups) (Mason et al., 2005; Pavoine & Bonsall, 2011). Thus, one must be specific when using the term.

Why Measure Functional Diversity?

i. Ecosystem Functioning

FD both affects and is affected by the environment (Díaz, Lavorel, Chapin III, et al., 2007). As mentioned earlier, FD has a greater effect on ecosystem functioning than species diversity (Cadotte et al., 2011; Huang et al., 2019; Lanta & Lepš, 2006; Tilman et al., 1997). Although not empirically proven, a logical reason for this could be functional redundancy (i.e., when species have a similar function and, thus, a repetitive influence on an ecosystem) (Rosenfield, 2002). A greater number of ecosystem functions might be expected given high species diversity, but if there is high functional redundancy then this assumption would be flawed. Thus, a certain level of uncertainty would exist when predicting ecosystem functioning based on species diversity.

FD, on the other hand, is directly correlated with trait variety. Since organisms interact with the environment through the traits they display, it makes sense that it is a greater predictor of ecosystem functioning.

Each component of FD, including kind, range, and relative abundance of traits, has been shown to affect ecosystem functioning (Díaz, Lavorel, Chapin III, et al., 2007). FD affects many different ecosystem functions, including productivity, stability, and resource dynamics (Tilman, 2001). Specifically, increased FD has been shown to increase primary productivity, stability, and access to resources as a result of niche partitioning and resource complementarity (Cadotte et al., 2011; Gorczynski et al., 2021; Hallett et al., 2017; Hao et al., 2020; Hooper et al., 2005; Hooper & Vitousek, 1997; Lanta & Lepš, 2006; Tilman, 2001; Vallina et al., 2017).

With Earth undergoing major changes as a result of human induced climate change and land alteration associated with industrialized agriculture and urbanization, ecosystems are increasingly threatened (Bellard et al., 2012; Dudley & Alexander, 2017; Kondratyeva et al., 2020). This makes understanding ecosystem functioning and measuring FD a priority, especially in agroecosystems where human impacts have been profound (Dudley & Alexander, 2017).

ii. Ecosystem Services

Ecosystem services are defined as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005). Given that FD influences ecosystem functioning, it also affects ecosystem services (Cadotte et al., 2011; Díaz, Lavorel, De Bello, et al., 2007; Lavorel, 2013). If an ecosystem has a greater level of FD, there would be more opportunity for that ecosystem to provide ecosystem services.

Some common ecosystem services provided by plants include carbon sequestration, water/air purification and erosion reduction (Jose, 2009; Kurtz et al., 1991). These ecosystem services have a direct benefit to humans, but indirect services can exist when humans intend for an ecosystem to accomplish a purpose. For instance, in agricultural systems which have the purpose of supporting a large, high quality crop yield overtime, ecosystem services would also include ecosystem functions which enrich and stabilize the growing environment. For instance, trees act as windbreaks (Osorio et al., 2019) which can reduce soil erosion and protect top soil. This is something which may not directly benefit people, but in instances where it improves crop yield as was described by Osorio et al. (2019), it could be considered an ecosystem service.

Ultimately, an organism's traits determine its effect on ecosystem functioning and the services that it provides. Plant functional traits can be used in agroecosystems to assess ecosystem services for crop management (Faucon et al., 2017) and environmental benefits (Jose, 2009). Ecosystem services can be targeted by measuring FD and promoting certain traits/functions (see Cresswell et al., 2018 for an example of targeting plant characteristics to increase pollinator benefits).

Lastly, although the term "ecosystem services" is used, it is important to remember that ecosystems do not serve people (Comberti et al., 2015). Ecosystem services demonstrate that the ecosystems we are part of influence us, but the reverse, that we influence them, is also true. (Comberti et al., 2015). To protect the benefits we receive from ecosystems, we must protect ecosystems themselves and maintain their FD.

Functional Traits

As Díaz et al. (2013) states, functional traits are "morphological, biochemical, physiological, structural, phenological, or behavioural characteristics that are expressed in phenotypes of individual organisms and considered relevant to… their effects on ecosystem properties". In other words, they are chemical and physical characteristics of plants (i.e., leaves, roots, tissues, etc.) which affect ecosystem functioning (Laureto et al., 2015) (see figure 1). The relationship between functional traits and ecosystem functioning can be convoluted because multiple traits can be involved in determining an ecosystem function or single traits can affect multiple functions (Hanisch et al., 2020). Other complications involve species interactions and keystone species (Díaz, Lavorel, Chapin III, et al., 2007; Hooper et al., 2005). The effects which the traits of keystone species have on ecosystem functioning can be undervalued (Díaz, Lavorel, Chapin III, et al., 2007).

FD is determined by the range, kind, and relative abundance of functional traits present (Díaz, Lavorel, Chapin III, et al., 2007). Consequently, the traits in an ecosystem can be used to measure FD as well as predict ecosystem functioning and services (Díaz, Lavorel, Chapin III, et al., 2007). For instance, it has been found that SLA is positively correlated with soil water content (De La Riva et al., 2016; Poorter et al., 2009). Higher values of SLA could indicate that an ecosystem has greater water availability (De La Riva et al., 2016; Poorter et al., 2009). Depending on what ecological functions/services are selected as points of interest, one can decide upon the specific traits to measure (Laureto et al., 2015; Nock et al., 2016). Multiple reviews now exist of the many plant functional traits that can be measured (Cornelissen et al., 2003; Pérez-Harguindeguy et al., 2013; Weiher et al., 1999). That being said, there are several key plant traits which have been shown to have strong predictive capacity for ecosystem functioning and have been termed "functional markers" (Garnier et al., 2004). These traits include specific leaf area (SLA), leaf dry matter content (LDMC), and leaf nitrogen content (LNC) (Díaz et al., 2016; Garnier et al., 2004; Westoby et al., 2004).

Once it is decided what functional traits to measure, they can be used to calculate FD. For instance, one could use the range of SLA values to calculate functional divergence. Issues for calculating FD with plant functional traits include the difficulty in selecting traits (Laureto et al., 2015) and the labour intensity of measuring traits (Lavorel et al., 2007). To avoid measuring traits, databases are sometimes employed (Lavorel et al., 2007). Plants are classified to species level and trait values are generated through databases (Lavorel et al., 2007). This requires accurate species level identification, complete databases, and fails to account for intraspecific variation (Lavorel et al., 2007; Májeková et al., 2016; Taugourdeau et al., 2014).

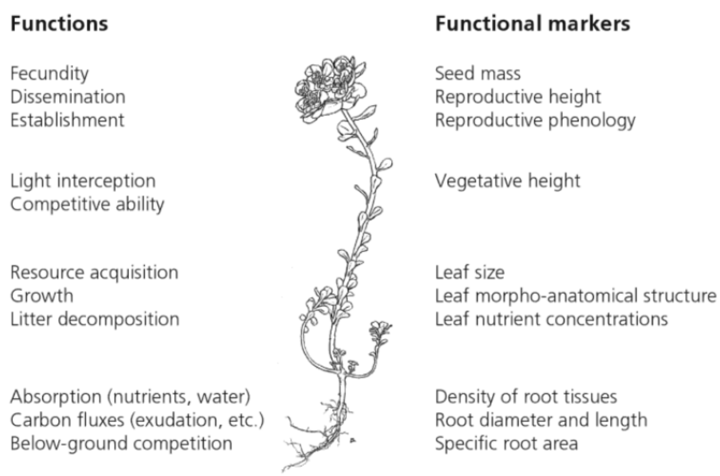

Figure 1 - Examples of ecosystem functions and corresponding functional traits (Garnier et al., 2016)

Functional Groups

Functional groups (also known as "functional types") can also be used to measure FD. Functional groups contain species with similar traits and, therefore, functions (Hooper et al., 2005). By calculating the abundance of species in various functional groups, inferences can be made about ecosystem functioning. For example, Diaz & Cabido (1997) used eight plant functional types (PFTs) in central-western Argentina to make accurate predictions about community structure.

