ubcfarm
CENTRE FOR SUSTAINABLE FOOD SYSTEMS

UBC Farm Long-Term Biodiversity Monitoring Plan

March 2019

Summary

Widespread biodiversity loss is occurring rapidly worldwide, often driven by agricultural activities. At the same time, the biodiversity present in agricultural systems contributes to the critical processes that underlie food production and a variety of ecosystem services that benefit people. The UBC Farm provides a unique opportunity to investigate the linkages between agriculture and biodiversity and test how to effectively measure and understand these relationships on diversified, organic farms.

This document outlines a vision and rationale for a biodiversity monitoring plan at the UBC Farm and describes in detail what such a plan should include to meaningfully contribute to the research, teaching, learning, and outreach goals of both the farm and the University of British Columbia. The report is a first step towards a vision where the UBC Farm supports a world-class biodiversity monitoring program that provides catalytic research, teaching, learning, and communication opportunities alongside evidence of the links between biodiversity and food system sustainability.

The report lays out the reasons for monitoring biodiversity at the UBC Farm and outlines a rationale for choosing biodiversity indicators, describes a potential sampling scheme and protocols, discusses considerations around data management and access, presents an equipment budget, describes opportunities for collaboration with the UBC community and beyond, and outlines potential avenues for communication of biodiversity monitoring results with an aim to increase engagement of students, researchers, and the wider community with the UBC Farm.

The proposed plan focuses on monitoring three key aspects of biodiversity at the UBC Farm – landscape/habitat diversity, crop diversity, and the "wild" or unplanned species diversity that provides the numerous ecosystem services that underlie food production. Additionally, specific farm management indicators are identified to help link management actions to changes in biodiversity. Within the species diversity category, monitoring focuses on key groups that have been pinpointed as important biodiversity indicators for the diversified agricultural landscape of the UBC Farm. This includes bumblebees and native bees, vascular plants (including weeds, field margin, hedgerow, and forest plant species), earthworms, birds, mammals, and soil microbes. For each of these groups, methods have been developed that attempt to balance scientific rigour with logistical feasibility given the resources of the farm and the Centre for Sustainable Food Systems.

Monitoring biodiversity effectively over the long-term depends on three key supporting pieces. The first is managing collected data in a way that is flexible and allows researchers and the public to easily access, explore, and analyze it. The second, is securing funding for monitoring over the long-term, not just for two or three years. Initial start-up costs for equipment and supplies are estimated at approximately $5,500, with costs for subsequent years of around $500. Thirdly, the modest costs for the monitoring plan depend on taking advantage of the unique opportunities present at the UBC Farm. In particular, this includes the ability to collaborate with researchers, students, courses, and the wider public to engage in monitoring activities. Effective collaboration on biodiversity monitoring through a variety of venues, should provide valuable education and outreach opportunities.

UBC Farm is a diversified farm in every sense of the word – agriculturally, biologically, and socially. Understanding how these different diversities interact and how to collectively manage them to build a sustainable food system is a key challenge that the UBC Farm. A long-term biodiversity monitoring program is a crucial piece of this work and will ensure UBC is uniquely positioned to address this challenge.

TABLE OF CONTENTS

1. INTRODUCTION ... 5

1.1. OVERVIEW ... 5
1.2. VISION, SCOPE & RATIONALE ... 5
1.3. PURPOSE AND OUTCOMES ... 6

2. BACKGROUND ... 7

2.1. WHAT IS AGRICULTURAL BIODIVERSITY? ... 7
2.2. THE IMPORTANCE OF AGRICULTURAL BIODIVERSITY ... 7
2.3. THE NEED FOR BIODIVERSITY MONITORING AT THE UBC FARM ... 8
2.3.1. Overview of the UBC Farm ... 8
2.3.2. Connection to UBC Farm guiding principles and goals ... 9
2.3.3. Connection to wider UBC initiatives and plans ... 10

3. AGRICULTURAL BIODIVERSITY INDICATORS ... 11

3.1. INDICATORS OF AGRICULTURAL BIODIVERSITY ... 11
3.1.1. What is a biodiversity indicator? ... 11
3.1.2. Challenges in measuring agricultural biodiversity ... 12
3.1.3. Review of relevant agricultural biodiversity indicator systems and literature ... 12
3.1.4. Assessment of biodiversity monitoring at other long-term research farms/sites ... 13
3.1.5. Current and historical biodiversity monitoring at the UBC Farm ... 14

