Spring 3-2023

Assessing Functional Biodiversity for the Future of Plants, Planet, and People

Ali Loker

University of Nebraska-Lincoln, aloker2@huskers.unl.edu

ASSESSING FUNCTIONAL BIODIVERSITY FOR THE FUTURE OF PLANTS, PLANET, AND PEOPLE

by

Ali Loker

A DOCTORAL DOCUMENT

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Plant Health

Major: Plant Health

Under the Supervision of Professors Gary L. Hein and Jeffrey Bradshaw

Lincoln, Nebraska

March, 2023

ASSESSING FUNCTIONAL BIODIVERSITY FOR THE FUTURE OF PLANTS, PLANET, AND PEOPLE

Ali Loker, D.P.H.

University of Nebraska, 2023

Advisors: Gary L. Hein, Jeffrey Bradshaw

Biodiversity plays a critical role in supporting life in global ecosystems and its links to ecosystem services and sustainability are recognized by scientific and non-scientific communities. Growing awareness of the importance of biodiversity is accelerated by discussions of its loss, and how to design interventions to conserve and mitigate a biodiversity crisis. Stakeholders are funding and implementing assessment strategies at various scales to help direct conservation efforts. There is also growing interest in measuring and communicating biodiversity outcomes.

Functional biodiversity characterizes the multiplicity of life forms into groups based on their diverse contributions to natural and agro-ecosystems. Assessing functional biodiversity can elucidate mechanisms of relationships among species and ecosystems to help explain and predict ecosystem processes. Functional biodiversity assessments involve defining the purposes, ecosystem functions and traits to measure; how to put relative weights on each trait and create indices; and exploring how these can be used to evaluate agroecosystems and forests. Case studies from both agroecosystems and forest systems are presented along with a discussion of barriers and opportunities in designing and implementing functional biodiversity assessments. Participation from three

stakeholder groups is discussed as a method to include relevant human dimensions and achieve more robust and effective conservation outcomes from functional biodiversity assessments.

Acknowledgements

I am filled with tremendous gratitude to everyone who has played a role, large or small, in my completion of the Doctor of Plant Health program. I could write another doctoral document of acknowledgements, but here is a non-inclusive list of thank yous instead.

To my family: thank you for being my number one fans throughout the DPH and in life. I truly won the lottery to be part of such a caring, supportive, funny, and compassionate family. Em, you are my inspiration to be present in my interactions with others and myself, to challenge the status quo, and to never stop fighting for what is right. Of all my identities, being your sister is my favorite. Mom, your unwavering support and kindness have guided me through so many exciting and challenging times in my life, knowing you'd be there no matter what. Dad, your optimism and altruism remind me that there is so much light and goodness in this world and that music makes everything better. Mochi, thank you for the reminders to rest and get outside, and for being a constant source of joy in my life (and yes, I'm thanking my dog :)).

To my friends, near and far: your support is immeasurable and invaluable. I am fortunate to have friends from many times in my life – some whom I've known since 3rd grade, and others whom I've met only this year. You have each shown up for me in countless ways before and throughout this program. Some have empathized deeply with the graduate school experience, and we've been a part of each other's journeys. Others have provided a much-needed grounding in my identity before grad school and reminders of the "outside world". I can't wait to spend even more time together in the future and show up for you all in ways I couldn't during school. A special thanks to current and

former DPH students: you've paved the way for me and future students, both personally and professionally. I can't wait to join you all as plant health practitioners and see the impact we can have together.

To the DPH team: thank you for creating and sustaining such a unique and critical program, and for being pivotal in this life-changing experience. Dr. Hein, thank you for your authentic leadership and dedication to this program and the students. I value the mentorship you offered me, helping me address numerous course deficiencies and consistently instilling confidence in me that I belonged in the DPH program. Dr. Bradshaw, thank you for getting me across the finish line. I admire your willingness to jump in during my final semester and thank you for making the writing process, dare-I-say, enjoyable. Kelly, you are a gift. You keep the program together, offer valuable perspectives and insights (and chocolate!), and I always leave your office in a better mood than when I arrived.

To my committee members: thank you for being so generous with your time, energy, and connections. Dr. Wortman, your enthusiastic support is humbling, thank you for being a joy to work with and for your creativity and innovation. Suk, thank you for connecting me with the Arbor Day Foundation to develop a meaningful internship experience - I love seeing you around the office. Dr. Francis, thank you for your willingness to push the envelope and inspiration to always ask more questions than provide answers. Barb, thank you for warmly welcoming me into your garden, driveway, and kitchen table – your friendship and travel stories have been a highlight of my Lincoln experience. Dr. Giesler, thank you for your support of the DPH program and indulging me in talking about social science-plant pathology connections.

To my colleagues at Gerber/Nestle and the Arbor Day Foundation: thank you for facilitating internship experiences that allowed me to synthesize and apply my coursework. It was incredibly rewarding to have so many “aha” moments in my two internships where concepts started clicking. These internships helped motivate me to continue and complete the DPH. A special thank you to the Gerber growers who allowed me to run around with a sweep net, hang sticky traps, and take soil cores on their farms.

Thank you all.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION AND CONTEXT

Introduction

Biodiversity is a contraction of the terms "biological" and "diversity". The Convention on Biological Diversity (CBD) defines biodiversity as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (United Nations Environmental Program, 1992). This definition encompasses three levels of biodiversity: genetic, species, and ecosystem.

Educators have adapted the board game Jenga® (Hasbro, n.d.) to depict interactions among species and their resulting interdependence (Evans, 2020). Each brick in the "Biodiversity Jenga" tower represents one species (including humans), and extinction occurs when players remove bricks from the tower. At first, the "extinction" of a single species does not significantly affect the stability of the tower; however, the tower grows more and more precarious as "extinctions" continue. This educational tool is a useful way to communicate the importance of biodiversity to a broad audience.

Growing awareness of the importance of biodiversity is accompanied by discussions of biodiversity loss and how to design interventions to conserve biodiversity and mitigate a biodiversity crisis. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is an independent intergovernmental body established by the United Nations in 2012 to enhance collaboration between science and policy with a goal of sustaining long-term biodiversity and ecosystem services (Intergovernmental Platform for Biodiversity and Ecosystem Services, n.d.-a). In their

2019 Global Assessment on Biodiversity and Ecosystem Services, the IPBES found that about 1 million species are at risk of extinction, more than ever before (Diaz et al., 2019). The Assessment details how humans are perpetuating and accelerating biodiversity loss (Diaz et al., 2019). The four key messages of the report are:

1. Nature and its fundamental contributions to people are deteriorating worldwide.
2. Direct and indirect drivers of biodiversity change have accelerated during the past 50 years.
3. Transformative economic, social, political, and technological changes are needed since goals for conserving nature and achieving sustainability[1] cannot be met by current trajectories.
4. Conserving nature is complementary to achieving other global societal goals, including those for food, energy, and human health. (Diaz et al., 2019)

The CBD is a legally-binding commitment to conserve and sustainably use components of biodiversity, and to equitably share benefits that come from using genetic resources (Secretariat of the CBD, 2000). The CBD was introduced for signature at the United Nations (UN) Conference on Environment and Development in 1992 and has since been ratified by most UN countries, but notably not the United States. The CBD develops global strategic plans and targets for biodiversity conservation. The latest global plan is the Kunming-Montreal Global Biodiversity Framework (GBF), which was signed

[1] The IPBES uses the following definition of sustainability: “A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs.” (Intergovernmental Platform for Biodiversity and Ecosystem Services, n.d.-b)

by 196 countries at COP 15 in December 2022. The framework contains four long-term goals to be achieved by 2050:

1. Area of natural ecosystems is increased, human-induced extinction of threatened species is stopped, rate and risk of extinction decreases by tenfold, and genetic diversity is maintained.
2. Sustainable use[2] and management of biodiversity, including restoration of ecosystem functions and any services in decline.
3. Equitable access and sharing of monetary and non-monetary benefits from the use of genetic resources, protect traditional knowledge of these resources.
4. Adequate financial, scientific, capacity, and technological resources are secured and equitably accessible to all parties. (UNEP & CBD, 2022)

Local, regional, national, and international efforts to conserve biodiversity exist around the world. The IPBES and CBD are two highly visible international initiatives working to conserve biodiversity and sustainably use resources as we mitigate the present crisis. While there is consensus that biodiversity is important to protect, international plans such as the Kunming-Montreal GBF have been met with mixed reactions (Surma, 2023). Some concerns include the non-binding nature of the framework itself, which leaves governments responsible to protect human rights and the rights of indigenous peoples and local communities. Additional concerns were raised about the tactical implementation of the Kunming-Montreal GBF. Given that countries failed to meet any targets of the CBD's 2011-2020 biodiversity plan, this concern may be warranted.

---

[2] CBD defines sustainable use as "the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations." (Hesselink et al., 2007)

Assessing biodiversity is an important way to measure progress towards the goals of the GBF and other international biodiversity efforts.

You can’t manage what you don’t measure

“If you can’t measure it, you can’t manage it” is a famous quote attributed to statistician and quality-control expert Edwards Deming (2018). This quote is central to biodiversity conservation. We must be able to measure biodiversity to prioritize interventions and assess their efficacy to mitigate impacts of the current crisis. Biodiversity assessments that are well designed and implemented can provide information about the state of biodiversity and help with decision-making at various scales (Vermeulen & Koziell, 2002).

Multiple stakeholder groups are interested in assessing biodiversity, including governments, non-governmental organizations, private sector actors, and local groups who directly manage ecosystems. Governments may be motivated to undertake biodiversity assessments to conserve the environmental processes that biodiversity supports. Non-governmental organizations may have various motivations for biodiversity assessments, depending on their missions and activities. Private sector actors may experience consumer or regulatory pressures, or both, as an impetus for biodiversity assessments. Sophisticated private sector actors may also undertake biodiversity assessments because they recognize the business case for conservation. Local groups may assess biodiversity because their livelihoods directly depend on natural resources. The purpose, scope, methods, and results of biodiversity assessments conducted by different stakeholder groups will vary; however, integrating the results of assessments is essential to measure progress towards broader international conservation goals, like those of the IPBES and CBD.

Values play a significant role in determining the purpose, scope, and methods of biodiversity assessments at different scales. Vermeulen and Koziell (2002) present three types of values relevant to biodiversity assessments: indirect, direct, and non-use values (pg. 12). Indirect use values are those derived from environmental services that biodiversity may enhance, e.g., regulation of air and water quality. Direct use values are monetary or subsistence values gained from raw materials or resources resulting from biodiversity, e.g., the use of medicinal plants. Non-use values represent the inherent value of biodiversity and the availability of this resource in the future.

Values differ according to who is conducting the biodiversity assessment and these values impact the purpose, methods, results, and application of the assessment. In general, governments assess biodiversity through a "global" (indirect and non-use) value lens, and local groups typically assess biodiversity according to "local" (direct use) values (Vermeulen & Koziell, 2002). Non-governmental organizations and private sector actors may assess a combination of global and local values, depending on the scope and purpose of the biodiversity assessment (Vermeulen & Koziell, 2002). Local values are not commonly included in biodiversity assessments that focus on global values, creating a gap between on-the-ground realities and broader conservation goals. Therefore, it is ideal to integrate stakeholder values from different scales when developing biodiversity assessments.

Links between biodiversity, ecosystem services, and sustainability

Biodiversity plays an integral role in supporting life on Earth (Diaz et al., 2019; Morton & Hill, 2015; UNEP & CBD, 2022). The Millennium Ecosystem Assessment (MEA) was conducted in 2001-2005 by over 1,360 experts worldwide to evaluate the effects of ecosystem change on human well-being and to identify opportunities for conservation (Millennium Ecosystem Assessment, 2005). The MEA concentrates on the links between ecosystems and human well-being, particularly through “ecosystem services”. Ecosystem services can be defined as the benefits people receive from ecosystems, including provisioning, regulating, cultural, and supporting services critical to life (Millennium Ecosystem Assessment, 2005). The MEA posits that biodiversity directly affects these ecosystem services.

Links between biodiversity and ecosystem services, such as water and air quality and pollination, are well-recognized by the scientific and non-research communities (Diaz et al., 2019; Romanelli et al., 2015). Additionally, biodiversity and human health are inextricably linked, with relationships between biodiversity and food quality and security, medicines, pathogens, and mental and cultural well-being (Romanelli et al., 2015). However, the details of relationships between biodiversity and ecosystem services are complex, and there are many unresolved questions (Diaz et al., 2019; Fischer et al., 2010; Laureto et al., 2015; Moonen & Bàrberi, 2008; Petchey & Gaston, 2006).

As the links between biodiversity and ecosystem services are elucidated, so too become the connections between biodiversity and sustainability. The ecosystem services supported by biodiversity also directly contribute to the economic, social, and environmental pillars of sustainability (Niesenbaum, 2019). Further research can help inform efforts to conserve biodiversity and expand sustainable land use practices.

Biodiversity assessments can help us better understand the relationships between biodiversity and ecosystem services and, subsequently, sustainability. Long-term, field-level experiments that include biodiversity assessments can offer valuable insights into interactions and relationships between biodiversity and ecosystem services (Fischer et al., 2010).

Characterizing biodiversity

Biodiversity can be characterized by the three primary attributes of an ecosystem: composition, structure, and function (Noss, 1990). Composition includes the species present in an ecosystem and the genetic diversity. Structure describes the organization or the patterns of an ecosystem, or both. Function comprises evolutionary and ecological processes in an ecosystem. Noss (1990) presents these attributes of biodiversity as a nested hierarchy, where composition, structure, and function are interconnected within a larger sphere, representing Earth [Figure 1, Noss, 1990]. The nested hierarchy model emphasizes the importance of assessing compositional, structural, and functional attributes of biodiversity at different spatiotemporal scales to address increasingly complex questions.

The goal or objective of the biodiversity assessment will dictate which attributes to measure. While composition, structure, and function are all important attributes of biodiversity, the remainder of this paper will discuss functional biodiversity. My motivation for assessing functional biodiversity is the belief that biodiversity's relationship to ecosystem functioning and the services the ecosystem provides to humans is a compelling argument for funding further research and conservation efforts. Functional biodiversity assessments may also be used to direct funding towards projects that could best protect or enhance desired ecosystem services, such as pollination and nutrient cycling. Additionally, functional biodiversity assessments can be a tool to increase public awareness of the interconnectedness and interdependency among species, including humans. Lastly, I believe that a functional approach to biodiversity assessments can help motivate behavior change towards a more reciprocal relationship with nature.

Functional biodiversity – the basics

Functional biodiversity characterizes the variety of life into groups based on a diversity of functions (Malaterre et al., 2019). Tilman (2001) presents a well-cited definition of functional biodiversity: “the range and value of those species and organismal traits that influence ecosystem functioning”. This definition emphasizes two aspects of functional biodiversity—that the members of the functional group collectively provide an ecosystem service and the diversity of traits is important to realize the ecosystem service. Functional biodiversity offers a mechanistic link between organisms and ecosystems (Petchey & Gaston, 2006), which can inform management and policy decisions.