Classifying species into functional groups does not require accurate species level identification. Thus, using them to calculate FD requires less labour than measuring functional traits of each plant. The difficulty arises in determining how groups are classified (e.g. what traits to consider when making groupings and how many groupings there are) (Tilman, 2001). As of yet there are no universal PFTs, despite being created at local levels, and abundant challenges exist for doing so (Díaz et al., 1999).

Methods

Sampling Techniques

To calculate plant FD, plants must be sampled. For practical reasons, not every plant at a site can be sampled. Thus, methods exist, including transects and quadrats, for demarcating subsections of sites to sample. It is assumed that the samples taken of subsections are representative of the entire site and appropriate sampling methods should be selected to satisfy this assumption. The following section will describe transects, quadrats, and quadrats along transects.

i. Transects

A transect is a line placed within a site along which samples are taken (Anderson et al., 1979) (see figure 2). Samples can be taken along the entire length of a transect or within specified intervals only. Sampled plants can consist of those which directly intersect the transect or can include plants contained within a set distance on either side of the transect (referred to as the "transect width") (Anderson et al., 1979; Grant et al., 2004) (see figure 2). The length and width of the transect depends on the site size, number of transects, and type/distribution of plants being sampled. For herbaceous communities transects less than 50m can be used, whereas transects greater than 50m are more suited for shrub/tree communities (Caratti, 2006). This will vary depending on the density of plants (Caratti, 2006).

Transects can be placed randomly or non-randomly – either originating from a random point and/or having a random direction or not – but should be distributed throughout a site (Anderson et al., 1979; US Forest Service, 2003). If an environmental gradient is present, it is recommended that the transects are placed to represent the entirety of the gradient - known as a gradsect - to maximize the number of plant species represented (Gillison & Brewer, 1985) (see figure 3). Additionally, in the presence of non-random features (e.g., a pollinator strip), transects would have to be placed non-randomly to represent plant communities both within and outside of this feature (see figure 3).

Once transects have been planned, the next step is to set them up in the field. This can be done by stretching a rope - knotted at the required distances if needed - or measuring tape between two pegs secured in the ground (figure 4).

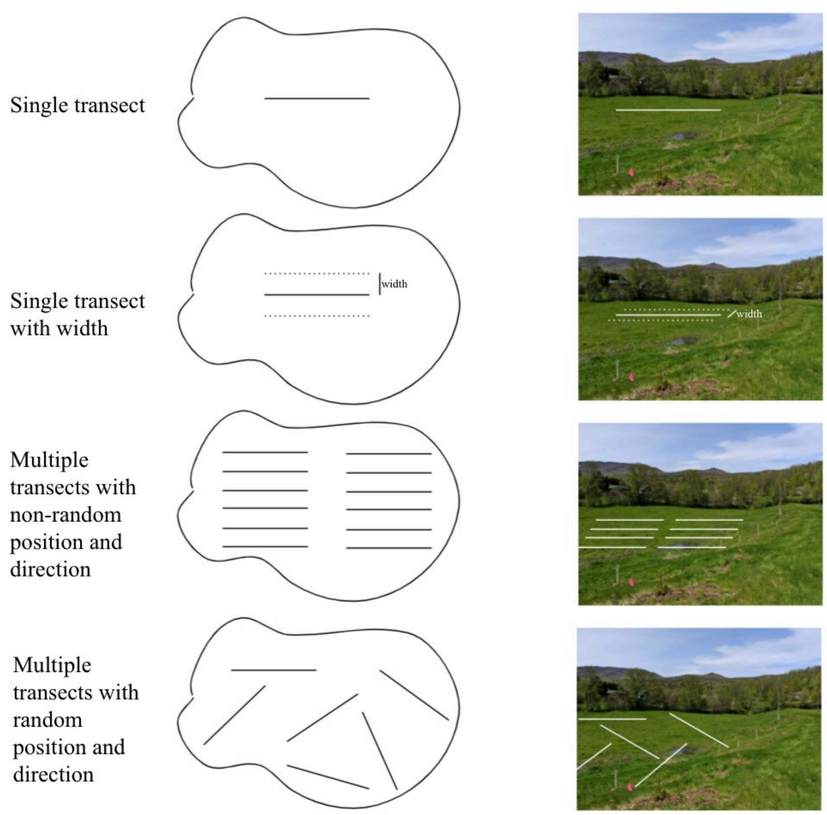

Figure 2 - Different arrangements of transects in an illustrated versus actual site

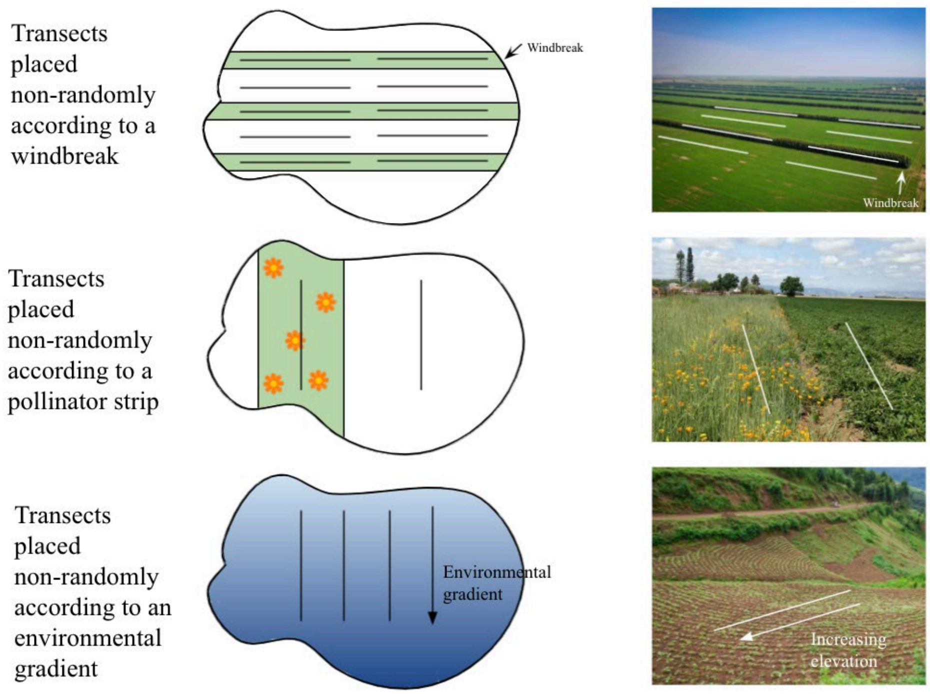

Figure 3 - Arrangement of transects given windbreaks, pollinator strips, or environmental gradients

Figure 4 - Transect set up on a farm

ii. Quadrats

Quadrats are plots within which samples are taken. Size and shape are the two main concerns when planning quadrats (Krebs, 2017). Firstly, size is dependent on the type of plants which are being sampled, the size of the study site, the amount of time available, and the distribution of plants (Goodall, 1952; Krebs, 2017). Often, the quadrat size will be determined based on the precedence set by previous studies (Krebs, 2017). For instance, 10m x 10m plots are typically used for trees and 1m x 1m plots are typically used for herbaceous species (Krebs, 2017). If time permits, more accurate statistical methods exist for determining the best quadrat size (see Krebs, 2017).