4. BIODIVERSITY INDICATORS FOR THE UBC FARM ... 18

4.1. INDICATOR SELECTION APPROACH ... 18
4.1.1. Criteria for indicator selection ... 18
4.1.2. UBC community participation in indicator selection ... 19
4.2. LANDSCAPE/HABITAT DIVERSITY INDICATORS ... 19
4.2.1. Landscape/Habitat diversity overview ... 19
4.2.2. Habitat Categories ... 19
4.2.3. Selected landscape/habitat indicators ... 21
4.3. SPECIES DIVERSITY INDICATORS ... 21
4.3.1. Species diversity overview ... 21
4.3.2. Selected indicator species groups ... 22
4.3.3. Selected species diversity indicators ... 26
4.4. CROP DIVERSITY INDICATORS ... 26
4.4.1. Dimensions of crop diversity ... 26
4.4.2. Selected crop diversity indicators ... 26
4.5. FARM MANAGEMENT INDICATORS ... 27
4.5.1. Linking farm management with biodiversity ... 27
4.5.2. Selected farm management indicators ... 27

5. BIODIVERSITY MONITORING SAMPLING PLAN ... 29

5.1. LANDSCAPE/HABITAT DIVERSITY ... 29
5.2. SPECIES DIVERSITY ... 29
5.2.1. Rationale and sampling principles ... 29
5.2.2. Sampling locations and plan ... 30
5.2.3. Sampling methods overview ... 31
5.2.4. Species diversity sampling schedule ... 33
5.2.5. Potential automated species diversity monitoring options ... 35
5.3. CROP DIVERSITY ... 36
5.4. FARM MANAGEMENT ... 36

6. DATA MANAGEMENT ... 37

7. COSTS & BUDGET ... 38

8. OPPORTUNITIES FOR COLLABORATION 41
8.1. RESEARCHERS 41
8.2. UBC COURSES 41
8.3. OTHER UBC INITIATIVES AND GROUPS 41
8.4. COMMUNITY GROUPS AND ORGANIZATIONS 43
8.5. OPPORTUNITIES FOR CITIZEN-SCIENCE EVENTS 44
9. COMMUNICATION AND OUTREACH 46
9.1. INFORMAL COMMUNICATION 46
9.2. FORMAL REPORTING 46
9.3. EDUCATION OPPORTUNITIES 47
9.4. COMMUNITY OUTREACH 47
9.5. SOCIAL MEDIA AND INTERNET 47
9.6. DATA SHARING AND CITIZEN-SCIENCE 48
10. REFERENCES 49

LIST OF FIGURES

FIGURE 1. UBC FARM 2012 LAND COVER 8
FIGURE 2. BIODIVERSITY INDICATORS AND RELATIONSHIPS WITHIN THE OECD FRAMEWORK. 11
FIGURE 3. LAND USE/LAND COVER CLASSIFICATION FOR THE UBC FARM. 20
FIGURE 4. POSITION IN FOOD CHAIN AND SCALE OF SPATIAL DISTRIBUTION/RESPONSE TO ENVIRONMENTAL CONDITIONS FOR SELECT BIODIVERSITY INDICATORS. 22
FIGURE 5. BIODIVERSITY SAMPLING SCHEME IN LINEAR HABITATS, PRODUCTION FIELDS, AND FOREST HABITATS. 32

LIST OF TABLES

TABLE 1. SUMMARY OF BIODIVERSITY MEASURES INCLUDED IN MONITORING AT OTHER RESEARCH FARMS AND ECOLOGICAL NETWORKS. 14
TABLE 2. SUMMARY OF CURRENT BIODIVERSITY MONITORING EFFORTS AT THE UBC FARM. 15
TABLE 3. HISTORICAL BIODIVERSITY MONITORING EFFORTS AT THE UBC FARM. 17
TABLE 4. LAND USE/LAND COVER HABITAT CATEGORIES, SUB-CATEGORIES AND EXAMPLES. 20
TABLE 5. SELECTED LANDSCAPE/HABITAT INDICATORS, DEFINITIONS, AND RATIONALE 21
TABLE 6. SELECTED LANDSCAPE/HABITAT INDICATORS, DEFINITIONS, AND RATIONALE 23
TABLE 7. SELECTED SPECIES DIVERSITY INDICATORS, DEFINITIONS, AND RATIONALE 26
TABLE 8. SELECTED CROP DIVERSITY INDICATORS, DEFINITIONS, AND RATIONALE 27
TABLE 9. POTENTIAL FARM MANAGEMENT INDICATORS, DEFINITIONS, AND RATIONALE 27
TABLE 10. CORE SAMPLES TO BE COLLECTED AT EACH SAMPLING LOCATION. 31
TABLE 11. POTENTIAL SUMMER SAMPLING SCHEDULE FOR UBC FARM BIODIVERSITY MONITORING PLAN 34
TABLE 12. EQUIPMENT COSTS AND BUDGET FOR THE CORE BIODIVERSITY MONITORING PLAN. 38
TABLE 13. EQUIPMENT COSTS AND BUDGET FOR AUTONOMOUS BIODIVERSITY MONITORING OPTION. 39
TABLE 14. CURRENT AND POTENTIAL UBC COURSES THAT COULD CONTRIBUTE TO BIODIVERSITY MONITORING. 42