Functional traits and groups must be identified and measured as part of assessing functional biodiversity. A functional trait is a feature that contributes to an organism’s participation in ecological processes or services. For the purposes of this paper, ‘functional trait’ will refer to functional <u>effect</u> traits, which are features of organisms that contribute to ecosystem processes. These contrast with functional <u>response</u> traits, which are features that influence an organism’s survival (Malaterre et al., 2019). A functional group represents a cluster of organisms that provide a similar ecosystem service (Moonen & Bàrberi, 2008). This contrasts with the classical ecology definition of functional groups as species with similar life-history and ecophysiological traits and is used to describe the ecosystem's state rather than its services (Moonen & Bàrberi, 2008).

Assessing functional biodiversity complements other biodiversity assessment approaches (e.g., taxonomic) and involves several general steps. Table 1.1 presents an outline of an ideal process to measure functional biodiversity (Malaterre et al., 2019; Petchey & Gaston, 2006; Vermeulen & Koziell, 2002):

Table 1.1 Steps to assess functional biodiversity

Step	Description
1	Establish goal or purpose of assessment
2	Identify ecosystem services to be assessed, sort functions into functional groups and categories
3	Determine appropriate functional traits to include and exclude from measurement
4	Measure trait diversity
5	Weight traits according to their relative functional importance
6	Measure and quantify functions through indices to explain and predict variation in ecosystem processes

While this process may appear simple, implementing a functional biodiversity assessment requires nuanced and value-laden decision-making at each stage. Descriptions of each step are included in the follow sections.

1. Establish a goal or purpose of assessment

A clearly defined and communicated goal or purpose guides the design and implementation of the assessment and has equity implications for those impacted by the results. Stakeholder values are reflected in the goal of the biodiversity assessment. All relevant stakeholders should be meaningfully included in the process of defining the biodiversity assessment's purpose. Soliciting stakeholder input at this early stage can help improve the relevance of results, especially to direct managers of biodiversity resources. Participatory processes can help ensure equitable distribution of labor and benefits associated with conducting a functional biodiversity assessment. After the purpose is defined, the assessment should be designed accordingly to meet the stated purpose.

2. Identify ecosystem services to be assessed, sort functions into functional groups and categories

Selecting which ecosystem services to assess inherently involves value judgements, as stakeholders must determine which functions are most important. Again, this step depends on the stakeholders involved and should align with the purpose of the assessment. Vermeulen and Koziell (2002) suggest making values explicit throughout this process for transparency and equity and to help make optimal decisions based on assessment results.

Ecosystem services can also be grouped according to their broad functions. For example, ecosystem services for agricultural production may be categorized into direct services, food web services, gene flow, and soil-related processes (Moonen & Bàrberi, 2008). Additionally, ecosystem services vary spatially and over time, and therefore may impact the goal of an assessment. The level of detail at which ecosystem services are defined impacts the composition of functional groups related to that service (Moonen & Bàrberi, 2008). Identifying functional groups and categories leads to the next step: identifying priority functional traits.

3. Determine appropriate functional traits to include and exclude from measurement

The relationship between functional traits and ecosystem services is complex, as a single trait can affect multiple ecosystem services and an ecosystem service can in turn be affected by multiple traits (Laureto et al., 2015). One approach to trait selection is to define the function of interest and assess all ecologically meaningful traits for that function and nothing else (Laureto et al., 2015; Malaterre et al., 2019; Petchey & Gaston, 2006). Other considerations for trait selection include the level or granularity of defining and measuring traits, practicality of measuring, and spatiotemporal variability of traits (Malaterre et al., 2019). The number and type of traits should be selected to sufficiently capture the function of interest while remaining practical to measure (Laureto et al., 2015). Measuring trait values involves tradeoffs between the quantity and quality of information collected and some traits are difficult to measure (Petchey & Gaston, 2006).

4. Measure trait diversity

Trait diversity can be measured with discontinuous or continuous measures, each of which has advantages and disadvantages. Discontinuous measures can be derived from the number of functional types represented by a single species in a community and continuous measures can be obtained by grouping species with similar trait values and summing the number of groups present in an assemblage (Petchey & Gaston, 2006). Grouping species by traits and functions requires many decisions and assumptions, and discrete measures may not accurately reflect trait variation (Petchey & Gaston, 2006).

Villéger et al. (2008) describe the primary functional biodiversity components: functional richness, functional evenness, and functional divergence. Functional richness represents the amount of functional space a community occupies; functional evenness describes how evenly the abundance is distributed in a functional trait space; and functional divergence measures how abundance is spread over a functional trait axis (Villéger et al., 2008). These components may be weighted and combined to form functional biodiversity indices.

5. Weight traits according to their relative functional importance

Weighting traits recognizes that certain traits may be more important to the function of interest than others. Weighting affects the results of functional biodiversity assessments, as higher-weighted traits have the potential to influence the outcomes of the assessment and subsequent decision-making more strongly. Standardizing variability across traits is recommended and weights should be justified with empirical evidence whenever possible (Petchey & Gaston, 2006; Villéger et al., 2008).

6. Measure and quantify functions through indices to explain and predict variation in ecosystem processes

Trait measures can be weighted and incorporated into indices to help explain and predict ecosystem processes and enable comparisons among sites. Many indices have been developed using different types of functional data and mathematical functions (Malaterre et al., 2019; Petchey & Gaston, 2006; Villéger et al., 2008). Different indices can be used to answer various research questions related to functional biodiversity. More work is needed to standardize statistical approaches to enable comparisons of indices across space and time, as well as among different studies to inform management and decision-making (Malaterre et al., 2019).

Conclusion

Ecosystem functions underpin ecosystem services that are critical for the well-being and survival of life on Earth, including humans. Ecosystem services and biodiversity are related in complex and yet-to-be-discovered ways. Assessing biodiversity through a functional biodiversity lens can aid in management and policy decisions, as well as help target conservation funding. Ultimately, better understanding functional biodiversity can elucidate the interdependence among species. Finally, assessing functional biodiversity can help align management and policy decisions to help create a more reciprocal relationship between humans and nature.

Assessing functional biodiversity can help explain and predict ecosystem processes by providing a mechanistic link between organisms and ecosystems (Malaterre et al., 2019; Petchey & Gaston, 2006). Functional biodiversity assessments involve defining the purpose, ecosystem functions and traits to measure, weights of traits, and indices. Value judgements are inherent in each step of functional biodiversity assessments and should be made explicit to minimize bias and maximize transparency.

Chapter 2 discusses functional biodiversity assessments in two different contexts: fruit and vegetable agroecosystems and forests. I was introduced to biodiversity assessments during my DPH internships at Gerber and the Arbor Day Foundation. Chapter 2 will include my direct experiences, case studies from the broader scientific literature, and my reflections on functional biodiversity assessments in agroecosystems and forest restoration efforts.

References

Deming, W. E. (2018). *The new economics for industry, government, education*. MIT press.

Diaz, S., Settele, J., & Brondizio, E. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://www.biologicaldiversity.org/programs/biodiversity/pdfs/Summary-for-Policymakers-IPBES-Global-Assessment.pdf

Evans, D. (2020, March 18). *Wildlife conservation needs to change – and the game of Jenga can help us see why*. The Conversation. http://theconversation.com/wildlife-conservation-needs-to-change-and-the-game-of-jenga-can-help-us-see-why-131534

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., Renner, S., Schöning, I., Schumacher, U., Wells, K., Buscot, F., Kalko, E. K. V., Linsenmair, K. E., Schulze, E.-D., & Weisser, W. W. (2010). Implementing large-scale and long-term functional biodiversity research: The Biodiversity Exploratories. *Basic and Applied Ecology*, *11*(6), 473–485. https://doi.org/10.1016/j.baae.2010.07.009

Hasbro. (n.d.). *Classic Jenga*. Hasbro Games. Retrieved February 20, 2023, from https://shop.hasbro.com/en-us/product/classic-jenga/2622533E-5056-9047-F5C4-A77AA2A86686

Hesselink, F., Goldstein, W., van Kempen, P. P., Garnett, T., & Dela, J. (2007). *Communication, Education and Public Awareness (CEPA) A toolkit for National Focal Points and NBSAP coordinators*. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/cepa/toolkit/2008/doc/CBD-Toolkit-Complete.pdf

Intergovernmental Platform for Biodiversity and Ecosystem Services. (n.d.-a). *About | IPBES Secretariat*. IPBES. Retrieved January 8, 2023, from https://ipbes.net/about

Intergovernmental Platform for Biodiversity and Ecosystem Services. (n.d.-b). *Sustainability | IPBES secretariat*. IPBES. Retrieved February 20, 2023, from https://ipbes.net/glossary-tag/sustainability

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

Malaterre, C., Dussault, A. C., Mermans, E., Barker, G., Beisner, B. E., Bouchard, F., Desjardins, E., Handa, I. T., Kembel, S. W., Lajoie, G., Maris, V., Munson, A. D., Odenbaugh, J., Poisot, T., Shapiro, B. J., & Suttle, C. A. (2019). Functional biodiversity: An Epistemic Roadmap. *BioScience*, *69*(10), 800–811. https://doi.org/10.1093/biosci/biz089

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-Being: Biodiversity Synthesis*. World Resources Institute. https://www.millenniumassessment.org/documents/document.354.aspx.pdf

Moonen, A.-C., & Bàrberi, P. (2008). Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems & Environment*, *127*(1), 7–21. https://doi.org/10.1016/j.agee.2008.02.013

Morton, S., & Hill, R. (2015). What is biodiversity, and why is it important? In *Biodiversity: Science and solutions for Australia* (pp. 1–12). CSIRO Publishing. https://www.researchgate.net/profile/Rosemary-Hill-4/publication/279197478_What_is_biodiversity_and_why_is_it_important/links/558ea75508ae1e1f9bacd67b/What-is-biodiversity-and-why-is-it-important.pdf

Niesenbaum, R. A. (2019). The Integration of Conservation, Biodiversity, and Sustainability. *Sustainability*, *11*(17), Article 17. https://doi.org/10.3390/su11174676

Noss, R. F. (1990). Indicators for Monitoring Biodiversity: A Hierarchical Approach. *Conservation Biology*, *4*(4), 355–364. https://www.jstor.org/stable/2385928

Petchey, O. L., & Gaston, K. J. (2006). Functional biodiversity: Back to basics and looking forward. *Ecology Letters*, *9*(6), 741–758. https://doi.org/10.1111/j.1461-0248.2006.00924.x

Romanelli, C., Cooper, D., Campbell-Lendrum, D., Maiero, M., Karesh, W., Hunter, D., & Golden, C. (2015). *Connecting global priorities: Biodiversity and human health: A state of knowledge review*. World Health Organization/Secretariat of the UN Convention on Biological Diversity. https://www.who.int/publications-detail-redirect/9789241508537

Secretariat of the Convention on Biological Diversity. (2000). *Sustaining life on Earth: How the Convention on Biological Diversity promotes nature and human well-being*. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/doc/publications/cbd-sustain-en.pdf

Surma, K. (2023, January 2). Nearly 200 Countries Approve a Biodiversity Accord Enshrining Human Rights and the ‘Rights of Nature.’ *Inside Climate News*. https://insideclimatenews.org/news/02012023/cop15-biodiversity-agreement/

Tilman, D. (2001). Functional biodiversity. In S. A. Levin (Ed.), *Encyclopedia of Biodiversity* (pp. 109–120). Elsevier. https://doi.org/10.1016/B0-12-226865-2/00132-2

UNEP, & CBD. (2022, December 7). *Kunming-Montreal Global biodiversity framework*. CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY, Montreal, Canada. https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf

United Nations Environmental Program. (1992). *Chapter XXVII. Environment. 2*. https://treaties.un.org/doc/Treaties/1992/06/19920605%2008-44%20PM/Ch_XXVII_08p.pdf

Vermeulen, S., & Koziell, I. (2002). *Integrating global and local values: A review of biodiversity assessment*. International Institute for Environment and Development. https://pubs.iied.org/sites/default/files/pdfs/migrate/9100IIED.pdf?

Villéger, S., Mason, N. W. H., & Mouillot, D. (2008). New Multidimensional Functional Biodiversity Indices for a Multifaceted Framework in Functional Ecology. *Ecology*, *89*(8), 2290–2301. https://doi.org/10.1890/07-1206.1

CHAPTER 2: FUNCTIONAL BIODIVERSITY ASSESSMENTS IN AGROECOSYSTEMS AND FORESTS

Introduction

Biodiversity plays a critical role in supporting life in global ecosystems (Diaz et al., 2019; Morton & Hill, 2015; UNEP & CBD, 2022). The links between biodiversity, ecosystem services, and sustainability are recognized by scientific and non-scientific communities, and the mechanisms underlying these relationships are still under investigation (Diaz et al., 2019; Fischer et al., 2010; Laureto et al., 2015; Moonen & Bàrberi, 2008; Petchey & Gaston, 2006). Assessing functional biodiversity can help explain and predict ecosystem processes by providing a mechanistic link between organisms and ecosystems (Malaterre et al., 2019; Petchey & Gaston, 2006). This chapter will explore how functional biodiversity is assessed in two ecosystems: agroecosystems and forests.

Agroecosystems and relationship with biodiversity

Agroecosystems are ecological systems modified by humans to produce food, fiber, and other agricultural products (Conway, 1987). Agroecosystems with higher functional biodiversity tend to be more resilient to disturbances because of increased ecological redundancy (Altieri et al., 2017; Martin et al., 2019).

The relationship between biodiversity and agroecosystems can be thought of as bidirectional: biodiversity can be managed to support agroecosystems, and agroecosystems can be managed to support biodiversity (Bàrberi et al., 2010) (see Fig. 2.1). Managing biodiversity is considered an ecological approach to increase yields and improve the sustainability of agricultural production (Altieri, 1999). For example, increased aboveground biodiversity can increase nutrient cycling, which in turn can increase crop biomass; crop diversification can improve biological control and disease antagonists; and increased belowground biodiversity can improve biogeochemical cycles, which in turn can enhance crop nutrition and health (Altieri et al., 2017; Hainzelin, 2015). Managing agroecosystems with sustainable agricultural practices can increase biodiversity, reduce pests, and improve yields (Redlich et al., 2021). Additionally, land use (e.g., cropland vs. grassland) impacts functional biodiversity (Scherer et al., 2020; Yin et al., 2020).

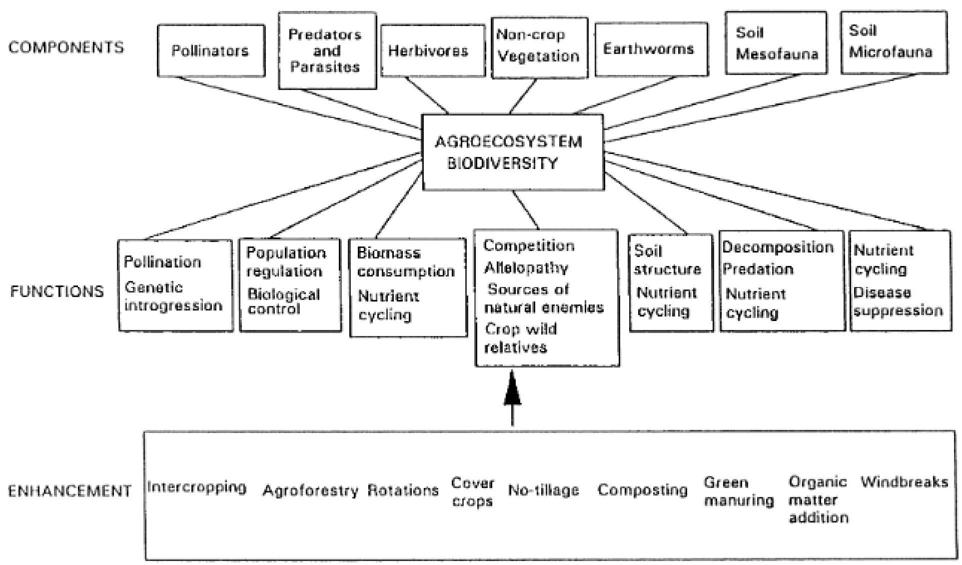

Figure 2.1 Components, functions, and enhancement strategies for biodiversity in agroecosystems (Alteiri, 1994).