Another consideration is quadrat shape. The decision of whether to include a plant placed on the perimeter of the quadrat is subjective and introduces a degree of error; this is known as *edge effect* (Krebs, 2017). Depending on the shape of the quadrat chosen, the perimeter can be minimized whilst the area is maximized. Circles are best at minimizing edge effect followed by squares and rectangles. Since circle shaped quadrats may be more difficult to set up in the field, precise results must be balanced with practicality when deciding upon the optimal quadrat shape.

The placement of quadrats can be random or non-random (e.g. in a grid) (see figure 5). When using a grid arrangement, the number of plots within the grid that are sampled can also be selected randomly or non-randomly (see figure 5).

After planning quadrats, the next step is to set up in the field. Quadrats can be constructed beforehand using a wooden frame or other similar methods (see figure 6). Otherwise, quadrats can be marked on-site using rope/measuring tapes.

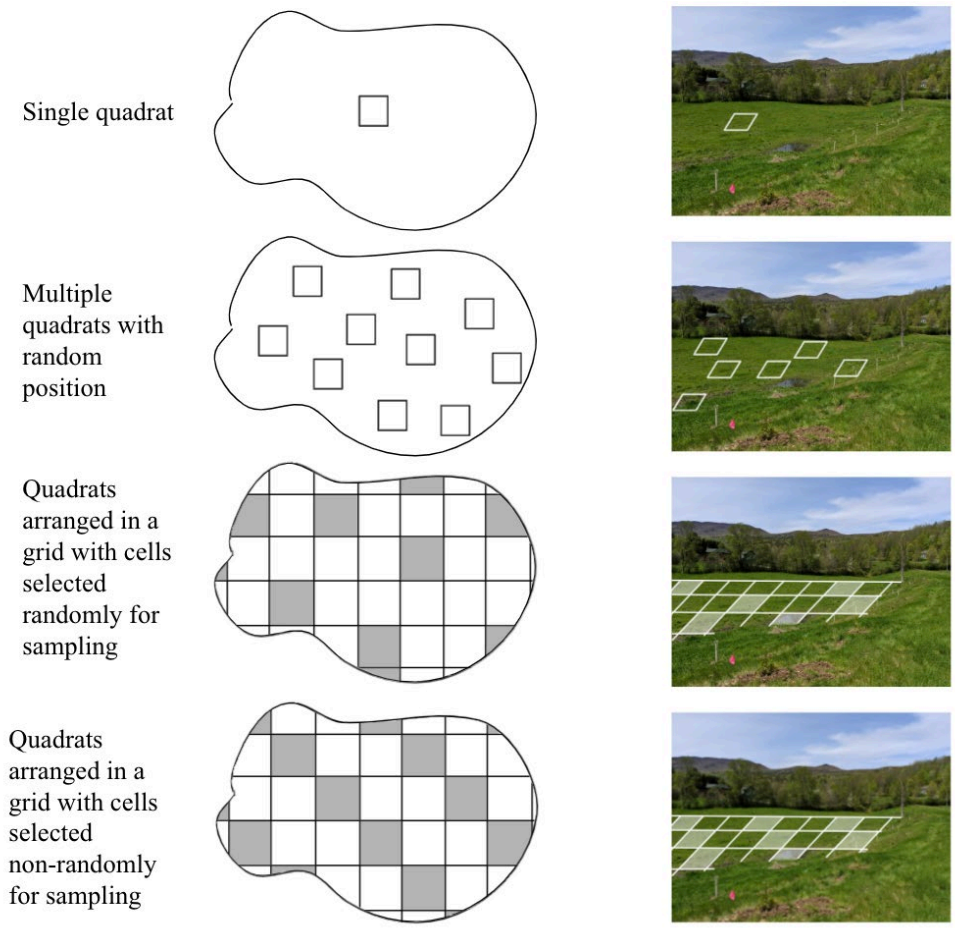

Figure 5 - Different Arrangements of Quadrats in an illustrated versus actual site

Figure 6 - Quadrat for measuring herbaceous species set up in a field

iii. Quadrats along a transect

Another effective way to place quadrats is along a transect (see figure 7). As mentioned before, all plants along a transect can be sampled or only those within specified sections.

Quadrats can be used to mark these sections. When placing quadrats along a transect, one must decide upon the distance between each quadrat or select points - either randomly or non-randomly - on which to place quadrats (see figure 7). All rules for planning transects listed above must be followed.

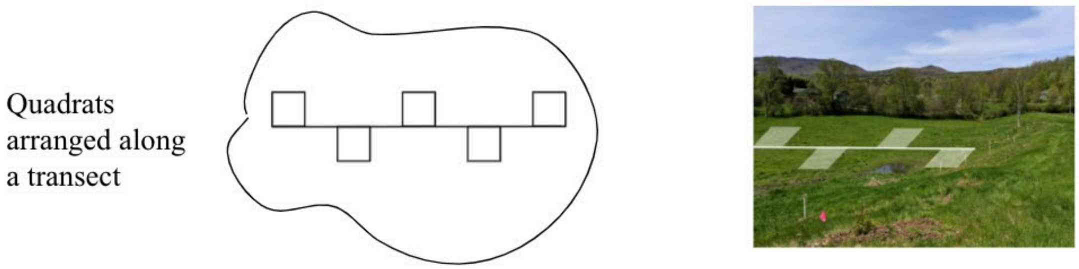

Figure 7 – Quadrats along a transect in an illustrated versus actual site

Plant Sampling Time and Identification

i. Sampling time

The growing seasons of different species will be different and samples are usually taken multiple times throughout the growing season when measuring FD. If the number of times which a site can be visited is limited, however, then the time to sample should be selected based on the types of species which will be focused upon. Sampling species during peak flowering/production or when other distinguishable traits are apparent allows for easier identification (Barnett et al., 2019). In the Northern hemisphere, peak flowering season occurs in mid-summer to early fall.

ii. Classifying Plants

Plants can either be classified on-site or off-site by using high quality photographs. Classifying plants on-site can be achieved through prior knowledge of the local ecology or plant identification books/websites. Classifying plants using photographs may not be as reliable, but easier with the use of plant identification apps (e.g. PlantNet or iNaturalist) (Jones, 2020). The advantage of calculating FD using functional groups is that plants do not have to be accurately identified to species level so long as they are classified in the correct group. If a plant species cannot be identified, it can be listed as "species *x*" and placed in the appropriate functional group after further analysis. Of course, being able to classify plants to their species level will give more information about the site and indicate the presence of keystone or rare species whose value may not be captured in FD metrics (Díaz, Lavorel, Chapin III, et al., 2007)

iv. Calculating Functional Group Cover

It is necessary to know the relative abundances of each functional group when calculating FD using functional groups. Relative abundances of functional groups can be represented by measuring plant species cover – what percentage of the area each plant species occupies – and adding the cover of plants within functional groups (Fehmi, 2009). This is easily done when using quadrats to sample. Species cover is often measured using visual estimates and ordinal scales to assign plants to a percentage range (Damgaard, 2014). One example of this is the Braun-Blanquet scale (Wikum & Shanholtzer, 1978) (see figure 7). The midpoint of the range can be used for calculations.

Braun-Blanquet scale	Range of cover (%)	Midpoint of cover range (%)
5	75–100	87.5
4	50–75	62.5
3	25–50	37.5
2	5–25	15.0
1	<5	2.5
+	<5	0.1

Figure 7 - The Braun-Blanquet Scale converted to percent cover ranges (Wikum & Shanholtzer, 1978)

The total species cover can exceed one hundred percent (Fehmi, 2009). This is because species cover estimates can be done at different heights in the same quadrat (see figure 8). The relative cover of each functional groups can be found by dividing the original cover value by the total cover.