1. Introduction

1.1. Overview

Widespread biodiversity loss is happening rapidly around the world, often driven by agricultural activities[1]. At the same time, the biodiversity present in agricultural systems contributes to the many critical processes that underlie food production[2] as well as a variety of ecosystem services that benefit people[3,4]. The UBC Farm provides a unique opportunity to investigate the linkages between agriculture and biodiversity and test how to effectively measure and understand these relationships on diversified, organic farms. This document outlines a vision and rationale for a biodiversity monitoring plan at the UBC Farm and describes in detail what such a plan should include to meaningfully contribute to the research, teaching, learning, and outreach goals of the UBC Farm and UBC.

1.2. Vision, Scope & Rationale

The overarching vision for the UBC Farm Biodiversity Monitoring Plan is:

> *The UBC Farm supports a world-class biodiversity monitoring program that demonstrates how agricultural biodiversity and management on a diversified farm can be comprehensively and rigorously assessed and monitored over the long-term; provides catalytic research, teaching, learning, and communication opportunities; and provides evidence of the links between biodiversity and food system sustainability.*

A biodiversity monitoring plan at the UBC Farm — a model organic and diversified research farm with the capacity to comprehensively prototype and test methods to assess agricultural biodiversity and link this with farm management — will have clear research, teaching, outreach, and applied outcomes. These include:

- Evidence to help answer the following critical agroecological and food system research questions:
    - How can biodiversity, ecosystem service, and food production be best assessed on diversified farms?
    - How do different management actions and decisions on diversified farms affect biodiversity?
    - What biodiversity is present on the UBC Farm and how/why is it changing?
    - How does biodiversity contribute to ecosystem services and food production?
- Improved opportunities for classes and students be directly involved in biodiversity monitoring and citizen science at the UBC Farm;
- Facilitation of experiential teaching techniques that expose students to practical field methods for the assessment of the ecological and production outcomes on diversified farms;
- Opportunities to involve the wider UBC and Vancouver community in biodiversity monitoring, research, and citizen science at the UBC Farm;

- Through the UBC Farm Market, opportunities for students and researchers to develop their science communication and outreach skills through public presentations of monitoring plan results;
- The ability to prototype biodiversity monitoring methods for diversified farms at the UBC Farm and then apply these methods at other farms around British Columbia and North America through the Centre for Sustainable Food System's research network.

This document addresses the first steps to realize this vision, focusing on the rationale for such a monitoring plan, identification of key indicators and methods, and determination of the critical resources, people, courses, and groups that should be involved to ensure that a biodiversity monitoring plan is feasible and contributes to the goals of the UBC Farm and UBC. Additional opportunities for the plan to connect with UBC and regional initiatives not described here are likely to exist and will emerge in the future. Any long-term monitoring plan must be flexible and be able to adapt to changing conditions. Efforts have been made to create a plan that meets these criteria, without limiting the monitoring plan or prescribing how the plan should or will change in the future.

1.3. Purpose and Outcomes

This document outlines the vision and rationale for a biodiversity monitoring plan, and describes in detail the components and steps required to make the plan a reality and sustainable in the long-term. Building on the overarching vision above, the purpose of this plan is to provide a framework for the following specific outcomes:

- Connect the monitoring plan to the goals and policies of the Centre for Sustainable Food Systems and the UBC;
- Assess the previous biodiversity monitoring that has occurred at the UBC Farm;
- Describe an underlying scientific rationale and identify key indicators that should be included in creation of a biodiversity baseline for 2019 and an ongoing monitoring program going forward;
- Select and describe sampling locations and methods for standardized data collection, potential laboratory and statistical analyses, and costs and personnel requirements;
- Identify key stakeholders, researchers, and groups that are already monitoring biodiversity at the farm, or could contribute to future monitoring activities;
- Develop a detailed action plan to help guide and facilitate future implementation of the monitoring plan; and
- Describe key avenues and opportunities for communication of monitoring results to the research, student, university, and local public communities.