Biodiversity contributes to ecosystem services that are critical to agroecosystem functioning although the mechanics of these relationships are still being elucidated. Functional groups provide several types of ecosystem services that are critical to agroecosystem functioning. Soil-related services include nutrient cycling and water regulation; food web services include biological control; gene flow services are provided by pollinators; and direct crop production services are a combined result of all the aforementioned services (Moonen & Bàrberi, 2008).

Forest ecosystems and relationship with biodiversity

Globally, humans manage forest ecosystems to varying degrees depending on the objective or end. Forests can be classified as minimally managed or 'natural' forests, restored forests, and forests managed for agroforestry[3] or timber production. Forests provide critical habitats for an estimated three quarters of terrestrial taxa (CPF, 2008) and offer a variety of ecosystem services that are important for humans (Brockerhoff et al., 2017; Mori et al., 2017). Ecosystem services provided by forests are similar to those provided by agroecosystems, including food production, carbon sequestration, and pollination (Mori et al., 2017).

Moonen and Bàrberi (2008) highlight several ways that agroecosystems differ from 'natural' or minimally managed systems that are relevant to functional biodiversity: ecosystem services contributing to crop productivity are generally of highest value and there are interactions between managed and less- or un-managed areas around agricultural production sites. Therefore, functional biodiversity assessments in agroecosystems evaluate how functional groups work to provide ecosystem services and functional groups themselves are a result of human management of agroecosystems (Moonen & Bàrberi, 2008). Functional biodiversity assessments in forest ecosystems consider human management to the extent that this is practiced. For example, in a forest managed for timber production, functional biodiversity assessments should account for the effects of management practices such as thinning and will likely place more value on

[3] Agroforestry is defined as "the intentional combination of agriculture and forestry to create productive and sustainable land use practices." (USDA, n.d.)

ecosystem services that contribute to productivity such as biomass production (e.g., Lexer & Seidl, 2009). In this way, functional biodiversity assessments in agroecosystems and managed forests may be quite similar. In contrast, functional biodiversity assessments in minimally managed or 'natural' forests may look different from managed forests and agroecosystems, as the functional groups present are not a result of human management and different ecosystem services may be prioritized.

Assessing functional biodiversity in agroecosystems and forests

Functional biodiversity in agroecosystems and forests can be assessed following the steps presented in Chapter 1, Table 1.1. This section will discuss steps 3, 4, and 6 in depth and provide a cursory overview of steps 1, 2, and 5 in both agroecosystems and forests.

1 & 2. Establish goals and identify ecosystem services to assess

Goals of functional biodiversity assessments in agroecosystems and forests will vary according to the stakeholders involved and the environmental and socio-economic context. However, at a high level, the goal of functional biodiversity assessments is to understand the effect of diversity within functional groups as it relates to ecosystem processes and services (Moonen & Bàrberi, 2008). Soil-related, food web, gene flow, and direct crop production and their related processes are considered critical agroecosystem services (Moonen & Bàrberi, 2008). Ecosystem services provided by forests are similar and include food production, water regulation, carbon sequestration, and erosion control (Mori et al., 2017). The goals or purposes of the assessment will influence which ecosystem services are assessed, how each is weighted, and the detail at which ecosystem services are defined will influence the composition of functional groups included in the assessment (Moonen & Bàrberi, 2008).

3. Determine appropriate functional traits to include and exclude

Functional traits are features of organisms that contribute to ecosystem processes (Malaterre et al., 2019). Functional traits are related to bio-indicators; however, the two should not be conflated or used interchangeably. Bio-indicators are individual biota that respond to changes in the environment or reflect an environmental status that can be measured, but they do not necessarily interact to support ecosystem processes (Moonen & Bàrberi, 2008). Bio-indicators should therefore be used to measure the state, resilience, and overall biodiversity of agroecosystems and forests, but they should not be used to explain or predict ecosystem functioning (Moonen & Bàrberi, 2008). Additionally, some species may be better used as bio-indicators than in trait-based assessments because their functional traits are difficult to measure. For example, Malíček et al., (2019) conducted a trait-based assessment of lichen functional biodiversity in old-growth and managed forests in Central Europe. The lichen species in old-growth forests belonged to microlichens, and their microscopic functional traits could not be distinguished by non-lichenologists (Malíček et al., 2019). Due to the challenges in measuring functional traits, the authors conclude that lichens are very good bio-indicators that signal minor differences in forest types (Malíček et al., 2019).

Several studies have used functional traits of soil, plants, and arthropods to assess ecosystem services and environmental sustainability in agroecosystems and forests. It is important to note that functional traits are generally underrepresented in biodiversity assessments, and this is an area of research that warrants more attention (Ćosović et al., 2020).

a. Soil

Fusaro et al. (2018) examined the relationships among above- and below-ground biodiversity groups and ecosystem services in organic and conventional horticultural crops in Italy. The authors assessed agroecosystem services such as soil nutrient cycles, soil microbial activity, pollinator attraction, and natural pest control. Functional indicators were then selected to measure the efficiency of the ecosystem services, and each ecosystem service was associated with a minimum of two indicators. Indicators included various measures of soil enzymatic activity, entomophily index, and rates of parasitism (Fusaro et al., 2018). Several studies address soil parameters in forests to explore differences in biodiversity among sites (e.g., Damptey et al., 2022; Marker et al., 2022), but explicit studies of soil functional biodiversity in forests remains a research gap.

b. Plants

Scherer et al. (2020) used databases of plant traits and species to develop a framework for creating ecosystem quality factors for functional biodiversity in agricultural production on formerly forested land. The authors selected traits from a regional, life-history trait database for Northwest European flora. Traits were selected based on species coverage per trait, association among traits, and functional category, and all selected traits had continuous values (Scherer et al., 2020). Four traits were ultimately selected: canopy height, specific leaf area, seed number, and seed mass.

Njeru et al. (2014) examined the relationship between cover crop species and arbuscular mycorrhizal fungi (AMF) colonization of the subsequent maize crop. In this case, cover crop species identity was used as a proxy for the functional traits of cover crops that affect their ability to sustain AMF communities.

Damptey et al. (2022) explored relationships between plant functional traits and ecosystem functioning in active restored and natural forests and an agroforestry system in Ghana. The authors selected the following plant functional traits related to plant resource use, reproduction, and growth: specific leaf area, leaf carbon and nitrogen ratios, isotopic carbon fraction, stem dry matter content, seed mass, and plant height (Damptey et al., 2022). Rojas-Botero et al. (2020) used a trait-based approach to study the functional biodiversity effects of tropical forest restoration methods. The authors selected eleven functional traits that were proxies for plant competitiveness, biomass production, and stress tolerance: specific leaf area, seed mass, leaf dry matter content, leaf area, life and growth forms, life span, dispersion, pollination strategy, and maximum height (Rojas-Botero et al., 2020). These examples highlight how functional traits are selected based on their relationship to ecosystem services.

c. Arthropods

Martin et al. (2019) studied arthropod responses to different agricultural landscape compositions and configurations. Six categorical traits were selected based on their hypothesized influence on arthropod movement and dispersal: diet breadth, agricultural specialism, diet life history, overwintering habitat, dispersal, and stratum. The authors combined shared traits for organisms with shared responses to landscape filters into trait syndromes to characterize environmental responses of species groups

(Martin et al., 2019). Yin et al. (2020) explored the functional responses of Collembola in response to five types of land use (conventional and organic farming, intensively and extensively used meadows, and extensively used pasture) and climate change. Nine traits were used, including life-history (dispersal ability, habitat, and reproductive mode) and morphological (antenna, body size, pigmentation, furca, ocelli, and hair) traits. These traits were selected based on their hypothesized response to land use and climate change.

Marker et al. (2022) used a trait-based approach to investigate the effects of forested riparian buffer size and environmental variables on functional biodiversity in production forests in Sweden. For spiders, the authors selected species-level functional traits that affect community assemblage and functional and ecological strategies: body size, feeding guild, dispersal method, and preferences regarding humidity, light, and substrates (Marker et al., 2022).

d. Discussion

There are several considerations and challenges related to selecting functional traits. Callo-Concha (2009) explicitly states several assumptions that may be useful for selecting functional traits. The selected traits are not the only ones available, and there is not a ‘right’ set of traits or any one trait indicative enough to precisely represent functional biodiversity in ecosystems. Traits should be quantifiable, easy and cost-effective to assess, repeatable, and ecologically meaningful (Ferris & Humphrey, 1999). Where possible, it is most practical to distill traits down to primary indicators that are functionally linked to a range of other species (Erisman et al., 2016; Ferris & Humphrey, 1999); however, in some cases, finer-scale functional traits need to be measured to adequately assess their effects on ecosystem services (Alhadidi et al., 2019).

Additionally, Martin et al. (2019) found that combining several traits more effectively predicted ecosystem service provision than single traits. Another challenge is the reality that functional traits of arthropods and other invertebrates are still largely unknown, and the number of taxonomists dedicated to describing key traits is shrinking (Barberi & Moonen, 2020). Similarly, functional traits in certain species may be difficult for non-experts to measure (Malíček et al., 2019; Obrist & Duelli, 2010).

4. Measuring trait diversity

Functional biodiversity investigates the importance of diversity within a functional group to provide an ecosystem service. Functional biodiversity can be characterized in three ways to quantify these contributions in a more detailed manner: functional identity, composition, and diversity (Costanzo & Bàrberi, 2014). Functional identity refers to the presence of a set of homogenous phenotypic traits related to the expression of an ecosystem service; functional composition describes a complementary effect of different traits expressed by co-occurring elements; and functional biodiversity is the direct effect of heterogeneity on an ecosystem service (Barberi & Moonen, 2020). Some scientists measure functional divergence in lieu of functional biodiversity. Functional divergence communicates the variance among observations in the trait space (Mammola et al., 2021). The components of functional biodiversity are not mutually exclusive and can be combined to optimize ecosystem service provision (Barberi & Moonen, 2020). Measuring functional biodiversity enables us to elucidate the mechanisms underlying ecosystem services rather than traditional biodiversity measures (e.g., species richness and abundance) which tell us which and how many species are present but do not tell us what these species are doing.

a. Tools and technology to measure trait diversity

Trait diversity in soil, plants, and arthropods can be measured directly and indirectly. Direct methods involve observation and measurement of individuals, e.g., culturing, identifying, and counting microbes from soil samples; counting and measuring plants in the field; and trapping, identifying, and counting arthropods. Direct methods are resource-intensive due to the time, equipment, and labor costs of sampling and processing organisms; however, direct methods are still used in functional biodiversity assessment studies (e.g., Angelstam & Dönz-Breuss, 2004; Bustamante et al., 2016; Fusaro et al., 2018; Kujawa et al., 2020; Sigsgaard et al., 2017 and others). Data collection associated with measuring trait diversity is typically the most time-consuming step in functional biodiversity assessments (Angelstam & Dönz-Breuss, 2004), therefore there is significant interest in technologies and sampling methods that can increase the efficiency of trait diversity measurement.

Rapid biodiversity assessments (RBAs) have been developed to address some of the limitations of traditional assessment methods. The goal of RBAs is to assess biodiversity rapidly, reliably, cheaply, and comprehensively over large spatial scales (Yu et al., 2012). Some RBAs do not use DNA-based methods and instead rely on surrogate species, sampling, or taxonomy to conduct assessments more quickly. There is limited applicability of non-DNA based RBA methods to assess functional biodiversity because of the emphasis on traditional biodiversity measures, rather than functional measures. However, non-DNA based RBA methods may be used to measure functional groups that support ecosystem services. For example, Obrist & Duelli (2010) developed standardized methods for monitoring insects in forest and agriculture systems. Sampled insects were divided into morphospecies groups, which were then associated with ecosystem services such as pollination and biological control (Obrist & Duelli, 2010). Though these were crude, relative measures, this technique revealed the development of pollinator and natural enemy diversity over time (Obrist & Duelli, 2010), which could subsequently be used to assess temporal functional biodiversity. Rapid biodiversity assessment techniques can be applied to plants as well. Lavorel et al. (2008) found that rapid visual estimates of biomass and dominance ranks performed well compared to the more time-consuming hand sorting methods. The authors suggest that it is most important to assess the most abundant species when rapid methods are used to assess functional biodiversity. Therefore, rapid methods are best suited to situations with less-even abundances (Lavorel et al., 2008).

DNA-based RBA methods present a valuable opportunity to assess functional biodiversity, particularly for soil and arthropod diversity. Advanced techniques such as metabarcoding can provide manageable and meaningful information about bulk samples using next-generation sequencing and bioinformatics software (Ritter et al., 2019; Yu et al., 2012). For example, functional microarray platforms can detect functional genes associated with soil ecosystem services, such as nutrient cycling (He et al., 2010; Wakelin et al., 2016). This technology makes it possible to assess the functional capacity of a soil ecosystem and how it changes over time and space (Wakelin et al., 2016). Metabarcoding has been used in RBAs of arthropods, though the primary application has been in assessing traditional biodiversity measures, (e.g., Hupało et al., 2021; Yu et al., 2012) rather than functional biodiversity. This may be, in part, due to the limitations of using metabarcoding to empirically quantify ecological interactions (Evans et al., 2016).

Combining metabarcoding with ecological network analysis can address these limitations by depicting species interaction networks in a phylogenetically structured way (Evans et al., 2016). Additional limitations of metabarcoding for assessing arthropod diversity include the varying efficacy of trapping methods across different arthropod groups (Montgomery et al., 2021). Little information is available on the use of metabarcoding for assessing plant diversity which can be assessed rapidly using other techniques (Lavorel et al., 2008).

Remote sensing offers an opportunity to assess functional biodiversity variables such as changes in ecosystem function and species traits, particularly in plants (Cavender-Bares et al., 2020; Reddy et al., 2021; Skidmore et al., 2021). Skidmore et al. (2021) prioritized biodiversity measures observable through remote imagery to produce a list of operationally realistic remote sensing biodiversity variables. Fourteen variables were in the "ecosystem function" class of essential biodiversity variables, and ten were classified as "species traits" (Skidmore et al., 2021), indicating the potential use of remote sensing to measure functional biodiversity. The authors identified key compatibility issues between remote sensing and essential biodiversity variables that will need to be addressed by integrating other techniques, e.g., eDNA, and advanced technology to produce useful biodiversity measures via remote sensing (Skidmore et al., 2021). It is important to use remote sensing in conjunction with *in situ* observations to optimally measure functional biodiversity across spatial and temporal scales (Cavender-Bares et al., 2020; Cavender-Bares, Schneider, et al., 2022). Technological advances make it possible to derive plant functional traits from imaging spectroscopy and high-resolution satellites at large spatial scales which can complement in situ measurements to expand the scale of sampling (Cavender-Bares, Schneider, et al., 2022; Helfenstein et al., 2022). Remote sensing can also be used to categorize vegetation into phylogenetic-functional groups to ultimately predict below-ground processes (Cavender-Bares, Schweiger, et al., 2022; Madritch et al., 2014).