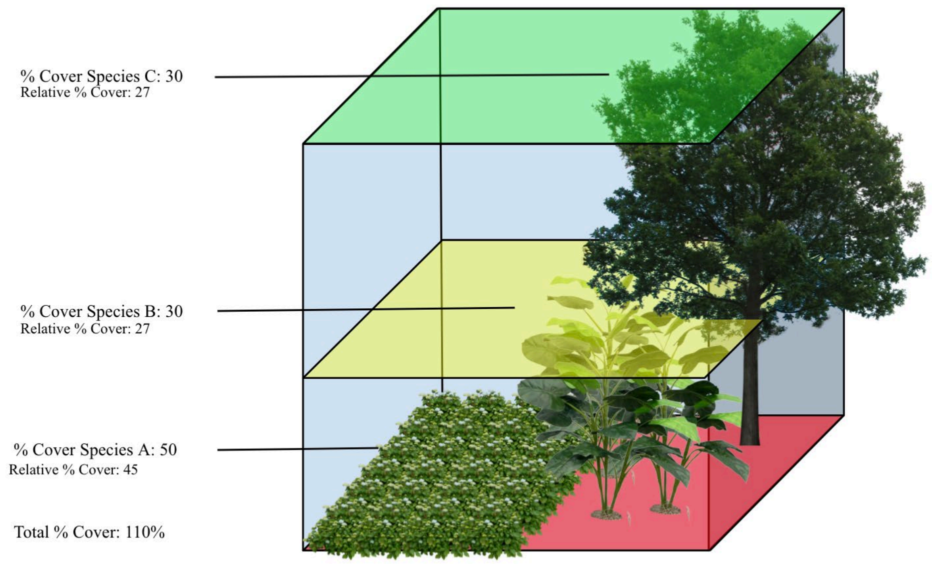

Figure 8 - Species of various heights allows for a total percent cover that exceeds one hundred percent

Analysis

Species Richness

Species richness – the number of species - is often measured as a byproduct when calculating FD. Although species richness has a weaker correlation with ecosystem functioning than FD, it can still provide useful information. For instance, species richness has been shown to increase ecosystem stability (Wilmers et al., 2002). This is also true within functional groups (Biggs et al., 2020; Naeem, 1998). With greater species richness within functional groups, it is more likely that functions will persist and ecosystems will remain stable even when species are lost. Thus, even when calculating FD, species richness can be a useful metric to consider. Additionally, if there is a large disparity between species and functional richness, this could indicate an inadequate number of functional groups.

Functional Group Richness

Functional group richness refers to the number of functional groups (Lanta & Lepš, 2006). The term functional group richness is distinct from 'functional richness' which sometimes refers to the number of functional groups, but other times to the amount of niche space occupied (this is related to the number/range of traits) (Schleuter et al., 2010). Greater species richness is likely to induce greater functional group richness (Schleuter et al., 2010). With a greater number of functional groups present, a greater number of ecosystem functions and services would be represented. Furthermore, increased functional group richness is associated with increased stability and productivity (Lanta & Lepš, 2006). Thus, assessing changes in functional group richness is useful. A difficulty in assessing functional group richness is that it is directly affected by the number of functional groups defined. Additionally, there is no objective standard for how to define functional groups and the number of traits which should be considered (Díaz et al., 1999). Even so, considering the change in functional group richness over time could give some indication of how ecosystem functioning might be affected (e.g., how many ecosystem functions are being provided in that ecosystem?).

Listed below is a table describing suggested standard PFTs which could be applied to any temperate ecosystem. These categories are based on Diaz & Cabido (1997) as well as traditional plant categories. Although general groupings, they could still be used for calculating FD and predicting ecosystem services. Depending on the site and the type of plants to be focused upon, these functional groupings can be refined as needed.

Table 1 - List of suggested plant functional types which could be applied to sites in temperate environments

Functional Groups	Ecosystem Service (focus on drought, pollinators, and nutrients)	Examples of plants (also add crops)
FT1 - Grasses, sedges, rushes	- Allows for herbivory (Briggs et al., 2008; Coughenour, 1985) - Provides habitats for arthropods, birds, and rodents (Kobal et al., 1998; Werling et al., 2014) - Potential to support pest predators and pest suppression (Nagy et al., 2020; Pfiffner & Luka, 2000) - Contains medicines (Kimmerer & Lake, 2001) - High soil organic matter (Conant et al., 2001) - Reduces erosion (Le Bissonnais et al., 2004) - Reduces runoff (Le Bissonnais et al., 2004)	- Big bluestem - Sweetgrass - Switchgrass - Hairy wood sedge
FT2 - Ferns and allies	- Low light plants (Gould et al., 2013), ideal for biomass production under shade - Palatable (Langhansova et al., 2021; Rowell et al., 1983) - Evidence that it improves the growth of trees (Gould et al., 2013) - Reduces erosion (Chau & Chu, 2017) - Reduces runoff (Chau & Chu, 2017)	- Royal fern - Lady fern - Marsh fern - Horsetail
FT3 – Legumes	- Increases nitrogen in soil	- Soybean - Clover - Alfalfa
FT4 – Crops	- Food for people/livestock	- Soybeans - Wheat - Corn - Coffee - Potatoes - Lettuce
FT5 - Other Herbaceous (Flowering) Plants	- Supports pollinators and other insects (Albrecht et al., 2020) - Highest species diversity - Some plants aid pest control (Albrecht et al., 2020) - Contributor to litter (Gilliam, 2007) - Allows for herbivory (Haukioja & Koricheva, 2000) - Quick decomposition in comparison to other functional groups (Rawlik et al., 2021)	- Golden rod - Aster - Jewel weed - Columbine - Boneset - Jack in the pulpit - Trillium
FT6 - Deciduous trees (>300cm)	- Litter input (Lousier & Parkinson, 1976) - Nutrient input to soil (Lousier & Parkinson, 1976)	- Red oak - Maple

	- Retains soil and stabilizes shallow (<50°) slopes (Lan et al., 2020; Schmaltz & Mergili, 2018) - Erosion and runoff reduction - Water purification - Reduces soil radiation exposure of understory plants - Allows for water redistribution (Bayala & Prieto, 2020) - Provides habitat for birds, rodents, and insects	- Black walnut - Birch - Sassafras - Horse chestnut - Pecan trees
FT7 - Coniferous trees (>300cm)	- Retains soil and stabilizes shallow (<50°) slopes (Lan et al., 2020; Schmaltz & Mergili, 2018) - Erosion and runoff reduction - Water purification - Reduces soil radiation exposure of understory plants - Aids the accumulation of carbon in soil (Lu et al., 2021) - Allows for water redistribution (Bayala & Prieto, 2020) - Food source for insects, rodents, and birds (Smith & Balda, 1979)	- Pine - Spruce - Cedar - Hemlock
FT8 - Shrubs (<300cm)	- Reduces soil radiation exposure of understory plants - Erosion and runoff reduction	- Barberry - Dogwood - Chokecherry - Serviceberry

Functional Group Approaches for FD Indexes

Though they may be useful for making general conclusions, both species richness and functional group richness have the disadvantage of not taking abundances into account. Consequently, many indices have been developed to measure FD and these have been compiled into lists in many reviews (see Casanoves et al., 2012; Lavorel et al., 2007; Pavoine & Bonsall, 2011; Schleuter et al., 2010). Many of these indices (e.g., Rao's Q, convex hull, etc.) rely on functional trait values (Botta-Dukát, 2005; Casanoves et al., 2012; Laliberte & Legendre, 2010). Given the time commitment required for ascertaining trait values, these indices may not be practical to implement. As such, indices which have been designed or adapted to use functional groups will be focused upon in this section. The following variables will remain consistent throughout this section: "i" refers to the PFT number, "S" refers to the total number of PFTs and

"a_i" refers to the relative abundance of each PFT (in decimal form as opposed to a percentage). See attached for spreadsheets to calculate FD using each of the indices below.

i. "Concord Method"

A website by the Concord Consortium describes how to calculate diversity (The Concord Consortium, 2010). This method can be adopted to calculate FD using functional groups. The equation is as follows:

$$diversity\ score = -2.303 \sum_{i=1}^{S} a_i log(a_i)$$

Using this equation, the diversity score will increase with functional group richness and a more even distribution of functional group abundances. That being said, the diversity score is more sensitive to changes in functional group richness than abundances.