While the main aim of this report is to describe a detailed plan to monitor biodiversity on the UBC Farm, a secondary goal is to provide a more general biodiversity monitoring framework that, once tested, could inform a wider long-term socio-ecological monitoring network on diversified farms and agricultural research stations in North America. Because biodiversity supports and is essential for many of the ecosystem services that agricultural systems provide[5], designing a biodiversity monitoring program provides one potential entry point to long term socio-ecological monitoring on the farm.

2. Background

2.1. What is agricultural biodiversity?

Agricultural biodiversity broadly defined includes all of the species, ecosystems, and genetic diversity that occur within agricultural landscapes or systems[6]. It includes "planned" biodiversity[7] that is directly under the control of people, such as the crop types and varieties planted, livestock breeds present, intentionally released biocontrol species, fungal inoculants, and domestic honeybees[8]. Agricultural biodiversity also encompasses the "associate" biodiversity[7] that occurs in the surrounding hedgerows, ditches, ponds, meadows, and forests that impact and are critical to agricultural production[8,9]. This associate biodiversity encompasses arthropods, molluscs, fungi, bacteria, plants, mammals, and birds, as well as the communities and ecosystems that they comprise. Associate biodiversity can be further separated into beneficial "resource" biota that contribute to agricultural production and "destructive" biota that damages the planned biodiversity[7] (e.g., pests, weeds, etc.).

At a broader spatial scale, agricultural biodiversity also includes the habitats and ecosystems that makeup agricultural landscapes. Landscape diversity refers to the variety of ecosystem types, land covers, and land uses that are present in a given region[9] that increases when greater numbers of crops are grown in the same area (through rotations, polycultures, or agroforestry) or when a greater number of habitats are present (e.g., forest patches, hedgerows, wetlands, meadows)[10].

Finally, agricultural biodiversity also includes the genetic diversity present in agricultural systems[6]. Generally, genetic agricultural biodiversity focuses on the planned biodiversity and the number of types and varieties of crops that are grown or types and breeds of livestock raised.

2.2. The importance of agricultural biodiversity

Agricultural systems are home to a large diversity of species, despite their management primarily being focused on a single ecosystem service — food production — and the limited number of crop species we use to grow our food. Agricultural biodiversity contributes to and affects all of the critical ecosystem functions and ecosystem services that underlie agricultural production[3]. This includes nutrient cycling, decomposition, soil formation, primary production, water flow, pollination, and gene flow[2,11]. Biodiversity contributes to these processes both through the presence of important species that disproportionately contribute to certain services (e.g., earthworms to soil stability[11], native pollinators to pollination[12]) and via insurance effects where the presence of multiple species can buffer environmental change and increase ecosystem stability[13].