5. Weighting traits according to their relative functional importance

Assigning weights to traits according to their relative functional importance remains an opportunity for further development. The process of assigning weights may be done in consultation with experts or other stakeholders using the functional biodiversity assessment. This approach leaves substantial room for subjectivity in assigning weights based on human values. Callo-Concha (2009) used a multicriteria analysis and analytical hierarchy process to systematically score and weight factors related to functional biodiversity in agroforestry systems in Brazil. Multicriteria analysis assists stakeholders in assigning the relative importance of various factors, and an analytical hierarchy process helps a researcher mathematically obtain an indicator of system performance (Callo-Concha, 2009). Multicriteria analysis and the analytical hierarchy process offer ways to reduce subjectivity and bias in assigning weights to traits.

6. Measure and quantify functions through indices to explain and predict variation in ecosystem processes

One benefit of assessing functional biodiversity is the ability to explain and predict variations in ecosystem processes. Indices can aggregate raw measurements and translate them into actionable data for decision-makers. Indices that are suitable for general use must include multiple traits, account for abundances, and measure all facets of functional biodiversity (Villéger et al., 2008). Functional richness, evenness, and divergence (as conceptualized by Villéger et al., 2008) are frequently used indices for quantifying functional biodiversity (e.g., Bàrberi, 2015; Helfenstein et al., 2022; Scherer et al., 2020; Yin et al., 2020 and others). Scherer et al. (2020) studied how functional biodiversity varied across different land use types. The authors found that functional richness and divergence decreased as environmental quality decreased, while functional evenness increased (Scherer et al., 2020). Yin et al. (2020) found that land use intensification decreased functional biodiversity; specifically functional richness decreased with increased intensification, while functional divergence did not change, and functional evenness increased. Both groups of authors were able to compare their results to other studies because they used common functional biodiversity indices. Rao's quadratic entropy index[4] is also commonly used to measure functional biodiversity (e.g., Aubin et al., 2013; Damptey et al., 2022; Malíček et al., 2019). Using a common set of functional biodiversity indices enables comparisons across studies to help us better understand the mechanistic links between organisms and ecosystems.

Other functional indices have been developed to assess functional biodiversity in specific contexts. For example, Fusaro et al. (2018) used several soil biological quality indices to evaluate soil quality based on the presence of arthropods and earthworms in organic and conventional horticultural crops. The authors also compared functional indices to traditional biodiversity indices and found that the taxonomic composition of groups did not always change but nearly all functional indicators had significantly higher values in organic production (Fusaro et al., 2018). These results highlight the importance

---

[4] Rao's quadratic entropy index describes the variation of species trait composition within a community by summing pairwise distances between species and weighting them by their relative abundances (Aubin et al., 2013)

of computing functional biodiversity indices in addition to traditional indices when comparing agroecosystem functioning under different production practices.

Case Study: On-Farm Biodiversity Assessment of Gerber Growers

Context

Gerber is a baby food company based in Fremont, Michigan, USA and is owned by Nestlé. Gerber works directly with many of its agricultural suppliers to source high-quality and safe ingredients. This sourcing strategy includes an industry-leading integrated pest management (IPM) program, a list of approved pesticides, and a soil testing program.

Nestlé joined One Planet Business for Biodiversity (OP2B) in 2019, committing to support and implement projects across three pillars: scaling up regenerative agriculture, enhancing cultivated biodiversity, and protecting high-value ecosystems (World Business Council for Sustainable Development, 2023). To support OP2B and Nestlé's internal reporting, Gerber conducted on-farm biodiversity assessments in June-August 2021 to establish baseline measurements for ongoing monitoring. A secondary goal of the assessment was to investigate any potential relationships between conventional or regenerative agriculture practices and biodiversity metrics.

This section details the methods, selected results, and future directions of the assessments conducted at six apple orchards and in two squash fields. The information presented in this section is from an unpublished internal report I delivered to Gerber/Nestlé at the end of my internship. All grower-identifying information has been anonymized or removed and I have received permission from Gerber to share this abbreviated version of the report.

Methods

Soil microbe and beneficial arthropod assessments were conducted to develop a more holistic picture of on-farm biodiversity and establish a baseline for future monitoring.

a. Site selection

A block/field supplied to Gerber (and therefore under Gerber's pesticide program) was identified by each grower and Gerber Procurement. Farms were paired by region and production practices ("conventional" or "regenerative"). Production practices were characterized based on the procurement team's knowledge of the grower's practices. Growers implementing soil health-building practices and advanced IPM programs were characterized as "regenerative", while growers who comply with Gerber's pesticide restriction program but do not implement additional soil health or IPM practices were characterized as "conventional". Site information is summarized in Table 2.1.

Table 2.1 Site information for farms and blocks included in biodiversity assessment.

Region	**Block/Field Size[1] (Acres)**	**Production Practices**	**Dominant Soil Type[1]**
		Apples	
West-Central	4	Conventional	Loam
	18.4	Regenerative	Loam
Southwest	14.8	Conventional	Loamy sand
	16.5	Regenerative	Loam
Northwest	14.8	Conventional	Sand
	9.4	Regenerative	Sand
		Squash	
West-Central	34.9	Conventional	Sand/Loamy sand
West-Central	1.92	Regenerative	Sand

[1]Block size and dominant soil type were determined using Web Soil Survey (USDA Natural Resources Conservation Service, 2019)

b. Soil microbiome assessment

During the first site visit, a composite soil sample was obtained by taking the top six inches of soil from 10 soil cores. A "W"-shaped pattern across the block/field was walked to obtain a representative sample. In orchards, soil cores were taken approximately two feet from trunks. Samples were kept cool during transport and were then frozen until shipping. A BeCrop® Test was conducted by Biome Makers, Inc. to identify bacteria and fungi present in the soil and derive information on soil nutrient cycling, health, and biodiversity. The BeCrop® Test uses a patented DNA sequencing and bioinformatic process to analyze the soil microbiome.

c. Beneficial arthropod sampling and monitoring

Beneficial arthropod presence was monitored at each site approximately every two weeks (four total monitoring events per site) using protocols adapted from Kay Cruz et al. (2019). All monitoring was conducted on a 200-foot transect using the locations and techniques in

Table 2.2.2. A new transect was randomly selected for each visit to minimize effects related to location. Monitoring was conducted at different times of day to minimize effects related to temperature and windspeed.

Table 2.2. Beneficial arthropod monitoring locations and techniques

Type	**Location in Orchard/Field**	**Technique**
Foliage	Alley/Field edge	Sweep net
Foliage	Branch/Leaf	Beat sheet, sticky trap
Floral	Alley/Field edge	Observation

d. Beneficial arthropod groups

The list of beneficial arthropod groups monitored was adapted from Kay Cruz et al. (2019) and can be found in Table 2.3, along with their ecological functions.

Table 2.3. Beneficial arthropod groups monitored and their corresponding ecological functions.

Arthropod group	**Ecological function(s)**
Bumble bee	Pollination
Honeybee	Pollination
Native bee	Pollination
Syrphid fly	Pollination (adults), preys on aphids and soft-bodied insects (larvae)
Predatory wasp	Preys on caterpillars, soft-bodied insects
Brown lacewing	Generalist predator, preys on aphids and whiteflies
Green lacewing	Preys on aphids, leafhoppers, lygus bugs, mealybugs, mites, psyllids, small caterpillars, soft scale, thrips, whiteflies, eggs of insect pests
Lady beetle	Preys on aphids, mealybugs, mites, soft scale, whiteflies, eggs of insect pests
Minute pirate bug	Preys on leafhoppers, mites, small caterpillars, thrips, eggs of insect pests
Spider	Preys on aphids, cucumber beetles, flea beetles, leafhoppers, lygus bugs, eggs of insect pests

Selected results and discussion

a. Soil microbial diversity

The BeCrop® Test report presented three qualitative indices developed by Biome Makers related to “biosustainability”, representing indicators of biological states or conditions of the agroecosystem where the block or field is located. These indices (biodiversity, functionality, resistance) are related to management practices. Low values are associated with more aggressive management practices, whereas high values are associated with less aggressive management practices. Results are presented in Table 2.4.

Table 2.4. Comparative results for three indices of biosustainability based on BeCrop® analysis of soil microbiome.

Region	**Production Practice**[1]	**Functionality**	**Resistance**	**Biodiversity**
			Apples	
West-Central	Conventional	Medium	Low	High
	Regenerative	High	Low	Very High
Southwest	Conventional	Very High	Very Low	High
	Regenerative	Very High	Low	High
Northwest	Conventional	High	Very Low	Very High
	Regenerative	Very High	Low	Very High
			Squash	
West-Central	Conventional	*TBD*[1]	*TBD*[1]	*TBD*[1]
West-Central	Regenerative	Very High	Medium	High

[1]Results of West-Central CV soil microbiome analysis were in-progress at the time of report

i. Functionality

The functionality index reports on the ability of soil microbial communities to perform multiple functions, such as nutrient cycling. Six of the eight assessed farms had either "high" or "very high" functionality ratings, indicating good soil management practices. The high functionality ratings for most assessed farms are likely a result of these appropriate soil management decisions.

ii. Resistance

The resistance index indicates how well the soil microbial communities can withstand stress due to disturbance, based on an ecological network analysis. Ecological network analysis looks at properties of system-level interactions that may not be evident through direct observation, like the ability of microbial communities or populations to withstand stress or disturbance (Fath et al., 2007). Six of the eight assessed farms had either "low" or "very low" resistance ratings. When calculating the resistance rating, a higher number of redundant microbial groups is correlated with higher resistance to disturbances (Dr. M. Hynes, personal communication, August 5, 2021). This implies that soils with “low” or “very low” resistance ratings have less redundancy of microbial groups that perform similar functions in the soil. Therefore, if a disturbance (e.g., tillage or pesticide application) harms a particular microbial group, another group may not be present to perform that function. Healthy soils typically have “backups” or multiple groups that provide redundance, and thus resistance to disturbance.

iii. Biodiversity

The biodiversity index reports the species richness (number of species) and evenness (relative abundance) found in the soil sample. Seven farms had “high” or “very high” biodiversity ratings. This is a result of good soil management practices implemented on farms. Orchards are permanent cropping systems with near complete ground coverage which can help maintain soil microbe populations and likely contribute to the high biodiversity ratings in orchards. Annual cropping systems can include practices to enhance and conserve soil microbial biodiversity. For example, the assessed field at the West-Central regenerative squash site had an overwintered rye cover crop, which provided food for soil microbes. Additionally, crop rotation and diversity in annual production systems can support a diversity of soil microbes, as different microbial communities prefer different crops. The high biodiversity ratings for all assessed farms highlight positive outcomes of their soil management practices.

iv. Future directions for functional biodiversity in soils

The preliminary soil microbiome analysis results provide multiple directions for future research. Specifically, the functionality and resistance indices offer insights into soil functional biodiversity. A detailed exploration of the West-Central conventional apple orchard's functionality index results could provide more specific information, e.g., which functional group(s) are present or absent in comparison to the other orchards, what are the implications of a "medium" functionality rating, and what practice(s) could be implemented to improve the functionality rating? Research questions regarding the resistance index could include: Are the same functional groups present or absent in the samples from apple orchards as compared to vegetable fields, e.g., is the lower resistance rating a result of the cropping system or something else? Is there something unique about annual or vegetable production that might explain the higher resistance, e.g., do more frequent disturbances select for microbial communities with higher resistance?

b. Beneficial arthropod diversity

The Shannon diversity index, a traditional biodiversity index, was calculated for each farm to account for species density and evenness of beneficial arthropods. Higher index values indicate higher diversity, while lower index values indicate lower diversity (Table 2.5).

Table 2.5. Shannon diversity index (SDI) values for beneficial arthropod diversity on assessed farms (cumulative from four monitoring events).

Region	**Production Practice (SDI)**	
	Conventional	**Regenerative**
	Apples	
West-Central	0.592	0.484
Southwest	1.208	1.290
Northwest	1.177	1.381
	Squash	
West-Central	1.738	1.357

Production practices did not have a consistent effect on Shannon diversity index values. Regenerative orchards had higher index values than conventional in two cases (Southwest and Northwest region pairs), while conventional farms or orchards had higher index values than regenerative in the other two cases (West-Central region pairs). Note that these results represent a small sample size (four monitoring events per site) and only a single season. Additionally, the amount of time between monitoring events and pesticide or herbicide application or mowing was not controlled and may have influenced arthropod counts. Time since application or mowing would be challenging variables to control, but these could be recorded in future years to better understand their potential effects on arthropod counts.

Population density can be affected by environmental conditions (e.g., air temperature, cloud cover) during sampling and by other biological factors, like nutrient inputs (Brewer, 1979). Efforts were made to minimize the effects of environmental and biological factors by sampling at different times of day and randomly selecting a new transect during each sampling event. Despite these efforts, it is possible that environmental and biological factors influenced population density measurements and introduced sampling variability. Environmental conditions were recorded for each monitoring event and further analysis could be conducted to account for their effect on species density. Evenness is affected by agricultural management practices, including pesticide use and integrated pest management approaches. There is some evidence to demonstrate an increase in evenness when organic or integrated/ecological approaches are adopted (Crowder et al., 2012; Porcel et al., 2018). Future measurements and analyses could investigate the potential influence of existing integrated or ecological practices on population density and evenness. These results can be used as a baseline by which to compare future results, particularly to examine the effects of new pest management or biodiversity-enhancing practices, e.g., creating arthropod habitat.

i. Future directions for functional biodiversity of above-ground arthropods

Functional biodiversity was not explicitly assessed in this study. Further analysis could be conducted on the functional groups of beneficial arthropods, i.e., pollinators and natural enemies, to assess the impacts of diversity on pollination and biological control. Additionally, data could be collected to compare herbivore diversity to measure the response of this functional group to different management practices. DNA-based RBA techniques, such as metabarcoding, could provide a complementary view of functional biodiversity on farms. Combining metabarcoding with ecological network analysis could be a useful way to depict species interaction networks with attention to phylogenetic relationships (Evans et al., 2016). Additional studies could be conducted to examine correlations between specific practices (e.g., pesticide timing to preserve beneficials, maintaining habitats or refuges) and functional biodiversity on farms.

c. Application of results and discussion of functional biodiversity

The results of this assessment are intended to serve as a baseline, and it is Gerber's intention to monitor populations over time. Growers were provided with a report, including a regional comparison with the paired farm. Growers may use the results of this assessment to understand past and present practices, and to inform future management practices to conserve and enhance soil microbial and arthropod biodiversity on their farm. Information resources about practices to enhance on-farm biodiversity were included at the end of the grower report. This baseline can also be used to evaluate any changes in biodiversity if new management practices are introduced.