It is important to note that the diversity score calculated using this method is not based on a scale and the only stipulation is that it is not below zero (The Concord Consortium, 2010). Thus, it is only useful to observe changes in the score overtime. For instance, if the score increases, then one can assume that there has been an increase in functional group richness or that the abundances are more evenly distributed.

ii. Shannon's Index

Shannon's index (H) is very similar to the Concord index and can also be adapted to calculate functional diversity using functional groups (Casanoves et al., 2012), as was done in a study on New World bat communities (Stevens et al., 2004). The equation is as follows:

$$H = -\sum_{i=1}^{S} a_i ln a_i$$

This score is also dependent on abundances and has no other stipulation other than not being less than zero. Biodiversity is considered higher with a higher score. Thus, this score is also only useful when making comparisons.

iii. Shannon's equitability or evenness

Shannon's index is used to calculate Shannon's equitability (E_H) which is a proxy for functional evenness (Casanoves et al., 2012). This refers to how evenly distributed the relative abundances of functional groups are. Shannon's equitability is scored on a scale of 0-1 with 1 representing complete evenness or equality in relative abundance distribution (Casanoves et al., 2012). The equation is as follows:

$$E_H = H/lnS$$

In this equation, "H" refers to the biodiversity score generated by Shannon's index (see above).

iv. Gini-Simpson index

The Gini-Simpson index (D) is another way to calculate FD (Izsák & Papp, 2000) which could use the relative abundances of functional groups. The Gini-Simpson index is based on a scale of 0-1 which represents the probability that two randomly selected entities are different. When applied to calculating FD with functional groups, this Gini-Simpson index represents the probability that two randomly selected organisms are of the same functional group. This probability will increase with functional group richness and equitability. The higher the probability, the greater the FD. The equation for the Gini-Simpson index is represented as the original Simpson equation (Simpson, 1949) subtracted from 1:

$$D = 1 - \sum_{i=1}^{S} a_i^2$$

Conclusion

The following points are the main conclusions of this review:

- FD (the kind, range, and relative abundance of traits and associated processes) is a better predictor of ecosystem functioning and services than species diversity.
- Plant FD can be measured using plant functional traits or PFTs. Using PFTs - groups of plants with similar traits and functioning - is a more practical way to measure plant FD. Eight broad PFTs are suggested in this review, but can be adapted depending on the site.
- Transects and quadrats or a combination can be used to decide upon subsections of a site to sample.
- Within quadrats, species cover estimates can be done visually using an ordinal scale. Relative PFT cover can be determined by summing the species cover within PFTs and dividing by the total species cover.
- Relative PFT cover can be used in various equations to calculate a plant FD score. Shannon's index is the only equation that has been applied in a study to determine FD using functional groups. The Gini-Simpson index and Shannon's equitability index are the only indexes which employ a scale.

In conclusion, a standard way to measure FD in agroecosystems is possible. PFT abundances can be determined using a combination of transects and quadrats and then applied in various biodiversity equations. Thus, biodiversity can be quantified and compared overtime. This being said, the scientific viability of these methods is uncertain. The eight broad PFTs suggested in this review have not been tested and it is not certain that they would show a relationship with ecosystem functioning (though similar PFTs have). To test whether these PFTs are scientifically viable, their abundances could be measured across environmental gradients and relationships could be identified. If PFT abundances show a relationship with environmental gradients, this would suggest that they can be used to predict ecosystem functioning.

It also uncertain whether the biodiversity indexes discussed in this review are scientifically viable given that none, other than Shannon's index, have been employed in a study using functional groups instead of species abundances. To determine the effectiveness of these equations at quantifying FD when using PFT abundances, they could be compared with other known, but more laborious, methods of measuring FD (e.g., measuring plant functional traits and using equations which use functional traits such as Rao's Q).

Ultimately, if the methods for measuring FD discussed in this paper are scientifically valid, this would allow for the evaluation of regenerative and restorative farming practices. For instance, a farming practice can be determined successful if it increases FD. Measures of FD will also provide information to refine farming practices. Information on what PFTs are present can inform future choices about farm management. Farming practices can be designed to target specific PFTs so that biodiversity is increased and specific ecosystem services are provided.

Additionally, the utilization of FD metrics forces one to consider the entirety of an agroecosystem. This prevents farming practices which focus on components of an agroecosystems in isolation. For instance, one might focus on planting trees to act as a greenhouse gas sink, but forget about the importance of having a diversity of trees to facilitate a variety of ecosystem services and interspecies interactions. By considering FD metrics, however, one would be reminded to plant a diverse array of trees. Thus, FD metrics which are responsive to all aspects of an ecosystem, encourage a holistic viewpoint which allows for the better emulation of the complex interactions present in natural ecosystems.

Being able to evaluate and refine farming practices while considering the entirety of an ecosystem would reduce the environmental impact of agroecosystems and aid in the move towards cleaner supply chains. In conclusion, different methods for measuring FD in agroecosystems are possible and could play a large role in informing future farm management and improving the environmental impact of agroecosystems.

References

Albrecht, M., Kleijn, D., Williams, N. M., Tschumi, M., Blaauw, B. R., Bommarco, R., Campbell, A. J., Dainese, M., Drummond, F. A., Entling, M. H., Ganser, D., Arjen de Groot, G., Goulson, D., Grab, H., Hamilton, H., Herzog, F., Isaacs, R., Jacot, K., Jeanneret, P., … Sutter, L. (2020). The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. *Ecology Letters*, *23*(10), 1488–1498. https://doi.org/10.1111/ele.13576

Anderson, D. R., Laake, J. L., Crain, B. R., & Burnham, K. P. (1979). Guidelines for Line Transect Sampling of Biological Populations. *The Journal of Wildlife Management*, *43*(1), 70. https://doi.org/10.2307/3800636

Barnett, D. T., Adler, P. B., Chemel, B. R., Duffy, P. A., Enquist, B. J., Grace, J. B., Harrison, S., Peet, R. K., Schimel, D. S., Stohlgren, T. J., & Vellend, M. (2019). The plant diversity sampling design for The National Ecological Observatory Network. *Ecosphere*, *10*(2). https://doi.org/10.1002/ecs2.2603

Bayala, J., & Prieto, I. (2020). Water acquisition, sharing and redistribution by roots: applications to agroforestry systems. *Plant and Soil*, *453*(1–2), 17–28. https://doi.org/10.1007/s11104-019-04173-z

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Biggs, C. R., Yeager, L. A., Bolser, D. G., Bonsell, C., Dichiera, A. M., Hou, Z., Keyser, S. R., Khursigara, A. J., Lu, K., Muth, A. F., Negrete, B., & Erisman, B. E. (2020). Does functional redundancy affect ecological stability and resilience? A review and meta-analysis. *Ecosphere*, *11*(7). https://doi.org/10.1002/ecs2.3184