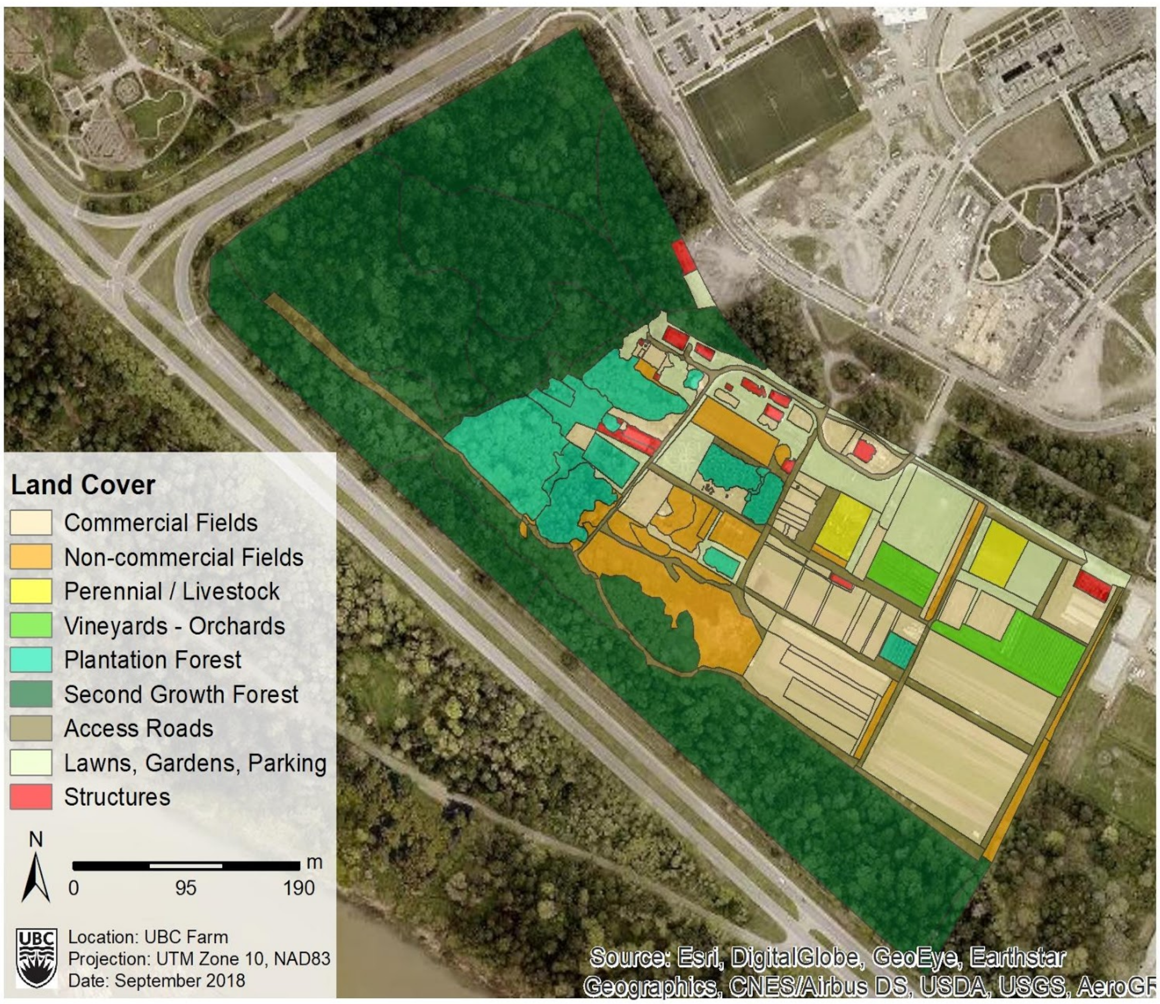
Agrobiodiversity also supports greater levels of ecosystem services and multi-functionality (i.e., the supply of multiple ecosystem services at the same time)[14,15]. For example, greater numbers of native pollinator species can improve seed set and fruit production in crops[16,17] and crop species diversity or landscape diversity can reduce herbivore damage[18,19]. Importantly, many of the ecosystem services that agroecosystems provide, such as water quality regulation, pest regulation, or soil erosion control, also contribute to food production in those landscapes[3], as well as directly to human wellbeing. Thus, within the context of long-term socioecological monitoring that includes ecosystem services, monitoring of key biodiversity indicators and understanding how they contribute to ecosystem service provision is essential.

2.3. The need for biodiversity monitoring at the UBC Farm

2.3.1. Overview of the UBC Farm

The UBC Farm is a 24-ha teaching and learning space, and integrated production farm, located on the traditional, ancestral, and unceded territory of the Musqueam people (Figure 1). It is a Living Laboratory focused on understanding and fundamentally transforming local and global food systems towards a more sustainable, food secure future. Situated within a 90-year-old coastal hemlock forest, the UBC Farm comprises a mosaic of cultivated annual crop fields, perennial hedgerows and orchards, pasture, teaching gardens, and forest stands. The UBC Farm is certified organic through North Okanagan Organic Association; grows over 200 varieties of fruits, vegetables, and herbs; and also features honeybee hives and egg-laying, open-pasture hens.

Figure 1. UBC Farm 2012 Land Cover



The UBC Farm also exists within, connects to, and is influenced by the broader socio-ecological systems it is a part of. This gives it a unique opportunity to function as a long-term agricultural/food systems socio-ecological monitoring station — to act as a prototype and hub for the measurement of the complex connections that exist between the ecological and human systems that make up food systems[20], and enable improved understanding about how these systems function, influence each other, and change through time. This sort of long-term knowledge is key to managing and influencing local and global food systems towards a more sustainable and food secure future[21].

Key to this understanding is assessing and monitoring the agricultural biodiversity on the UBC Farm. Currently, biodiversity at the UBC Farm is largely assessed in an *ad hoc* and unplanned way, making it difficult to determine how biodiversity is changing across the farm landscape or through time, how farm management is affecting biodiversity, or what ecosystem service impacts this is causing. There is a critical need for a biodiversity monitoring plan that systematically quantifies biodiversity indicators that connect to key ecosystem services and socio-ecological outcomes at the farm.

2.3.2. Connection to UBC Farm guiding principles and goals

A long-term biodiversity monitoring plan will contribute to a large number of the current goals of the UBC Farm and Centre for Sustainable Food Systems. Most importantly, it will help the Farm develop a Long-Term Research Station for Agroecological Innovation that "will conduct long term monitoring to develop adaptive pathways to food security and biodiversity conservation in the face of climate change" [22]. This is one of four strategic foci for the UBC Farm from 2016 to 2020.