This assessment offers farm-level above- and below-ground biodiversity data to begin to measure outcomes of farm-level practices on regenerative and conventional farms supplying to Gerber. These data, in combination with grower survey responses, can offer "ground-truthing" of the effects of regenerative agriculture practices on biodiversity. Gerber and Nestlé can utilize the results of this assessment to support reporting against internal and external commitments, e.g., Nestlé regenerative sourcing goals and OP2B membership.

Adopting a functional biodiversity perspective could be a useful way to communicate results to growers and other supply chain stakeholders. Growers have many different perspectives on functional biodiversity, its role in their operation, and how they make management decisions regarding functional biodiversity (Cardona et al., 2021; Erisman et al., 2016; Penvern et al., 2019). Gerber/Nestlé and other supply chain stakeholders may have different perspectives and values associated with biodiversity (Vermeulen & Koziell, 2002). The functional biodiversity approach offers a mechanistic link between organisms and ecosystems (Petchey & Gaston, 2006), which may help integrate values held by different stakeholders. Growers are more likely to hold indirect values, i.e., benefits derived from environmental services that biodiversity may enhance, while other supply chain stakeholders may hold a combination of indirect and non-use values, i.e., the inherent value of biodiversity and the option to use biodiversity in the future. A functional biodiversity perspective could help integrate these sets of values by better elucidating how biodiversity and agricultural production are connected than if traditional biodiversity measures were used.

Elements of the 2021 biodiversity assessment included a functional biodiversity perspective, and other elements could be adapted to incorporate functional biodiversity in the future. The assessment goal could be modified to place more emphasis on functional biodiversity, including soliciting grower input on the goal to align the assessment with their personal and operational objectives. The selected ecosystem services (nutrient cycling, stress adaptation, biological control, and pollination) align with a functional biodiversity lens. Biome Makers Inc. has selected various functional traits related to the soil microbiome which are incorporated into the BeCrop® Test. These traits include phytohormones produced by microbes related to plant growth, microbial metabolism related to stress adaptation, and microbial mobilization of nutrient pathways (Biome Makers, 2021). Functional traits were not defined when measuring aboveground biodiversity, but functional groups relating to pollination and biological control were defined. This level of definition was appropriate for the assessment goal and resources available. The BeCrop® Test was an effective way to measure functional traits associated with belowground microbial biodiversity. Molecular-based RBA techniques (e.g., eDNA) could be used to assess belowground arthropod biodiversity if desired (see Yin et al., 2020). The non-molecular RBA protocol for measuring aboveground biodiversity could be modified to monitor pollinators and natural enemies over a longer period with additional types of traps. However, depending on the scale, the mortality of beneficial arthropods may need to be considered. Traits were not weighted in this case study, and this represents another opportunity for grower input, as the potential users could be surveyed to provide relative weights for each trait. Functional biodiversity indices could be calculated in the future to complement traditional biodiversity indices and provide another layer of information to guide decision-making.

Case Study: Biodiversity Assessments in Carbon Offset Projects

Context

The Arbor Day Foundation is a national non-profit conservation and education organization whose mission is to "inspire people to plant, nurture, and celebrate trees" (Arbor Day Foundation, n.d.-a). Part of the Arbor Day Foundation's work involves helping corporate partners meet their climate and sustainability goals by funding global tree-planting efforts, including the sale of forestry carbon credits. Carbon credits are a way to quantify environmental benefits (e.g., the reduction of one metric ton of carbon dioxide) to compensate for or neutralize greenhouse gas emissions emitted elsewhere (Arbor Day Foundation, n.d.-b). The Arbor Day Foundation purchases and sells carbon credits generated by forests and invests in forestry projects that will generate new credits. There is substantial interest in assessing and communicating about "co-benefits" of forest carbon projects, including benefits to biodiversity. There is often an assumption that forest restoration has a positive impact on biodiversity; however, carbon projects can have a negative effect on biodiversity if low-carbon, high-biodiversity forests are replaced by high-carbon, low-biodiversity forests, e.g., monocultures (Bustamante et al., 2016). This case study will present two current standards that assess biodiversity in forest carbon projects and provide an analysis and recommendations for the inclusion of functional biodiversity in these standards.

Climate, Community, and Biodiversity Standards (Verified Carbon Standard Program)

The Climate, Community, and Biodiversity (CCB) Standards were designed to help develop and market projects that generate significant and valid benefits to climate, communities, and biodiversity (Verified Carbon Standard, 2017). Projects using the CCB Standards are certified by independent, third-party auditors to validate the project design and verify its implementation to demonstrate climate, community, and biodiversity benefits (Verra, n.d.). The CCB Standards must be used in conjunction with a carbon accounting standard to issue carbon credits (Verified Carbon Standard, 2017). This discussion will focus on the biodiversity section of the CCB Standards and is not intended to be a comprehensive overview of the Standards.

The CCB Standards require project proponents to describe the original biodiversity conditions in the project zone, anticipated changes without the project, and net positive biodiversity impacts over the lifetime of the project (Verified Carbon Standard, 2017). There is an emphasis on describing the original species diversity and habitat and rare ecosystems in the project zones, but there is no explicit mention of functional biodiversity. Predicting changes in the project zone in the absence of a project (i.e., "reference or baseline scenario") represents an opportunity to incorporate learnings from functional biodiversity studies, which can help explain or predict ecosystem processes based on changes in biodiversity.

Estimating net positive biodiversity impacts includes discussing the major biodiversity objectives of the project, planned project activities with expected biodiversity impacts, identifying and mitigating risks to biodiversity benefits, and implementing measures to ensure biodiversity benefits extend beyond the project's life

(Pitman, 2011). Project proponents can incorporate functional biodiversity into their major objectives, along with objectives related to compositional and structural biodiversity. Including objectives for the three types of biodiversity can lead to more holistic insights than focusing solely on one type of biodiversity.

Indicators are used to estimate and monitor expected biodiversity impacts of project activities and should be clearly linked to the project's biodiversity objectives and management interventions (Pitman, 2011). The process of selecting biodiversity indicators for monitoring is another opportunity to incorporate functional biodiversity into the project design. Selecting functional indicators or traits can help elucidate links between organisms and ecosystem processes. When selecting indicators, it may be useful to distill traits down to primary indicators that are functionally linked to a range of other species (Erisman et al., 2016; Ferris & Humphrey, 1999). Traits or indicators should be quantifiable, easy and cost-effective to assess, repeatable, and ecologically meaningful (Ferris & Humphrey, 1999; Pitman, 2011).

Plan Vivo Nature (Plan Vivo)

The Plan Vivo Foundation is an internationally recognized Standard in the voluntary carbon market and has developed Plan Vivo Nature (PV Nature) as a standalone Biodiversity Standard (Plan Vivo, 2022b). PV Nature certifies biodiversity conservation efforts and delivers biodiversity certificates representing benefits to nature to direct private investment into projects restoring or conserving biodiversity (Plan Vivo, 2022b). This discussion will focus on the biodiversity methodology underpinning PV Nature and is not intended to be a comprehensive overview of the Standard.

PV Nature requires project proponents to select a baseline or reference scenario, choose biodiversity metrics, and measure biodiversity uplift or avoided loss to calculate awardable biodiversity certificates (Plan Vivo, 2022a). PV Nature suggests the following considerations when identifying alternative land-use scenarios for the baseline scenario: historical trends, participatory information from communities, surveys of project region, and recent or plausible future changes to national or regional legislation (Plan Vivo, 2022a). The results of functional biodiversity studies in the region can offer additional insights on the relationships between organisms and ecosystem processes to complement the aforementioned sources.

PV Nature provides the following guidance to project proponents regarding the selection of biodiversity metrics:

1. Minimum of five metrics per project
2. Include at least one habitat or floral composition metric (if site is terrestrial)
3. Exclude carbon sequestration
4. Reflect conservation objectives for ecoregions and habitats in project site
5. Include metrics for all ecosystem services likely to be affected by proposed management plan (Plan Vivo, 2022a)

Functional biodiversity can be incorporated into conservation objectives for ecoregions and habits in the project sites and subsequently influence selected biodiversity metrics. The requirement to select metrics for all ecosystem services also represents an opportunity to incorporate functional biodiversity. Selecting functional traits related to a particular ecosystem service can contribute to a metric that adequately portrays the effects of changes in biodiversity on ecosystem services. Scores are assigned to data to minimize the risk of metrics being dominated by a small number of highly abundant species and to positively impact species of high conservation value (Plan Vivo, 2022a). There is an opportunity to include functional biodiversity in the scoring process. This can be done by including a score that rewards projects for increasing the functional biodiversity of species related to the assessed ecosystem services.

Biodiversity values from each metric are aggregated to quantify biodiversity uplift or avoided loss, which are then used to calculate awardable biodiversity certificates. All metrics are treated equally in this process; however, functional biodiversity could be included by assigning higher weights to metrics of higher functional importance.

Discussion

There is growing interest in assessing and quantifying biodiversity co-benefits of forest carbon offset projects (Pitman, 2011; Plan Vivo, 2022b; Verra, n.d.). The CCB Standards and PV Nature Standard present methods for assessing and communicating about biodiversity co-benefits, and, in the case of PV Nature, award biodiversity certificates. The CCB Standards do not explicitly address functional biodiversity, while PV Nature includes functional biodiversity considerations in its guidance for selecting biodiversity metrics. Functional biodiversity studies can help project proponents develop the baseline or reference scenario in both standards, by estimating biodiversity if the project activities did not occur. Project proponents pursuing either standard could include functional biodiversity objectives in their project objectives, which influence the project design. In the case of PV Nature, biodiversity metrics of higher functional importance could be more heavily weighted when calculating awardable biodiversity certificates. Functional biodiversity considerations should be included in these and future biodiversity standards to provide a more holistic assessment of forest carbon project impacts on biodiversity.

Conclusion

The case studies presented in this chapter are examples of real-world applications of functional biodiversity assessments in agroecosystems and forests. Both case studies demonstrate the significant potential to incorporate functional biodiversity into assessments, particularly in the selection of traits or indicators of biodiversity. Soil functional biodiversity was assessed in the Gerber case study, providing a snapshot of soil microbial functioning. Arthropod biodiversity was partially assessed through a functional lens, by sorting arthropods into groups based on their ecological function (e.g., pollination, predation). Incorporating functional biodiversity into the Gerber assessment could help increase grower buy-in by communicating the contributions of biodiversity to critical production ecosystem services, such as nutrient cycling and pollination. Functional biodiversity is implicitly assessed in biodiversity metric selection in the PV Nature standard, but it is not included in the CCB Standards. Incorporating functional biodiversity into the CCB and PV Nature Standards could help project proponents to holistically assess biodiversity and ultimately direct additional private investment to biodiversity conservation.

The general steps of functional biodiversity assessments can be used in both agroecosystems and forests with context-specific modifications. Agroecosystems and forests differ primarily in the degree of human management. For example, human management is omnipresent in agroecosystems; therefore, functional groups are a result of human management and assessments evaluate how functional groups work to provide ecosystem services related to production (Moonen & Bàrberi, 2008). Functional biodiversity assessments in minimally managed or 'natural' forests may look different from managed forests and agroecosystems, as the functional groups present are not a result of human management and different ecosystem services may be prioritized. A variety of tools and technologies can be used to measure functional biodiversity traits and indicators directly and indirectly. This is an area of substantial innovation and research. Functional biodiversity assessments will become more accessible and practical as technology and our understanding of functional traits evolves.

References

Alhadidi, S. N., Fowler, M. S., & Griffin, J. N. (2019). Functional biodiversity of predators and parasitoids does not explain aphid biocontrol efficiency. *BioControl*, *64*(3), 303–313. https://doi.org/10.1007/s10526-019-09936-2

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, *74*(1), 19–31. https://doi.org/10.1016/S0167-8809(99)00028-6

Altieri, M. A., Nicholls, C. I., & Lana, M. A. (2017). Agroecology: Using functional biodiversity to design productive and resilient polycultural systems. In D. Hunter, L. Guarino, C. Spillane, & P. C. McKeown (Eds.), *Routledge handbook of agricultural biodiversity* (1st ed., pp. 224–237). Routledge.

Angelstam, P., & Dönz-Breuss, M. (2004). Measuring Forest Biodiversity at the Stand Scale: An Evaluation of Indicators in European Forest History Gradients. *Ecological Bulletins*, *51*, 305–332. JSTOR. http://www.jstor.org.libproxy.unl.edu/stable/20113319

Arbor Day Foundation. (n.d.-a). *About the Arbor Day Foundation*. About the Arbor Day Foundation. Retrieved February 24, 2023, from https://www.arborday.org/about/

Arbor Day Foundation. (n.d.-b). *Carbon Credits Defined | Forestry Carbon Credits*. The Arbor Day Foundation. Retrieved February 24, 2023, from https://www.arborday.org/carbon/carbon-credits.cfm

Aubin, I., Venier, L., Pearce, J., & Moretti, M. (2013). Can a trait-based multi-taxa approach improve our assessment of forest management impact on biodiversity? *Biodiversity and Conservation*, *22*(12), 2957–2975. https://doi.org/10.1007/s10531-013-0565-6

Bàrberi, P. (2015). Functional biodiversity in organic systems: The way forward? *Sustainable Agriculture Research*, *4*(526-2016–37937).

Bàrberi, P., Burgio, G., Dinelli, G., Moonen, A. C., Otto, S., Vazzana, C., & Zanin, G. (2010). Functional biodiversity in the agricultural landscape: Relationships between weeds and arthropod fauna. *Weed Research*, *50*(5), 388–401. https://doi.org/10.1111/j.1365-3180.2010.00798.x

Barberi, P., & Moonen, A. C. (2020). Functional biodiversity for the provision of agroecosystem services. In *Reconciling agricultural production with biodiversity conservation* (pp. 101–146). Burleigh Dodds Science Publishing. http://dx.doi.org/10.19103/AS.2020.0071.12

Biome Makers. (2021). *BeCrop Test*. Biome Makers. Sacramento, CA.

Brewer, R. (1979). Population density and population regulation. In *Principles of ecology* (pp. 65–77). W.B. Saunders Company.