Botta-Dukát, Z. (2005). Rao's quadratic entropy as a measure of functional diversity based on multiple traits. *Journal of Vegetation Science*, *16*(5), 533–540. https://doi.org/10.1016/S0002-9394(34)90317-2

Briggs, J. M., Knapp, A. K., & Collins, S. L. (2008). Steppes and Prairies. *Encyclopedia of Ecology, Five-Volume Set*, 3373–3382. https://doi.org/10.1016/B978-008045405-4.00359-1

Cadotte, M. W., Carscadden, K., & Mirotchnick, N. (2011). Beyond species: Functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology*, *48*(5), 1079–1087. https://doi.org/10.1111/j.1365-2664.2011.02048.x

Caratti, J. F. (2006). Line Intercept (LI) Sampling Method. In *IEEE Transactions on Signal Processing*. http://frames.nbii.gov/metadata/documents/FIREMON_Integrated_Sampling_Strategy.html

Casanoves, F., Alejandro, J., & Rienzo, D. (2012). Functional Diversity Indices. In *Quantifying Functional Diversity*. SpringerBriefs. https://doi.org/10.1007/978-94-007-2648-2

Chau, N. L., & Chu, L. M. (2017). Fern cover and the importance of plant traits in reducing erosion on steep soil slopes. *Catena*, *151*, 98–106. https://doi.org/10.1016/j.catena.2016.12.016

Comberti, C., Thornton, T. F., Wylliede Echeverria, V., & Patterson, T. (2015). Ecosystem services or services to ecosystems? Valuing cultivation and reciprocal relationships between humans and ecosystems. *Global Environmental Change*, *34*, 247–262. https://doi.org/10.1016/j.gloenvcha.2015.07.007

Conant, R. T., Paustian, K., & Elliott, E. T. (2001). Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications*, *11*(2), 343–355. https://doi.org/10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Cornelissen, J. H. C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D. E., Reich, P. B., Ter Steege, H., Morgan, H. D., Van Der Heijden, M. G. A., Pausas, J. G., & Poorter, H. (2003). A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Australian Journal of Botany*, *51*(4), 335–380. https://doi.org/10.1071/BT02124

Coughenour, M. B. (1985). Graminoid responses to grazing by large herbivores: adaptations, exaptations, and interacting processes. *Annals - Missouri Botanical Garden*, *72*(4), 852–863. https://doi.org/10.2307/2399227

Cresswell, C. J., Cunningham, H. M., Wilcox, A., & Randall, N. P. (2018). What specific plant traits support ecosystem services such as pollination, bio-control and water quality protection in temperate climates? A systematic map. *Environmental Evidence*, *7*(1), 1–13. https://doi.org/10.1186/s13750-018-0120-8

Damgaard, C. (2014). Estimating mean plant cover from different types of cover data: A coherent statistical framework. *Ecosphere*, *5*(2), 1–7. https://doi.org/10.1890/ES13-00300.1

De La Riva, E. G., Olmo, M., Poorter, H., Ubera, J. L., & Villar, R. (2016). Leaf mass per area (LMA) and its relationship with leaf structure and anatomy in 34 mediterranean woody species along a water availability gradient. *PLoS ONE*, *11*(2), 1–18. https://doi.org/10.1371/journal.pone.0148788

Diaz, S., & Cabido, M. (1997). Plant functional types and ecosystem function in relation to global change. *Journal of Vegetation Science*, *8*(4), 463–474. https://doi.org/10.2307/3237198

Díaz, S., Cabido, M., & Casanoves, F. (1999). Functional implications of trait–environment linkages in plant communities. In E. Weiher & P. A. Keddy (Eds.), *Ecological Assembly Rules - Perspectives, Advances, Retreats* (pp. 338–362). Cambridge University Press. https://doi.org/10.1017/cbo9780511542237.013

Díaz, S., Kattge, J., Cornelissen, J. H. C., Wright, I. J., Lavorel, S., Dray, S., Reu, B., Kleyer, M., Wirth, C., Colin Prentice, I., Garnier, E., Bönisch, G., Westoby, M., Poorter, H., Reich, P. B., Moles, A. T., Dickie, J., Gillison, A. N., Zanne, A. E., … Gorné, L. D. (2016). The global spectrum of plant form and function. *Nature*, *529*(7585), 167–171. https://doi.org/10.1038/nature16489

Díaz, S., Lavorel, S., Chapin III, F. S., Tecco, P. A., Gurvich, D. E., & Grigulis, K. (2007). Functional Diversity - at the crossroads between Ecosystem Functioning and Environmental Filters. In *Terrestrial Ecosystems in a Changing World* (pp. 81–91). Springer.

Díaz, S., Lavorel, S., De Bello, F., Quétier, F., Grigulis, K., & Robson, T. M. (2007). Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(52), 20684–20689. https://doi.org/10.1073/pnas.0704716104

Díaz, S., Purvis, A., Cornelissen, J. H. C., Mace, G. M., Donoghue, M. J., Ewers, R. M., Jordano, P., & Pearse, W. D. (2013). Functional traits, the phylogeny of function, and ecosystem service vulnerability. *Ecology and Evolution*, *3*(9), 2958–2975. https://doi.org/10.1002/ece3.601

Dudley, N., & Alexander, S. (2017). Agriculture and biodiversity: a review. *Biodiversity*, *18*(2–3), 45–49. https://doi.org/10.1080/14888386.2017.1351892

Faucon, M. P., Houben, D., & Lambers, H. (2017). Plant Functional Traits: Soil and Ecosystem

Services. *Trends in Plant Science*, *22*(5), 385–394. https://doi.org/10.1016/j.tplants.2017.01.005

Fehmi, J. S. (2009). *Confusion among three common plant cover definitions may result in data unsuited for comparison Author (s): Jeffrey S . Fehmi Published by : Wiley Stable URL : http://www.jstor.org/stable/40925486 REFERENCES Linked references are available on JSTOR for . 2*(May 2016), 1–7.

Garnier, E., Cortez, J., Billès, G., Navas, M. L., Roumet, C., Debussche, M., Laurent, G., Blanchard, A., Aubry, D., Bellmann, A., Neill, C., & Toussaint, J. P. (2004). Plant functional markers capture ecosystem properties during secondary succession. *Ecology*, *85*(9), 2630–2637. https://doi.org/10.1890/03-0799

Garnier, E., Navas, M. L., & Grigulis, K. (2016). Trait based ecology: definitions, methods, and a conceptual framework. In *Plant Functional Diversity: Organism Traits, Community Structure, and Ecsystem Properties* (1st ed., p. 10). Oxford University Press.

Gilliam, F. S. (2007). The ecological significance of the herbaceous layer in temperate forest ecosystems. *BioScience*, *57*(10), 845–858. https://doi.org/10.1641/B571007

Gillison, A. N., & Brewer, K. R. W. (1985). The use of gradient directed transects or gradsects in natural resource surveys. *Journal of Environmental Management*, *20*(2), 103–127.

Goodall, D. W. (1952). Quantiative Aspects of Plant Distribution. *Biological Reviews*, *27*, 194–245.