A biodiversity monitoring plan will also help the Farm meet a number of goals from its academic plan - Cultivating Place[23] - including:

- Strive to demonstrate ways of understanding society's reliance on ecological systems as well as ways of enhancing this relationship while promoting cultural and biological diversity;
- Promote interdisciplinary and trans-academic activities that create and disseminate new knowledge and understanding of the connections between ecosystems and human health;
- Manage dynamic physical landscapes as living outdoor classrooms, offering innovative learning experiences that explore the connections between cultivated, forested, and urban areas, reveal the services these landscapes provide, and explore techniques and technologies for sustainable management of these systems;
- Manage the farm to maximize opportunities for research with both regional and global relevance, particularly in the fields of sustainable land use and community design, individual and community health, ecosystem services and biodiversity; and
- Provide the tools and practices necessary to define what sustainability means today and may mean in the future, facing the global challenges and opportunities sustainability offers, and being conversant about our interdependence with nature.

Finally, development of methods and tools to evaluate and monitor biodiversity at the UBC Farm will have application to current initiatives evaluating the ecological and socioecological outcomes of diversified farms. This has direct relevance for the Diversified Agroecosystem Research Excellence Cluster led by Professor and CSFS Director Hannah Wittman and its goal to develop a network of research and commercial farm to assess the multifunctional outcomes of agroecosystem diversification.

2.3.3. Connection to wider UBC initiatives and plans

As a global leader in sustainability research and practice, UBC strives for "excellence in research, learning and engagement" in pursuit of a sustainable and just society (UBC Strategic Plan: Shaping UBC's Next Century). The development of a long-term biodiversity monitoring program at the UBC Farm aligns with broader campus goals, through providing a platform for interdisciplinary research, increasing opportunity for student research and engagement, and connecting with the surrounding community. It will also help UBC:

- create a sustainable campus and act as a living laboratory (UBC Vancouver Campus Plan);
- provide opportunities and increase accessibility for students to sustainability learning opportunities (UBC Sustainability Academic Strategy);
- ensure the maintenance of healthy ecosystems (UBC Land Use Plan);
- ensure it models a sustainable and integrated food system that assesses the impacts of food production, transformation, and consumption on environmental and community health (UBC 20-Year Sustainability Strategy); and
- allow the UBC Farm to effectively connect with the current development of a UBC Urban Forest Strategy.

A biodiversity monitoring program at the UBC Farm will also connect with ongoing development of a Biodiversity Strategy for UBC. This is being led by staff associated with the CBIRD (Campus Biodiversity Project: Research & Demonstration) Project. CBIRD advocates for biodiversity enhancement, conservation, and stewardship through meaningful engagement and mutual learning, and advancement of sustainability education and research on campus. Specific goals of the CBIRD project relevant to biodiversity monitoring at the UBC Farm include:

- Data collection, spatial analysis, and metrics for the purpose of filling information gaps, monitoring, and baselining biodiversity on campus;
- Identification of green corridors and matrices;
- Development of a sustained network of biodiversity stakeholders;
- Enhanced experiential student learning and engagement of the local community through campus as a living lab; and
- Provision of a platform for information sharing and awareness-building of the importance of biodiversity within the built environment.