Brockerhoff, E. G., Barbaro, L., Castagneyrol, B., Forrester, D. I., Gardiner, B., González-Olabarria, J. R., Lyver, P. O., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I. D., van der Plas, F., & Jactel, H. (2017). Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodiversity and Conservation*, *26*(13), 3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Bustamante, M. M., Roitman, I., Aide, T. M., Alencar, A., Anderson, L. O., Aragão, L., Asner, G. P., Barlow, J., Berenguer, E., & Chambers, J. (2016). Toward an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity. *Global Change Biology*, *22*(1), 92–109. https://doi.org/doi: 10.1111/gcb.13087

Callo-Concha, D. (2009). *An approach to environmental services assessment: Functional biodiversity in tropical agroforestry systems (The case of Tomé-Açú, Northern Brazil)* [University of Bonn]. https://bonndoc.ulb.uni-bonn.de/xmlui/bitstream/handle/20.500.11811/3938/1671.pdf?sequence=1&isAllowed=y

Cardona, A., Tchamitchian, M., Penvern, S., Dufils, A., Kramer Jacobsen, S., Korsgaard, M., Porcel, M., Świergiel, W., Tasin, M., Warlop, F., & Sigsgaard, L. (2021). Monitoring methods adapted to different perceptions and uses of functional biodiversity: Insights from a European qualitative study. *Ecological Indicators*, *129*, 107883. https://doi.org/10.1016/j.ecolind.2021.107883

Cavender-Bares, J., Gamon, J., & Townsend, P. (Eds.). (2020). *Remote Sensing of Plant Biodiversity*. Springer Nature. https://doi.org/10.1007/978-3-030-33157-3

Cavender-Bares, J., Schneider, F. D., Santos, M. J., Armstrong, A., Carnaval, A., Dahlin, K. M., Fatoyinbo, L., Hurtt, G. C., Schimel, D., Townsend, P. A., Ustin, S. L., Wang, Z., & Wilson, A. M. (2022). Integrating remote sensing with ecology and evolution to advance biodiversity conservation. *Nature Ecology & Evolution*, *6*(5), Article 5. https://doi.org/10.1038/s41559-022-01702-5

Cavender-Bares, J., Schweiger, A. K., Gamon, J. A., Gholizadeh, H., Helzer, K., Lapadat, C., Madritch, M. D., Townsend, P. A., Wang, Z., & Hobbie, S. E. (2022). Remotely detected aboveground plant function predicts belowground processes in two prairie diversity experiments. *Ecological Monographs*, *92*(1), e01488. https://doi.org/10.1002/ecm.1488

Conway, G. R. (1987). The properties of agroecosystems. *Agricultural Systems*, *24*(2), 95–117. https://doi.org/10.1016/0308-521X(87)90056-4

Ćosović, M., Bugalho, M. N., Thom, D., & Borges, J. G. (2020). Stand structural characteristics are the most practical biodiversity indicators for forest management planning in Europe. *Forests*, *11*(3), 343. https://doi.org/doi:10.3390/f11030343

Costanzo, A., & Bàrberi, P. (2014). Functional agrobiodiversity and agroecosystem services in sustainable wheat production. A review. *Agronomy for Sustainable Development*, *34*(2), 327–348. https://doi.org/10.1007/s13593-013-0178-1

CPF. (2008). *Strategic framework for forests and climate change. A proposal by the Collaborative Partnership on Forests for a coordinated forest-sector response to climate change*.

Crowder, D. W., Northfield, T. D., Gomulkiewicz, R., & Snyder, W. E. (2012). Conserving and promoting evenness: Organic farming and fire-based wildland management as case studies. *Ecology*, *93*(9), 2001–2007. https://doi.org/10.1890/12-0110.1

Damptey, F. G., Birkhofer, K., Oliveras Menor, I., & de la Riva, E. G. (2022). The Functional Structure of Tropical Plant Communities and Soil Properties Enhance Ecosystem Functioning and Multifunctionality in Different Ecosystems in Ghana. *Forests*, *13*(2), Article 2. https://doi.org/10.3390/f13020297

Diaz, S., Settele, J., & Brondizio, E. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the*

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://www.biologicaldiversity.org/programs/biodiversity/pdfs/Summary-for-Policymakers-IPBES-Global-Assessment.pdf

Erisman, J. W., Eekeren, N. van, Wit, J. de, Koopmans, C., Cuijpers, W., Oerlemans, N., & Koks, B. J. (2016). Agriculture and biodiversity: A better balance benefits both. *AIMS Agriculture and Food*, *1*(2), 157–174. https://scholarlypublications.universiteitleiden.nl/access/item%3A3209880/view

Evans, D. M., Kitson, J. J., Lunt, D. H., Straw, N. A., & Pocock, M. J. (2016). Merging DNA metabarcoding and ecological network analysis to understand and build resilient terrestrial ecosystems. *Functional Ecology*, *30*(12), 1904–1916. https://doi.org/doi: 10.1111/1365-2435.12659

Fath, B. D., Scharler, U. M., Ulanowicz, R. E., & Hannon, B. (2007). Ecological network analysis: Network construction. *Ecological Modelling*, *208*(1), 49–55. https://doi.org/10.1016/j.ecolmodel.2007.04.029

Ferris, R., & Humphrey, J. (1999). A review of potential biodiversity indicators for application in British forests. *Forestry*, *72*(4), 313–328. https://doi.org/10.1093/forestry/72.4.313

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., Renner, S., Schöning, I., Schumacher, U., Wells, K., Buscot, F., Kalko, E. K. V., Linsenmair, K. E., Schulze, E.-D., & Weisser, W. W. (2010). Implementing large-scale and long-term functional biodiversity research: The Biodiversity Exploratories. *Basic and Applied Ecology*, *11*(6), 473–485. https://doi.org/10.1016/j.baae.2010.07.009

Fusaro, S., Squartini, A., & Paoletti, M. G. (2018). Functional biodiversity, environmental sustainability and crop nutritional properties: A case study of horticultural crops in north-eastern Italy. *Applied Soil Ecology*, *123*, 699–708. https://doi.org/10.1016/j.apsoil.2017.06.023

Hainzelin, E. (2015). *Enhancing the function and provisioning of ecosystem services in agriculture: Agroecological principles*. https://agritrop.cirad.fr/591590/1/ID591590.pdf

He, Z., Deng, Y., Van Nostrand, J. D., Tu, Q., Xu, M., Hemme, C. L., Li, X., Wu, L., Gentry, T. J., Yin, Y., Liebich, J., Hazen, T. C., & Zhou, J. (2010). GeoChip 3.0 as a high-throughput tool for analyzing microbial community composition, structure and functional activity. *The ISME Journal*, *4*(9), 1167–1179. https://doi.org/10.1038/ismej.2010.46

Helfenstein, I. S., Schneider, F. D., Schaepman, M. E., & Morsdorf, F. (2022). Assessing biodiversity from space: Impact of spatial and spectral resolution on trait-based functional biodiversity. *Remote Sensing of Environment*, *275*, 113024. https://doi.org/10.1016/j.rse.2022.113024

Hupało, K., Majaneva, M., Czachur, M. V., Sire, L., Marquina, D., Lijtmaer, D. A., Ivanov, V., Leidenberger, S., Čiampor Jr, F., Čiamporová-Zaťovičová, Z., Mendes, I. S., Desiderato, A., Topstad, L., Meganck, K., Hariz Z. A., D., Kjærstad, G., Lin, X.-L., Price, B., Stevens, M., … Deiner, K. (2021). An urban

Blitz with a twist: Rapid biodiversity assessment using aquatic environmental DNA. *Environmental DNA*, *3*(1), 200–213. https://doi.org/10.1002/edn3.152

Hynes, M., Dr. (2021, August 5). *More details on the resistance index* [Personal communication].

Kay Cruz, J., Vaughn, M., Heidel-Baker, T., & Bolte, K. (2019). *Beneficial Insect Scouting Guide*. Xerces Society for Invertebrate Conservation. https://xerces.org/sites/default/files/publications/19-061.pdf

Kujawa, K., Bernacki, Z., Kowalska, J., Kujawa, A., Oleszczuk, M., Sienkiewicz, P., & Sobczyk, D. (2020). Annual Wildflower Strips as a Tool for Enhancing Functional Biodiversity in Rye Fields in an Organic Cultivation System. *Agronomy*, *10*(11), Article 11. https://doi.org/10.3390/agronomy10111696

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

Lavorel, S., Grigulis, K., McIntyre, S., Williams, N. S., Garden, D., Dorrough, J., Berman, S., Quétier, F., Thébault, A., & Bonis, A. (2008). Assessing functional biodiversity in the field–methodology matters! *Functional Ecology*, *22*(1), 134–147.

Lexer, M. J., & Seidl, R. (2009). Addressing biodiversity in a stakeholder-driven climate change vulnerability assessment of forest management. *Forest Ecology and Management*, *258*, S158–S167. https://doi.org/10.1016/j.foreco.2009.07.011

Madritch, M. D., Kingdon, C. C., Singh, A., Mock, K. E., Lindroth, R. L., & Townsend, P. A. (2014). Imaging spectroscopy links with below-ground landscape scales. *Philosophical Transactions of the Royal Society B*, *369*, 20130194. http://dx.doi.org/10.1098/rstb.2013.0194

Malaterre, C., Dussault, A. C., Mermans, E., Barker, G., Beisner, B. E., Bouchard, F., Desjardins, E., Handa, I. T., Kembel, S. W., Lajoie, G., Maris, V., Munson, A. D., Odenbaugh, J., Poisot, T., Shapiro, B. J., & Suttle, C. A. (2019). Functional biodiversity: An Epistemic Roadmap. *BioScience*, *69*(10), 800–811. https://doi.org/10.1093/biosci/biz089

Malíček, J., Palice, Z., Vondrák, J., Kostovčík, M., Lenzová, V., & Hofmeister, J. (2019). Lichens in old-growth and managed mountain spruce forests in the Czech Republic: Assessment of biodiversity, functional traits and bioindicators. *Biodiversity and Conservation*, *28*(13), 3497–3528. https://doi.org/10.1007/s10531-019-01834-4

Mammola, S., Carmona, C. P., Guillerme, T., & Cardoso, P. (2021). Concepts and applications in functional biodiversity. *Functional Ecology*, *35*(9), 1869–1885. https://doi.org/10.1111/1365-2435.13882

Marker, J., Bergman, E., Lutz Eckstein, R., & Lafage, D. (2022). Forested riparian buffer environmental variables are more important than size for species functional biodiversity in production forests. *Forest Ecology and Management*, *526*, 120599. https://doi.org/10.1016/j.foreco.2022.120599

Martin, E. A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., Garratt, M. P. D., Holzschuh, A., Kleijn, D., Kovács-Hostyánszki, A., Marini, L., Potts, S. G., Smith, H. G., Al Hassan, D., Albrecht, M., Andersson, G. K. S., Asís, J. D., Aviron, S., Balzan, M. V., … Steffan-Dewenter, I. (2019). The interplay of landscape composition and configuration: New pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecology Letters*, *22*(7), 1083–1094. https://doi.org/10.1111/ele.13265

Martin, E. A., Feit, B., Requier, F., Friberg, H., & Jonsson, M. (2019). Chapter Three—Assessing the resilience of biodiversity-driven functions in agroecosystems under environmental change. In D. A. Bohan & A. J. Dumbrell (Eds.), *Advances in Ecological Research* (Vol. 60, pp. 59–123). Academic Press. https://doi.org/10.1016/bs.aecr.2019.02.003

Montgomery, G. A., Belitz, M. W., Guralnick, R. P., & Tingley, M. W. (2021). Standards and Best Practices for Monitoring and Benchmarking Insects. *Frontiers in Ecology and Evolution*, *8*. https://www.frontiersin.org/articles/10.3389/fevo.2020.579193

Moonen, A.-C., & Bàrberi, P. (2008). Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems & Environment*, *127*(1), 7–21. https://doi.org/10.1016/j.agee.2008.02.013

Mori, A. S., Lertzman, K. P., & Gustafsson, L. (2017). Biodiversity and ecosystem services in forest ecosystems: A research agenda for applied forest ecology. *Journal of Applied Ecology*, *54*(1), 12–27. https://doi.org/doi: 10.1111/1365-2664.12669

Morton, S., & Hill, R. (2015). What is biodiversity, and why is it important? In *Biodiversity: Science and solutions for Australia* (pp. 1–12). CSIRO Publishing. https://www.researchgate.net/profile/Rosemary-Hill-4/publication/279197478_What_is_biodiversity_and_why_is_it_important/links/558ea75508ae1e1f9bacd67b/What-is-biodiversity-and-why-is-it-important.pdf

Njeru, E. M., Avio, L., Sbrana, C., Turrini, A., Bocci, G., Bàrberi, P., & Giovannetti, M. (2014). First evidence for a major cover crop effect on arbuscular mycorrhizal fungi and organic maize growth. *Agronomy for Sustainable Development*, *34*(4), 841–848. https://doi.org/10.1007/s13593-013-0197-y

Obrist, M. K., & Duelli, P. (2010). Rapid biodiversity assessment of arthropods for monitoring average local species richness and related ecosystem services. *Biodiversity and Conservation*, *19*(8), 2201–2220. https://doi.org/10.1007/s10531-010-9832-y

Penvern, S., Fernique, S., Cardona, A., Herz, A., Ahrenfeldt, E., Dufils, A., Jamar, L., Korsgaard, M., Kruczyńska, D., Matray, S., Ozolina-Pole, L., Porcel, M., Ralle, B., Steinemann, B., Świergiel, W., Tasin, M., Telfser, J., Warlop, F., & Sigsgaard, L. (2019). Farmers' management of functional biodiversity goes beyond pest management in organic European apple orchards. *Agriculture, Ecosystems & Environment*, *284*, 106555. https://doi.org/10.1016/j.agee.2019.05.014

Petchey, O. L., & Gaston, K. J. (2006). Functional biodiversity: Back to basics and looking forward. *Ecology Letters*, *9*(6), 741–758. https://doi.org/10.1111/j.1461-0248.2006.00924.x

Pitman, N. (2011). *Social and Biodiversity Impact Assessment (SBIA) Manual For REDD+ Projects: Part 3—Biodiversity Impact Assessment Toolbox*. Forest Trends, Climate, Community & Biodiversity Alliance, Rainforest Alliance, and Fauna & Flora International. https://www.forest-trends.org/wp-content/uploads/imported/sbia-part-3-pdf.pdf

Plan Vivo. (2022a). *Plan Vivo Biodiversity Standard (PV Nature) Biodiversity Methodology Version 1.1*. Plan Vivo. https://www.planvivo.org/Handlers/Download.ashx?IDMF=48306932-e026-4cb0-ba5a-2b30f4b5092b

Plan Vivo. (2022b). *Plan Vivo Biodiversity Standard (PV Nature) Project Requirements, Version 0.5*. Plan Vivo. https://www.planvivo.org/Handlers/Download.ashx?IDMF=a99f0ac6-f923-4463-9e89-5884cce2616e

Porcel, M., Andersson, G. K. S., Pålsson, J., & Tasin, M. (2018). Organic management in apple orchards: Higher impacts on biological control than on pollination. *Journal of Applied Ecology*, *55*(6), 2779–2789. https://doi.org/10.1111/1365-2664.13247

Reddy, C. S., Kurian, A., Srivastava, G., Singhal, J., Varghese, A. O., Padalia, H., Ayyappan, N., Rajashekar, G., Jha, C. S., & Rao, P. V. N. (2021). Remote sensing enabled essential biodiversity variables for biodiversity assessment and monitoring: Technological advancement and potentials. *Biodiversity and Conservation*, *30*(1), 1–14. https://doi.org/10.1007/s10531-020-02073-8

Redlich, S., Martin, E. A., & Steffan-Dewenter, I. (2021). Sustainable landscape, soil and crop management practices enhance biodiversity and yield in conventional cereal systems. *Journal of Applied Ecology*, *58*(3), 507–517. https://besjournals-onlinelibrary-wiley-com.libproxy.unl.edu/doi/pdfdirect/10.1111/1365-2664.13821

Ritter, C. D., Häggqvist, S., Karlsson, D., Sääksjärvi, I. E., Muasya, A. M., Nilsson, R. H., & Antonelli, A. (2019). Biodiversity assessments in the 21st century: The potential of insect traps to complement environmental samples for estimating eukaryotic and prokaryotic diversity using high-throughput DNA metabarcoding. *Genome*, *62*(3), 147–159. https://doi.org/10.1139/gen-2018-0096

Rojas-Botero, S., Solorza-Bejarano, J., Kollmann, J., & Teixeira, L. H. (2020). Nucleation increases understory species and functional biodiversity in early tropical forest restoration. *Ecological Engineering*, *158*, 106031. https://doi.org/10.1016/j.ecoleng.2020.106031

Scherer, L., van Baren, S. A., & van Bodegom, P. M. (2020). Characterizing Land Use Impacts on Functional Plant Diversity for Life Cycle Assessments. *Environmental Science & Technology*, *54*(11), 6486–6495. https://doi.org/10.1021/acs.est.9b07228

Sigsgaard, L., Warlop, F., Herz, A., Tchamitchian, M., Pfiffner, L., Kelderer, M., Jamar, L., Korsgaard, M., & Ozoliņa-Pole, L. (2017). EcoOrchard–collecting existing knowledge and generating new knowledge on functional biodiversity of organic orchards. *IOBC-WPRS Bulletin*, *122*, 147–150. https://orgprints.org/id/eprint/32292/1/iobc-wprs_bulletin_2017_122_EcoOrchard.pdf

Skidmore, A. K., Coops, N. C., Neinavaz, E., Ali, A., Schaepman, M. E., Paganini, M., Kissling, W. D., Vihervaara, P., Darvishzadeh, R., & Feilhauer, H. (2021). Priority list of biodiversity metrics to observe from space. *Nature Ecology & Evolution*, *5*(7), 896–906.