Gorczynski, D., Hsieh, C., Luciano, J. T., Ahumada, J., Espinosa, S., Johnson, S., Rovero, F., Santos, F., Andrianarisoa, M. H., Astaiza, J. H., Jansen, P. A., Kayijamahe, C., Moreira Lima, M. G., Salvador, J., & Beaudrot, L. (2021). Erratum: Tropical mammal functional diversity increases with productivity but decreases with anthropogenic disturbance (Proc. R. Soc. B (2021) 288 (20202098) DOI: 10.1098/rspb.2020.2098). *Proceedings of the Royal Society B: Biological Sciences*, *288*(1947), 0–7. https://doi.org/10.1098/rspb.2021.0432

Goswami, M., Bhattacharyya, P., Mukherjee, I., & Tribedi, P. (2017). Functional Diversity: An Important Measure of Ecosystem Functioning. *Advances in Microbiology*, *07*(01), 82–93. https://doi.org/10.4236/aim.2017.71007

Gould, R. K., Mooney, H., Nelson, L., Shallenberger, R., & Daily, G. C. (2013). Restoring native forest understory: The influence of ferns and light in a hawaiian experiment. *Sustainability (Switzerland)*, *5*(3), 1317–1339. https://doi.org/10.3390/su5031317

Grant, T. A., Madden, E. M., Murphy, R. K., Smith, K. A., & Nenneman, M. P. (2004). Monitoring native prairie vegetation: The belt transect method. *Ecological Restoration*, *22*(2), 106–112. https://doi.org/10.3368/er.22.2.106

Hallett, L. M., Stein, C., & Suding, K. N. (2017). Functional diversity increases ecological stability in a grazed grassland. *Oecologia*, *183*(3), 831–840. https://doi.org/10.1007/s00442-016-3802-3

Hanisch, M., Schweiger, O., Cord, A. F., Volk, M., & Knapp, S. (2020). Plant functional traits shape multiple ecosystem services, their trade-offs and synergies in grasslands. *Journal of Applied Ecology*, *57*(8), 1535–1550. https://doi.org/10.1111/1365-2664.13644

Hao, M., Messier, C., Geng, Y., Zhang, C., Zhao, X., & von Gadow, K. (2020). Functional traits influence biomass and productivity through multiple mechanisms in a temperate secondary forest. *European Journal of Forest Research*, *139*(6), 959–968. https://doi.org/10.1007/s10342-020-01298-0

Haukioja, E., & Koricheva, J. (2000). ToleranceToHerbivoryInWoodyHerbacious. *Evolutionary Ecology*, *14*, 551–562. https://doi.org/10.1023/A

Hooper, D. U., Chapin, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A. J., Vandermeer, J., & Wardle, D. A. (2005). Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecological Monographs*, *75*(1), 3–35. https://doi.org/10.1890/04-0922

Hooper, D. U., & Vitousek, P. M. (1997). The effects of plant composition and diversity on ecosystem processes. *Science*, *277*(5330), 1302–1305. https://doi.org/10.1126/science.277.5330.1302

Huang, X., Su, J., Li, S., Liu, W., & Lang, X. (2019). Functional diversity drives ecosystem multifunctionality in a Pinus yunnanensis natural secondary forest. *Scientific Reports*, *9*(1), 1–8. https://doi.org/10.1038/s41598-019-43475-1

Izsák, J., & Papp, L. (2000). A link between ecological diversity indices and measures of biodiversity. *Ecological Modelling*, *130*(1–3), 151–156. https://doi.org/10.1016/S0304-3800(00)00203-9

Jones, H. G. (2020). What plant is that? Tests of automated image recognition apps for plant identification on plants from the British flora. *AoB PLANTS*, *12*(6), 1–9. https://doi.org/10.1093/aobpla/plaa052

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, *76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Kimmerer, R. W., & Lake, F. K. (2001). The role of indigenous burning in land management. *Journal of Forestry*, *99*(11), 36–41. http://www.ingentaconnect.com/content/saf/jof/2001/00000099/00000011/art00008

Kobal, S. N., Payne, N. F., & Ludwig, D. R. (1998). Nestling food Habits of 7 grassland bird species and insect abundance in grassland habitats in northern Illinois. *Transactions of the Illinois State Academy of Science*, *91*(1 & 2), 69–75.

Kondratyeva, A., Knapp, S., Durka, W., Kühn, I., Vallet, J., Machon, N., Martin, G., Motard, E., Grandcolas, P., & Pavoine, S. (2020). Urbanization Effects on Biodiversity Revealed by a Two-Scale Analysis of Species Functional Uniqueness vs. Redundancy. *Frontiers in Ecology and Evolution*, *8*(March), 1–16. https://doi.org/10.3389/fevo.2020.00073

Krebs, C. J. (2017). Chapter 4 Estimating Density : Quadrat Counts. In *Ecological Methodology* (5th ed., pp. 135–204). Addison Wesley Educational Publishers Inc.

Kurtz, W. B., Thurman, S. E., Monson, M. J., & Garrett, H. E. (1991). The use of agroforestry to control erosion - financial aspects. *Forestry Chronicle*, *67*(3), 254–257. https://doi.org/10.5558/tfc67254-3

Laliberte, E., & Legendre, P. (2010). A distance-based framework for measuring functional diversity from multiple traits. *Ecology*, *91*(1), 299–305.

Lan, H., Wang, D., He, S., Fang, Y., Chen, W., Zhao, P., & Qi, Y. (2020). Experimental study on the effects of tree planting on slope stability. *Landslides*, *17*(4), 1021–1035. https://doi.org/10.1007/s10346-020-01348-z

Langhansova, L., Pumprova, K., Haisel, D., Ekrt, L., Pavicic, A., Zajíčková, M., Vanek, T., & Dvorakova, M. (2021). European ferns as rich sources of antioxidants in the human diet. *Food Chemistry*, *356*(July 2020). https://doi.org/10.1016/j.foodchem.2021.129637

Lanta, V., & Lepš, J. (2006). Effect of functional group richness and species richness in manipulated productivity-diversity studies: A glasshouse pot experiment. *Acta Oecologica*, *29*(1), 85–96. https://doi.org/10.1016/j.actao.2005.08.003

Laureto, L. M. O., Cianciaruso, M. V., & Samia, D. S. M. (2015). Functional diversity: An overview of its history and applicability. *Natureza e Conservacao*, *13*(2), 112–116. https://doi.org/10.1016/j.ncon.2015.11.001

Lavorel, S. (2013). Plant functional effects on ecosystem services. *Journal of Ecology*, *101*(1), 4–8. https://doi.org/10.1111/1365-2745.12031

Lavorel, S., Grigulis, K., McIntyre, S., Williams, N. S. G., Garden, D., Dorrough, J., Berman, S., Quétier, F., Thébault, A., & Bonis, A. (2007). Assessing functional diversity in the field - Methodology matters! *Functional Ecology*, *22*(1), 134–147. https://doi.org/10.1111/j.1365-2435.2007.01339.x

Le Bissonnais, Y., Lecomte, V., & Cerdan, O. (2004). Grass strip effects on runoff and soil loss. *EDP Sciences*, *24*(3), 129–136.

Lousier, J. D., & Parkinson, D. (1976). Litter decomposition in a cool temperate deciduous forest. *Canadian Journal of Botany*, *54*(5–6), 419–436. https://doi.org/10.1139/b76-041

Lu, C., Kotze, D. J., & Setälä, H. M. (2021). Evergreen trees stimulate carbon accumulation in urban soils via high root production and slow litter decomposition. *Science of the Total Environment*, *774*, 145129. https://doi.org/10.1016/j.scitotenv.2021.145129

Májeková, M., Paal, T., Plowman, N. S., Bryndová, M., Kasari, L., Norberg, A., Weiss, M., Bishop, T. R., Luke, S. H., Sam, K., Le Bagousse-Pinguet, Y., Lepš, J., Götzenberger, L., & De Bello, F. (2016). Evaluating Functional diversity: Missing trait data and the importance of species abundance structure and data transformation. *PLoS ONE*, *11*(2), 1–17. https://doi.org/10.1371/journal.pone.0149270

Mason, N. W. H., Mouillot, D., Lee, W. G., & Wilson, J. B. (2005). Functional richness, functional evenness and functional divergence: The primary components of functional diversity. *Oikos*, *111*(1), 112–118. https://doi.org/10.1111/j.0030-1299.2005.13886.x

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: A Framework for Assessment*.