3. Agricultural biodiversity indicators

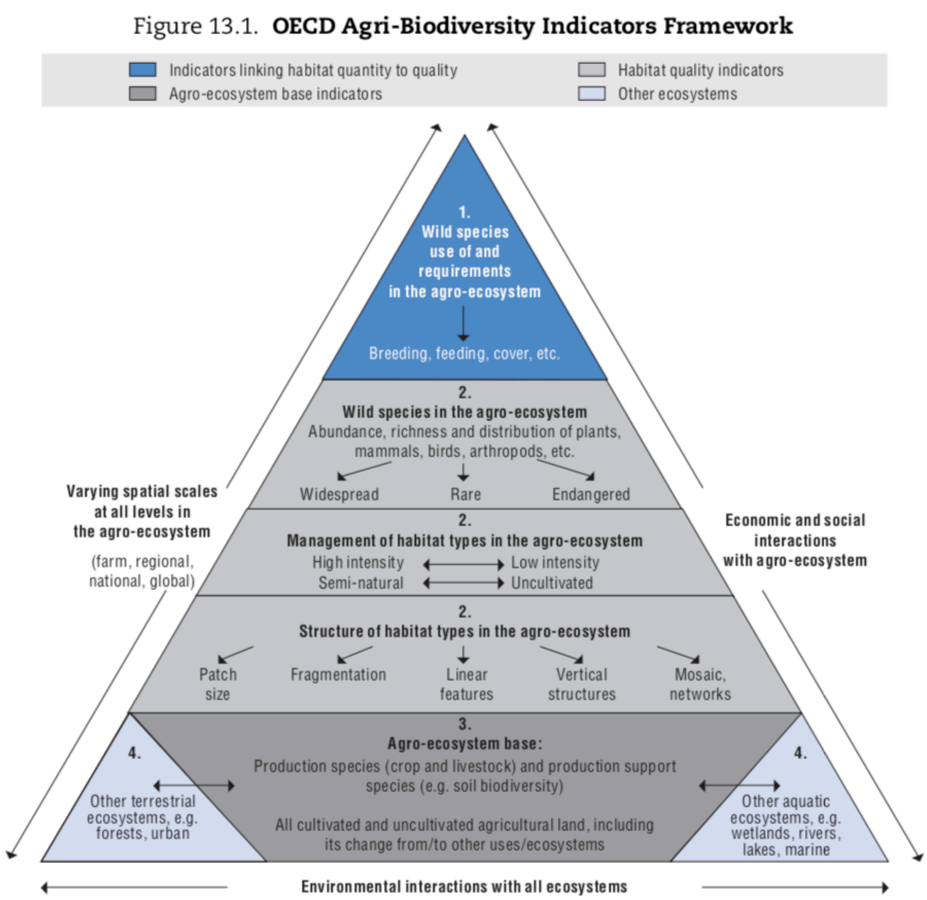
3.1. Indicators of agricultural biodiversity

3.1.1. What is a biodiversity indicator?

For biodiversity, an indicator is "a species or group of species that readily reflects the abiotic or biotic state of an environment; represents the impact of environmental change on a habitat, community or ecosystem; or is indicative of the diversity of a subset of taxa, or wholesale diversity, within an area" [24]. An ideal indicator accurately represents biodiversity as a whole[25]. In other words, measuring that species or group of species faithfully represents changes in the diversity of all other groups of interest.

Within an agroecosystem, indicators can measure a variety of different components at different spatial scales (Figure 2), including the abundance and richness of wild species; amount, management, and diversity of habitats across the landscape; and diversity of managed species.

Figure 2. Biodiversity indicators and relationships within the OECD framework.



Source: OECD (2003), *Agriculture and Biodiversity: Developing Indicators for Policy Analysis*, OECD Publishing, *www.oecd.org/tad/sustainable-agriculture/agri-environmentalindicators.htm*.

3.1.2. Challenges in measuring agricultural biodiversity

Measuring all of the species and biodiversity in an agricultural field, let alone across an agricultural landscape is extremely challenging. In general, attractive, charismatic, and well-known groups are usually favoured[26]. In any scheme, measuring agricultural biodiversity is time-consuming and difficult. Options to reduce sampling effort can include developing standard functions (rarefaction curves) that relate the number of individuals collected to species diversity for a given location, or determining the minimum level of sampling needed to capture the majority of species[26]. For example, in Switzerland, three weeks of spring sampling and two week of summer have been found to be the most efficient method to sample agricultural arthropods[26].

Identification of a broad number of species can also be tedious, time-consuming and expensive. Focusing on well-known groups (plants, vertebrates) can address this, but may not give a complete picture of the biodiversity present[26]. Options include classifying species to broader groups (e.g., family or genus)[26], or identifying specific indicator groups that are highly correlated with other species groups but that can be identified with minimal effort[27].

3.1.3. Review of relevant agricultural biodiversity indicator systems and literature

Instead of measuring all species in agricultural landscapes, specific taxa have been proposed as indicators of biodiversity. While a number of different groups and systems have been proposed, results have varied, with some studies showing strong correlations between species groups and the potential for strong indicators[28], and other showing weak relationships between species groups but stronger relationships with landscape complexity and the amount of semi-natural habitat present in the landscape[29-31]. For example, vascular plants and birds were found to be the best indicators or plant and invertebrate diversity in Austrian agricultural landscapes[32]

A variety of formal indicator systems have been created for agricultural biodiversity. While the overall goals of each are somewhat different, in general they all aim to quantify the biodiversity important for agriculture using species groups that are relatively easy to measure and assess. These indicators can also be assessed at different levels or scales, including the field level and the landscape or farming system level[33]. Systems and the indicators they use include:

- Organization for Economic Co-operation and Development (OECD)[34,35]
    - *Landscape*: agricultural land cover, habitat proportion, share of organic agriculture
    - *Species*: farmland breeding birds, abundance of wild species, abundance of non-native species
    - *Genetic*: unknown
- Food and Agriculture Organization (FAO)[33,36]
    - *Landscape*: proportion of habitats, fragmentation of natural habitats, proportion of habitats converted
    - *Species*: trends in population of species
    - *Genetic*: # of crop species in regular use, # of crop varieties in regular use, relative areas sown in different cultivars and genetic relatedness of cultivars
- Biodiversity Indicators for European Farming Systems (BioBio)