UNEP, & CBD. (2022, December 7). *Kunming-Montreal Global biodiversity framework*. CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY, Montreal, Canada.

https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf

USDA. (n.d.). *Agroforestry Practices*. USDA National Agroforestry Center. Retrieved February 23, 2023, from https://www.fs.usda.gov/nac/practices/index.shtml

USDA Natural Resources Conservation Service. (2019). *Web Soil Survey*. United States Department of Agriculture. https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

Verified Carbon Standard. (2017). *The Climate, Community, and Biodiversity Standards v 3.1*. Verified Carbon Standard. https://verra.org/wp-content/uploads/2017/12/CCB-Standards-v3.1_ENG.pdf

Vermeulen, S., & Koziell, I. (2002). *Integrating global and local values: A review of biodiversity assessment*. International Institute for Environment and Development. https://pubs.iied.org/sites/default/files/pdfs/migrate/9100IIED.pdf?

Verra. (n.d.). CCB Program Details. *Verra*. Retrieved February 24, 2023, from https://verra.org/programs/ccbs/ccbs-program-details/

Villéger, S., Mason, N. W. H., & Mouillot, D. (2008). New Multidimensional Functional Biodiversity Indices for a Multifaceted Framework in Functional Ecology. *Ecology*, *89*(8), 2290–2301. https://doi.org/10.1890/07-1206.1

Wakelin, S., Cave, V., Dignam, B., D'Ath, C., Tourna, M., Condron, L., Zhou, J., Van Nostrand, J., & O'Callaghan, M. (2016). Analysis of soil eDNA functional genes: Potential to increase profitability and sustainability of pastoral agriculture. *New Zealand Journal of Agricultural Research*, *59*(4), 333–350. https://doi.org/10.1080/00288233.2016.1209529

World Business Council for Sustainable Development. (2023). *One Planet Business for Biodiversity*. World Business Council for Sustainable Development. https://www.wbcsd.org/Projects/OP2B

Yin, R., Kardol, P., Thakur, M. P., Gruss, I., Wu, G.-L., Eisenhauer, N., & Schädler, M. (2020). Soil functional biodiversity and biological quality under threat: Intensive land use outweighs climate change. *Soil Biology and Biochemistry*, *147*, 107847. https://doi.org/10.1016/j.soilbio.2020.107847

Yu, D. W., Ji, Y., Emerson, B. C., Wang, X., Ye, C., Yang, C., & Ding, Z. (2012). Biodiversity soup: Metabarcoding of arthropods for rapid biodiversity assessment and biomonitoring. *Methods in Ecology and Evolution*, *3*(4), 613–623. https://doi.org/10.1111/j.2041-210X.2012.00198.x

CHAPTER 3: MAKING THE FUTURE FUNCTIONAL AND PARTICIPATORY

Chapter 1 provides a background on the importance of biodiversity and a justification for assessing functional biodiversity; Chapter 2 presents the mechanics of conducting functional biodiversity assessments in agroecosystems and forests. Chapter 3 will summarize the barriers to and opportunities for assessing functional biodiversity and how participation from producer groups, Indigenous Peoples and Local Communities (IPLCs)[5], and citizens can address these barriers and opportunities.

Introduction – making the future functional

Biodiversity plays a critical role in supporting life in global ecosystems (Diaz et al., 2019; Morton & Hill, 2015; UNEP & CBD, 2022), and its links to ecosystem services and sustainability are recognized by scientific and non-scientific communities. Assessing functional biodiversity[6] can elucidate mechanisms underlying these relationships to help explain and predict ecosystem processes (Diaz et al., 2019; Fischer et al., 2010; Laureto et al., 2015; Malaterre et al., 2019; Moonen & Bàrberi, 2008; Petchey & Gaston, 2006). Functional biodiversity assessments are complementary to other biodiversity assessment approaches and follow a series of general steps that can be used in agroecosystems and forests (see Table 1, Chapter 1). Existing and emerging tools and technology can be used to measure functional traits as part of functional biodiversity assessments. Additional research that describes key functional traits is needed to leverage these tools to assess functional biodiversity.

---

[5] Indigenous Peoples and Local Communities are "typically ethnic groups who are descended from and identify with the original inhabitants of a given region" (IPBES, n.d.).
[6] Functional biodiversity is "the range and value of those species and organismal traits that influence ecosystem functioning" (Tilman, 2001).

Conservation social science is the use of social science to understand and improve policies, practices, and outcomes of conservation efforts (Bennett et al., 2017). Conservation social science includes classical and applied social science disciplines, as well as the arts and humanities and can offer insights at a variety of scales (Bennett et al., 2017). While there is growing recognition of the role social sciences can play in conservation, there is substantial room to engage with the human dimensions of conservation for more effective outcomes, including functional biodiversity. Including relevant human dimensions in functional biodiversity assessments can help address barriers and opportunities to their design and implementation.

Barriers to assessing functional biodiversity

Assessing functional biodiversity is a complex undertaking and several barriers exist. Multiple stakeholders are often involved in functional biodiversity assessments, and it can be challenging, but critical, to integrate the different values, priorities, and objectives of all stakeholder groups (Vermeulen & Koziell, 2002). Often these key players have incommensurate goals, that is their goals are in conflict or cannot all be achieved in a given project. Additionally, there is a declining number of taxonomists dedicated to describing key traits and many functional traits of arthropods and other invertebrates are unknown (Barberi & Moonen, 2020). Many traits are challenging to measure, especially by non-experts without experience and equipment (Malíček et al., 2019; Obrist & Duelli, 2010). Furthermore, there are inherent tradeoffs among time, technology, knowledge, and resources required for biodiversity monitoring programs in general (Pitman, 2011). Current and future tools and technology may address some of these barriers; however, the human dimensions of addressing these barriers should also be considered.

Opportunities for assessing functional biodiversity

The interest in measuring and communicating about biodiversity outcomes is a primary opportunity for functional biodiversity assessments. Various stakeholder groups may have funding to conduct functional biodiversity assessments and may also carry out the assessment themselves. There is an opportunity to engage stakeholder groups in all stages of functional biodiversity assessments to achieve more positive environmental and socio-economic outcomes (Dawson et al., 2021). Results of functional biodiversity assessments can inform land management practices to enhance biodiversity and ecosystem services, including agroecosystem or forest productivity (e.g., Bàrberi et al., 2010; Ćosović et al., 2020). Functional biodiversity assessments can contribute to our broader scientific understanding about the links among sustainable land use management, biodiversity, and ecosystem services. Finally, there are opportunities to develop new tools and technologies to help measure trait diversity more efficiently, both *in situ* and remotely (e.g., Cavender-Bares et al., 2020; Wakelin et al., 2016; Yu et al., 2012). To address these opportunities, we must consider the human dimensions connected to designing and implementing functional biodiversity assessments. The remainder of this chapter discusses the importance of participation of three stakeholder groups whose participation can help implement and scale functional biodiversity assessments.

Making the future participatory

The need for participatory biodiversity assessments comes from the demand for data to inform conservation efforts and the acknowledgement of the value and relevance of different knowledge systems, e.g., traditional ecological knowledge, in natural resource management (Lawrence, 2010). Participation in this context involves people sharing information and decisions, and includes issues of power, governance, and ownership (Lawrence, 2010). Ideally, participatory biodiversity assessments allow for the following:

> *"different stakeholders can have different objectives, knowledge, information needs, cultures and power relations, as well as methods for collecting and sharing information; but these different positions and needs can be accommodated through partnerships which can provide distinct but complementary and mutually rewarding outcomes"* (Lawrence, 2010).

Participation must be thoughtfully included in the design and implementation of biodiversity assessments, as participation alone will not yield positive outcomes. Issues of the reliability and trustworthiness of knowledge; alignment of objectives and outcomes; trust, ownership, and participation; planning and practicalities; methods and trainings; and institutions and governance are all salient to and have implications for participatory biodiversity assessments (Lawrence, 2010). Participation can be incorporated into each stage of functional biodiversity assessments (Table 1.1, Chapter 1) and can be one way to make stakeholder values and knowledge explicit in assessments (Lawrence, 2010). Producers, IPLCs, and citizens are three stakeholder groups that are relevant to include in functional biodiversity assessments.

Producer participation in agroecosystem functional biodiversity assessments

Producers can participate in functional biodiversity assessment design and implementation. This participation can be valuable because producers have first-hand experience with biodiversity components in their own operations and will ultimately be responsible for implementing any changes in production practices because of the assessment. Therefore, when viewed through a behavior-change lens, it is important to consider producer perceptions of functional biodiversity, their attitudes towards managing functional biodiversity, and drivers of and barriers to adoption.

Cardona et al. (2021) surveyed and conducted focus groups with organic fruit producers in France, Sweden, and Denmark about their perspectives on functional biodiversity and various monitoring methods. The authors found that most producers perceive functional biodiversity as a complex and multifunctional concept that is difficult to grasp (Cardona et al., 2021). The study identified four different attitudes towards managing functional biodiversity (Table 3.1). Similarly, Erisman et al. (2016) proposed four levels of producer ambition that led to an increase or decrease in functional biodiversity in dairy farms (Table 3.1). The attitudes and levels of ambition demonstrate that producer management for functional biodiversity lies on a spectrum from little to no management through complex management to achieve multiple objectives. The categories from both studies generally align but have nuanced differences. For example, the “regulation” attitude in Cardona et al.'s (2021) research on European organic orchard producers explicitly mentions managing functional biodiversity for pest regulation. In contrast, the “conscious” level of ambition in dairy producers emphasizes managing functional biodiversity for soil ecosystem services (Erisman et al., 2016). This suggests that producer attitudes toward functional biodiversity management in agroecosystems can be broadly categorized and will differ slightly depending on the production system and environmental context. Understanding producer attitudes towards functional biodiversity management can help align results of assessments with producer objectives and on-the-ground realities.

Table 3.1. Producer attitudes and levels of ambition towards functional biodiversity management in agroecosystems.

Cardona et al. (2021)	Erisman et al. (2016)
"Wait-and-see": producers observe positive and negative interactions between the orchard and the environment, but do not attempt to interact due to ignorance or perceive insignificance.	*"Business as usual"*: little to no explicit focus on stimulating functional biodiversity and maximum productional levels are emphasized.
"Naturalist": conservation and restoration are priorities and producers establish a diversity of plants and animals in the orchard and surrounding environment.	*"Basic"*: no change to on-farm intensity or management strategy, but specific functional biodiversity is stimulated.
"Regulation": producers explicitly and strategically use functional biodiversity to regulate pests.	*"Conscious"*: cropland is managed for soil functional biodiversity and various landscape elements are present to support functional biodiversity.
"Multifunctional": producers use functional biodiversity to regulate pests and meet other objectives.	*"Best biodiversity practice"*: functional biodiversity is used at all levels (e.g., soil, crop, landscape), a transition to a resilient system is underway, and cost of production may increase.

Penvern et al. (2019) surveyed European orchard producers about perceptions and values towards functional biodiversity, as well as practices implemented and drivers of adoption. The authors identified three clusters of producers based on their perspectives on functional biodiversity and the number of functional biodiversity techniques implemented: 1) "passive approach" – skeptical of functional biodiversity, implement fewer functional biodiversity techniques, not managing for functional biodiversity or yield; 2) "active approach" – generally convinced of importance of functional biodiversity, implement more functional biodiversity techniques, functional biodiversity is focus of production; 3) "integrated approach" – implemented more functional biodiversity techniques, redesigned techniques, highlight more positive and negative aspects of functional biodiversity (Penvern et al., 2019). These clusters generally align with the categories from Cardona et al. (2021) and Erisman et al. (2016) and provide insight into the connections between perceptions and practice implementation. The authors found that producers were more likely to implement functional biodiversity techniques if they had training, used resistant cultivars, and had new orchard plantings (Penvern et al., 2019). These results can be used to optimize practice changes based on results of functional biodiversity assessments by identifying complementary resources (e.g., trainings) and producer groups more likely to implement functional biodiversity practices (e.g., those using resistant cultivars or with new plantings).

Indigenous Peoples and Local Communities (IPLCs) participation in forest functional biodiversity assessments[7]

Indigenous Peoples and Local Communities are recognized as important stakeholders for assessments at different scales and scopes. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has involved IPLCs in global assessments because of their extensive interactions with the environment and resulting accumulation of knowledge, i.e., Indigenous and Local Knowledge (ILK)[8], as well as the impacts of natural resource management decisions on IPLCs (McElwee et al., 2021). The IPBES engages IPLCs via task forces, using an approach that positions

[7] This section provides a limited overview of IPLCs in participatory biodiversity assessments. Lawrence (2010) is a good starting point for more detailed information on this topic.
[8] IPBES defines Indigenous and Local Knowledge as "knowledge and know-how accumulated across generations, which guide human societies in their innumerable interactions with their surrounding environment" (IPBES, 2014).

ILK as equal to globally generated "science", and through principles and phases that recognize and work with ILK throughout the assessment process (McElwee et al., 2021). These methods of participation could serve as a model for other large-scale assessments, including functional biodiversity assessments.

Dawson et al. (2021) conducted a systematic literature review of governance and conservation outcomes, with specific attention on IPLCs. The study found that good governance and effective conservation are inextricably linked. Locally-controlled efforts tended to have more positive outcomes for the environment and well-being of IPLCs, while top-down approaches tended to have less effective environmental outcomes and negative effects on well-being (Dawson et al., 2021). This suggests that local governance of functional biodiversity assessments could contribute to positive outcomes for both IPLCs and the environment.