Naeem, S. (1998). Species redundancy and ecosystem reliability. *Conservation Biology*, *12*(1), 39–45. https://doi.org/10.1046/j.1523-1739.1998.96379.x

Nagy, R. K., Bell, L. W., Schellhorn, N. A., & Zalucki, M. P. (2020). Role of grasslands in pest suppressive landscapes: how green are my pastures? *Austral Entomology*, *59*(2), 227–237. https://doi.org/10.1111/aen.12464

Nock, C. A., Vogt, R. J., & Beisner, B. E. (2016). Functional Traits. *ELS*, *February 2018*, 1–8. https://doi.org/10.1002/9780470015902.a0026282

Osorio, R. J., Barden, C. J., & Ciampitti, I. A. (2019). GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska. *Agroforestry Systems*, *93*(4), 1567–1576. https://doi.org/10.1007/s10457-018-0270-2

Pavoine, S., & Bonsall, M. B. (2011). Measuring biodiversity to explain community assembly: A unified approach. *Biological Reviews*, *86*(4), 792–812. https://doi.org/10.1111/j.1469-185X.2010.00171.x

Pérez-Harguindeguy, N., Díaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M. S., Cornwell, W. K., Craine, J. M., Gurvich, D. E., Urcelay, C., Veneklaas, E. J., Reich, P. B., Poorter, L., Wright, I. J., Ray, P., Enrico, L., Pausas, J. G., De Vos, A. C., … Cornelissen, J. H. C. (2013). New handbook for standardised measurement of plant functional traits worldwide. *Australian Journal of Botany*, *61*(3), 167–234. https://doi.org/10.1071/BT12225

Pfiffner, L., & Luka, H. (2000). Overwintering of arthropods in soils of arable fields and adjacent semi-natural habitats. *Agriculture, Ecosystems and Environment*, *78*(3), 215–222.

https://doi.org/10.1016/S0167-8809(99)00130-9
Poorter, H., Niinemets, Ü., Poorter, L., Wright, I. J., & Villar, R. (2009). Causes and consequences of variation in leaf mass per area (LMA): A meta-analysis. *New Phytologist*, *182*(3), 565–588. https://doi.org/10.1111/j.1469-8137.2009.02830.x
Rawlik, K., Nowiński, M., & Jagodziński, A. M. (2021). Short life–fast death: decomposition rates of woody plants leaf- and herb-litter. *Annals of Forest Science*, *78*(1). https://doi.org/10.1007/s13595-020-01019-y
Rosenfield, J. (2002). Functional Redundancy In Ecology And Conservation. *Oikos*, *98*(1).
Rowell, C. H. F., Rowell-Rahier, M., Braker, H. E., Cooper-Driver, G., & P, L. D. G. (1983). The Palatability of Ferns and the Ecology of Two Tropical Forest Grasshoppers. *Biotropica*, *15*(3), 207. https://doi.org/10.2307/2387830
Schleuter, D., Daufresne, M., Massol, F., & Argillier, C. (2010). A user's guide to functional diversity indices. *Ecological Monographs*, *80*(3), 469–484. https://doi.org/10.1890/08-2225.1
Schmaltz, E. M., & Mergili, M. (2018). Integration of root systems into a GIS-based slip surface model: computational experiments in a generic hillslope environment. *Landslides*, *15*(8), 1561–1575. https://doi.org/10.1007/s10346-018-0970-8
Simpson, E. H. (1949). Measurment of Diversity. *Nature*, *163*(1943), 688. https://doi.org/10.1038/163688a0
Smith, C. C., & Balda, R. P. (1979). Competition among insects, birds and mammals for conifer steeds. *Integrative and Comparative Biology*, *19*(4), 1065–1083. https://doi.org/10.1093/icb/19.4.1065
Stevens, R. D., Willig, M. R., & De Fox, I. G. (2004). Comparative community ecology of bats from eastern Paraguay: Taxonomic, ecological, and biogeographic perspectives. *Journal of Mammalogy*, *85*(4), 698–707. https://doi.org/10.1644/BWG-128
Taugourdeau, S., Villerd, J., Plantureux, S., Huguenin-Elie, O., & Amiaud, B. (2014). Filling the gap in functional trait databases: Use of ecological hypotheses to replace missing data. *Ecology and Evolution*, *4*(7), 944–958. https://doi.org/10.1002/ece3.989
The Concord Consortium. (2010). *ConcordWebsite.pdf*. Calculating the Biodiversity Index. https://staff.concord.org/~btinker/GL/web/water/biodiversity_index.html
Tilman, D. (2001). Functional Diversity. In *Encyclopedia of Biodiversity* (Vol. 3, pp. 109–120). Academic Press. https://doi.org/10.1016/b0-12-226865-2/00132-2
Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., & Siemann, E. (1997). The influence of functional diversity and composition on ecosystem processes. *Science*, *277*(5330), 1300–1302. https://doi.org/10.1126/science.277.5330.1300
US Forest Service. (2003). Ecological Monitoring Tools and Methods. In *Multiparty Monitoring and Assessment Guidelines for Community-based Forest Restoration in Southwestern Ponderosa Pine Forests*. http://www.fs.fed.us/r3/spf/cfrp/monitoring/
Vallina, S. M., Cermeno, P., Dutkiewicz, S., Loreau, M., & Montoya, J. M. (2017). Phytoplankton functional diversity increases ecosystem productivity and stability. *Ecological Modelling*, *361*, 184–196. https://doi.org/10.1016/j.ecolmodel.2017.06.020
Weiher, E., Werf, A., Thompson, K., Roderick, M., Garnier, E., & Eriksson, O. (1999). Challenging Theophrastus: A common core list of plant traits for functional ecology. *Journal of Vegetation Science*, *10*(5), 609–620. https://doi.org/10.2307/3237076
Werling, B. P., Dickson, T. L., Isaacs, R., Gaines, H., Gratton, C., Gross, K. L., Liere, H., Malmstrom, C. M., Meehan, T. D., Ruan, L., Robertson, B. A., Robertson, G. P., Schmidt,

T. M., Schrotenboer, A. C., Teal, T. K., Wilson, J. K., & Landis, D. A. (2014). Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(4), 1652–1657. https://doi.org/10.1073/pnas.1309492111

Westoby, M., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Diemer, M., others, Wright, I. J., Reich, P. B., Ackerly, D. D., & Cornelissen, J. H. . (2004). The worldwide leaf economics spectrum. *Nature*, *428*, 821–827. www.nature.com/nature%0Ahttps://idp.nature.com/authorize/casa?redirect_uri=https://www.nature.com/articles/nature02403&casa_token=CtYdn6u63BcAAAAA:cNAkoHi669d547DoKaM3keUixX15dhKLnmyUD_oX2GBEB1VTe9mtWcMdFoXauJPFpb4iQItw5D0oAvb3

Wikum, D. A., & Shanholtzer, G. F. (1978). Application of the Braun-Blanquet cover-abundance scale for vegetation analysis in land development studies. *Environmental Management*, *2*(4), 323–329. https://doi.org/10.1007/BF01866672

Wilmers, C. C., Sinha, S., & Brede, M. (2002). Examining the Effects of Species Richness on Community Stability : An Assembly Model Approach. *Oikos*, *99*(2), 363–367.