Boissière et al. (2010) synthesized results from ten case studies that utilized the Multidisciplinary Landscape Assessment (MLA)[9] approach to assess biodiversity in tropical landscapes. The authors found that the MLA approach acted as a bridge between local communities and authorities and is an effective way to engage potential users of results (e.g., local decision-makers and institutions) at an early stage (Boissière et al., 2010). Each of the case studies made modifications to the length, scale, communication approach, and tools used in the MLA approach according to the context of the assessment (Boissière et al., 2010). The MLA approach is one framework that could be applied to

[9] The MLA approach was started by the Center for International Forestry Research and combines technical surveys of habitats, species, and landscapes with an assessment of their significance to local people. The MLA survey links biophysical data to local relevance, then local perceptions are used to inform and guide the biophysical studies (Boissière et al., 2010).

functional biodiversity assessments to integrate local knowledge and involve IPLCs in the assessment process more effectively.

Leveraging citizen participation to scale functional biodiversity assessments

Citizen participation in science, “citizen science”, contributes to conservation efforts, informs management and policy decisions, and nurtures public input and engagement (McKinley et al., 2017). While many projects could potentially benefit from citizen science, it is important to match the scientific needs with citizen involvement at a project and methodological level (McKinley et al., 2017). Several efforts have leveraged data generated by citizen science programs to assess functional biodiversity at the trait level.

Schiller et al., (2021) and Wolf et al. (2022) both used data from the citizen-science platform, iNaturalist, an “online social network of people sharing biodiversity information” (iNaturalist, n.d.). iNaturalist shares citizen-generated data with researchers to expand the scale and scope of biodiversity research. Wolf et al. (2022) used iNaturalist data in combination with the TRY plant trait database (Kattge et al., 2011) to analyze global plant functional trait patterns. The generated maps were highly correlated with open-sourced trait maps (Wolf et al., 2022) produced with *in situ* data (sPlotOpen, Sabatini et al., 2021). Schiller et al. (2021) combined iNaturalist data with the TRY plant trait database using convolutional neural networks to predict plant traits at a global scale. The authors produced a series of global trait maps which indicated qualitative trends and were well-correlated to published maps (Schiller et al., 2021). These studies demonstrate the potential role citizen science can play in generating and improving maps of plant functional traits, which could facilitate rapid ecosystem monitoring (Sabatini et al., 2021).

Conclusion

Producer, IPLC, and citizen participation has the potential to address several barriers to and opportunities for implementing functional biodiversity assessments. Participation can help integrate stakeholder values, priorities, and objectives into the assessment design. This may increase the likelihood of behavior change based on the results of the assessment (e.g., Penvern et al., 2019). Specifically, involving IPLCs in the governance of conservation programs tends to lead to more positive environmental and well-being outcomes (Dawson et al., 2021). Participation should be prioritized early in the process to clarify any local concerns or priorities (Boissière et al., 2010). Citizen science offers a powerful way to address resource constraints on data collection and can help increase the scale of functional biodiversity assessments (McKinley et al., 2017; Schiller et al., 2021). Participation is one method to incorporate human dimensions into functional biodiversity assessments. Integrating social sciences into functional biodiversity assessments and other elements of conservation efforts and help facilitate more robust, relevant, and effective conservation outcomes (Bennett et al., 2017).

References

Bàrberi, P., Burgio, G., Dinelli, G., Moonen, A. C., Otto, S., Vazzana, C., & Zanin, G. (2010). Functional biodiversity in the agricultural landscape: Relationships between weeds and arthropod fauna. *Weed Research*, *50*(5), 388–401. https://doi.org/10.1111/j.1365-3180.2010.00798.x

Barberi, P., & Moonen, A. C. (2020). Functional biodiversity for the provision of agroecosystem services. In *Reconciling agricultural production with biodiversity conservation* (pp. 101–146). Burleigh Dodds Science Publishing. http://dx.doi.org/10.19103/AS.2020.0071.12

Bennett, N. J., Roth, R., Klain, S. C., Chan, K., Christie, P., Clark, D. A., Cullman, G., Curran, D., Durbin, T. J., Epstein, G., Greenberg, A., Nelson, M. P., Sandlos, J., Stedman, R., Teel, T. L., Thomas, R., Veríssimo, D., & Wyborn, C. (2017). Conservation social science: Understanding and integrating human dimensions to improve conservation. *Biological Conservation*, *205*, 93–108. https://doi.org/10.1016/j.biocon.2016.10.006

Boissière, M., Sassen, M., Sheil, D., Van Heist, M., De Jong, W., Cunliffe, R., Wan, M., Padmanaba, M., Liswanti, N., Basuki, I., Evans, K., Cronkleton, P., Lynam, T., Koponen, P., & Bairaktari, C. (2010). Researching local perspectives on biodiversity in tropical landscapes: Lessons from ten case studies. In A. Lawrence (Ed.), *Taking Stock of Nature: Participatory Biodiversity Assessment for Policy, Planning and Practice* (pp. 113–141). Cambridge University Press. https://doi.org/10.1017/CBO9780511676482.006

Cardona, A., Tchamitchian, M., Penvern, S., Dufils, A., Kramer Jacobsen, S., Korsgaard, M., Porcel, M., Świergiel, W., Tasin, M., Warlop, F., & Sigsgaard, L. (2021). Monitoring methods adapted to different perceptions and uses of functional biodiversity: Insights from a European qualitative study. *Ecological Indicators*, *129*, 107883. https://doi.org/10.1016/j.ecolind.2021.107883

Cavender-Bares, J., Gamon, J., & Townsend, P. (Eds.). (2020). *Remote Sensing of Plant Biodiversity*. Springer Nature. https://doi.org/10.1007/978-3-030-33157-3

Ćosović, M., Bugalho, M. N., Thom, D., & Borges, J. G. (2020). Stand structural characteristics are the most practical biodiversity indicators for forest management planning in Europe. *Forests*, *11*(3), 343. https://doi.org/doi:10.3390/f11030343

Dawson, N., Coolsaet, B., Sterling, E., Loveridge, R., Gross-Camp, N., Wongbusarakum, S., Sangha, K., Scherl, L., Phan, H., Zafra-Calvo, N., Lavey, W., Byakagaba, P., Idrobo, C. J., Chenet, A., Bennett, N., Mansourian, S., & Rosado-May, F. (2021). The role of Indigenous peoples and local communities in effective and equitable conservation. *Ecology and Society*, *26*(3). https://doi.org/10.5751/ES-12625-260319

Diaz, S., Settele, J., & Brondizio, E. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

https://www.biologicaldiversity.org/programs/biodiversity/pdfs/Summary-for-Policymakers-IPBES-Global-Assessment.pdf

Erisman, J. W., Eekeren, N. van, Wit, J. de, Koopmans, C., Cuijpers, W., Oerlemans, N., & Koks, B. J. (2016). Agriculture and biodiversity: A better balance benefits both. *AIMS Agriculture and Food*, *1*(2), 157–174. https://scholarlypublications.universiteitleiden.nl/access/item%3A3209880/view

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., Renner, S., Schöning, I., Schumacher, U., Wells, K., Buscot, F., Kalko, E. K. V., Linsenmair, K. E., Schulze, E.-D., & Weisser, W. W. (2010). Implementing large-scale and long-term functional biodiversity research: The Biodiversity Exploratories. *Basic and Applied Ecology*, *11*(6), 473–485. https://doi.org/10.1016/j.baae.2010.07.009

iNaturalist. (n.d.). *What is it*. INaturalist. Retrieved March 6, 2023, from https://www.inaturalist.org/pages/what+is+it

Kattge, J., Díaz, S., Lavorel, S., Prentice, I. C., Leadley, P., Bönisch, G., Garnier, E., Westoby, M., Reich, P. B., Wright, I. J., Cornelissen, J. H. C., Violle, C., Harrison, S. P., Van BODEGOM, P. M., Reichstein, M., Enquist, B. J., Soudzilovskaia, N. A., Ackerly, D. D., Anand, M., … Wirth, C. (2011). TRY – a global database of plant traits. *Global Change Biology*, *17*(9), 2905–2935. https://doi.org/10.1111/j.1365-2486.2011.02451.x

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

Lawrence, A. (2010). Introduction: Learning from experiences of participatory biodiversity assessment. In *Taking Stock of Nature* (pp. 1–29). Cambridge University Press. https://doi.org/10.1017/CBO9780511676482.001

Malaterre, C., Dussault, A. C., Mermans, E., Barker, G., Beisner, B. E., Bouchard, F., Desjardins, E., Handa, I. T., Kembel, S. W., Lajoie, G., Maris, V., Munson, A. D., Odenbaugh, J., Poisot, T., Shapiro, B. J., & Suttle, C. A. (2019). Functional biodiversity: An Epistemic Roadmap. *BioScience*, *69*(10), 800–811. https://doi.org/10.1093/biosci/biz089

Malíček, J., Palice, Z., Vondrák, J., Kostovčík, M., Lenzová, V., & Hofmeister, J. (2019). Lichens in old-growth and managed mountain spruce forests in the Czech Republic: Assessment of biodiversity, functional traits and bioindicators. *Biodiversity and Conservation*, *28*(13), 3497–3528. https://doi.org/10.1007/s10531-019-01834-4

McElwee, P., Ngo, H. T., Fernandez-Llamazares, A., Reyes-Garcia, V., Molnar, Z., Gueze, M., Aumeruddy-Thomas, Y., Diaz, S., & Brondizio, E. S. (2021). INCLUDING INDIGENOUSAND LOCAL KNOWLEDGE IN THE WORK OF THE INTERGOVERNMENTALSCIENCE-POLICY PLATFORM ON BIODIVERSITY AND ECOSYSTEM SERVICES (IPBES) GLOBAL ASSESSMENT : Outcomes and lessons for the future. In *ROUTLEDGE HANDBOOK OF INDIGENOUS ENVIRONMENTAL KNOWLEDGE* (1st ed., pp. 343–355). Routledge. https://helda.helsinki.fi/bitstream/handle/10138/344111/McElwee_et_al._2020_accepted_version.pdf?sequence=1

McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C., Evans, D. M., French, R. A., Parrish, J. K., Phillips, T. B., Ryan, S. F., Shanley, L. A., Shirk, J. L., Stepenuck, K. F., Weltzin, J. F., Wiggins, A., Boyle, O. D., Briggs, R. D., Chapin, S. F., … Soukup, M. A. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, *208*, 15–28. https://doi.org/10.1016/j.biocon.2016.05.015

Moonen, A.-C., & Bàrberi, P. (2008). Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems & Environment*, *127*(1), 7–21. https://doi.org/10.1016/j.agee.2008.02.013

Morton, S., & Hill, R. (2015). What is biodiversity, and why is it important? In *Biodiversity: Science and solutions for Australia* (pp. 1–12). CSIRO Publishing. https://www.researchgate.net/profile/Rosemary-Hill-4/publication/279197478_What_is_biodiversity_and_why_is_it_important/links/558ea75508ae1e1f9bacd67b/What-is-biodiversity-and-why-is-it-important.pdf

Obrist, M. K., & Duelli, P. (2010). Rapid biodiversity assessment of arthropods for monitoring average local species richness and related ecosystem services. *Biodiversity and Conservation*, *19*(8), 2201–2220. https://doi.org/10.1007/s10531-010-9832-y

Penvern, S., Fernique, S., Cardona, A., Herz, A., Ahrenfeldt, E., Dufils, A., Jamar, L., Korsgaard, M., Kruczyńska, D., Matray, S., Ozolina-Pole, L., Porcel, M., Ralle, B., Steinemann, B., Świergiel, W., Tasin, M., Telfser, J., Warlop, F., & Sigsgaard, L. (2019). Farmers' management of functional biodiversity goes beyond pest management in organic European apple orchards. *Agriculture, Ecosystems & Environment*, *284*, 106555. https://doi.org/10.1016/j.agee.2019.05.014

Petchey, O. L., & Gaston, K. J. (2006). Functional biodiversity: Back to basics and looking forward. *Ecology Letters*, *9*(6), 741–758. https://doi.org/10.1111/j.1461-0248.2006.00924.x

Pitman, N. (2011). *Social and Biodiversity Impact Assessment (SBIA) Manual For REDD+ Projects: Part 3—Biodiversity Impact Assessment Toolbox*. Forest Trends, Climate, Community & Biodiversity Alliance, Rainforest Alliance, and Fauna & Flora International. https://www.forest-trends.org/wp-content/uploads/imported/sbia-part-3-pdf.pdf

Sabatini, F. M., Lenoir, J., Hattab, T., Arnst, E. A., Chytrý, M., Dengler, J., De Ruffray, P., Hennekens, S. M., Jandt, U., Jansen, F., Jiménez-Alfaro, B., Kattge, J., Levesley, A., Pillar, V. D., Purschke, O., Sandel, B., Sultana, F., Aavik, T., Aćić, S., … Bruelheide, H. (2021). SPlotOpen – An environmentally balanced, open-access, global dataset of vegetation plots. *Global Ecology and Biogeography*, *30*(9), 1740–1764. https://doi.org/10.1111/geb.13346

Schiller, C., Schmidtlein, S., Boonman, C., Moreno-Martínez, A., & Kattenborn, T. (2021). Deep learning and citizen science enable automated plant trait predictions from photographs. *Scientific Reports*, *11*(1), Article 1. https://doi.org/10.1038/s41598-021-95616-0

Tilman, D. (2001). Functional biodiversity. In S. A. Levin (Ed.), *Encyclopedia of Biodiversity* (pp. 109–120). Elsevier. https://doi.org/10.1016/B0-12-226865-2/00132-2

UNEP, & CBD. (2022, December 7). *Kunming-Montreal Global biodiversity framework*. CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY, Montreal, Canada. https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf

Vermeulen, S., & Koziell, I. (2002). *Integrating global and local values: A review of biodiversity assessment*. International Institute for Environment and Development. https://pubs.iied.org/sites/default/files/pdfs/migrate/9100IIED.pdf?

Wakelin, S., Cave, V., Dignam, B., D'Ath, C., Tourna, M., Condron, L., Zhou, J., Van Nostrand, J., & O'Callaghan, M. (2016). Analysis of soil eDNA functional genes: Potential to increase profitability and sustainability of pastoral agriculture. *New Zealand Journal of Agricultural Research*, *59*(4), 333–350. https://doi.org/10.1080/00288233.2016.1209529

Wolf, S., Mahecha, M. D., Sabatini, F. M., Wirth, C., Bruelheide, H., Kattge, J., Moreno Martínez, Á., Mora, K., & Kattenborn, T. (2022). Citizen science plant observations encode global trait patterns. *Nature Ecology & Evolution*, *6*(12), Article 12. https://doi.org/10.1038/s41559-022-01904-x

Yu, D. W., Ji, Y., Emerson, B. C., Wang, X., Ye, C., Yang, C., & Ding, Z. (2012). Biodiversity soup: Metabarcoding of arthropods for rapid biodiversity assessment and biomonitoring. *Methods in Ecology and Evolution*, *3*(4), 613–623. https://doi.org/10.1111/j.2041-210X.2012.00198.x