    - *Landscape*: habitat richness, habitat diversity, avg. size of habitat patches, length of linear elements, crop richness, treed habitats, percentage of farmland with shrubs, percentage of semi-natural habitats
    - *Species*: abundance and diversity of vascular plants, bumblebees and wild bees, spiders, and earthworms
    - *Genetic*: number of livestock breeds, number of crop varieties, origin of crops
- Streamlining European Biodiversity Indicators (SEBI)[37]
    - *Landscape*: area under management practices potentially supporting biodiversity, fragmentation of natural and semi-natural areas, ecosystem coverage
    - *Species*: abundance and distribution of birds and grassland butterflies, invasive alien species
    - *Genetic*: livestock genetic diversity
- Indicator Reporting on the Integration of Environmental Concerns into Agricultural Policy (IRENA)[38]
    - *Landscape*: landscape diversity, land use change
    - *Species*: population trends of farmland birds
    - *Genetic*: genetic diversity broadly defined

3.1.4. Assessment of biodiversity monitoring at other long-term research farms/sites

The UBC Farm is part of a community of academic research farms and sites around the world. A number of these other institutions have some type of biodiversity monitoring in an agricultural setting that could inform a biodiversity monitoring plan for the UBC Farm. A summary of this assessment is provided in Table 1.

In general, across the research farms and monitoring networks we reviewed, soil organisms and arthropods are most often included in monitoring, with plants and birds as secondary indicators. Pollinators and mammals are less often included in monitoring plans. However, there is a great deal of variation in the biodiversity metrics that other research farms, stations, and monitoring networks measure. This is mainly the result of the diverging missions and goals for each, which are often distinct from those of the UBC Farm. Similarly, the final indicators chosen for the UBC Farm Biodiversity Monitoring Plan will likely vary from the results of the review presented here, as they will need to be consistent with the research questions the UBC plan aims to answer. The UBC Farm may, however, be able to utilize existing protocols from biodiversity monitoring at these other farms and networks, especially those related to soil biota diversity and insect pest diversity.

A full description of the biodiversity monitoring that occurs across these different farms is provided in Appendix 1.

Table 1. Summary of biodiversity measures included in monitoring at other research farms and ecological networks.

Location	**Belowground**		**Aboveground**									
	Microbes	**Arthro-pods**	**Arthropods**			**Plants**					**Mammals**	**Birds**
			Pests	**Predators**	**Pollinators**	**Weeds**	**Vascular Plants**	**Seed Bank**	**Crops**	**Crop Yield**		
Russell Ranch	X	X	X	X		X			?	X		
Kellogg Farm	X	X	X	X		X	X	X	?	X		
Rothamsted Research Station			X	X	X	?	X		?	?	X	X
Emile A. Lods Research Centre	X	X										
Rangeland Research Institute	?	?									?	?
NEON (farm/range-land sites)	X		X	X			X				X	X
LTAR	X					X				X		
TomKat Ranch						X	X					X
UBC		*X*	*X*				*X*		*X*	*X*		*X*
Total	**5**	**4**	**5**	**4**	**1**	**4**	**5**	**1**	**1**	**4**	**2**	**4**

3.1.5. Current and historical biodiversity monitoring at the UBC Farm

A number of species groups are actively being monitored on the farm today. Nature Vancouver has been conducting monthly bird surveys since 2007, and 93 bird species have been sighted in various habitats throughout the farm. Forest plant diversity was last surveyed in 2013, where 16 tree species and 39 understory species were observed. Hedgerows were surveyed in 2011 and 22 woody plant species were recorded. An additional 42 hedgerow plant species have been observed at other times. In the production fields, weeds were surveyed in 2009 and 23 species were recorded. Since 2013, 15 insect pest species, 16 fungal diseases, and 3 bacterial diseases have also been recorded.

Unfortunately, the groups mentioned above are often sporadically monitored at the farm, usually for only a portion of the year. Data from these monitoring activities are also scattered and rarely given to the farm on a consistent basis. There is also little conscious direction at the farm with regards to consistent monitoring, both with respect to coordination of monitoring locations and consistent monitoring protocols. All monitoring that occurs typically originates from requests from community groups, farm staff, or faculty. A summary of monitoring that is currently occurring at the farm is provided in Table 2 and a summary of historic monitoring is provided in Table 3.

Table 2. Summary of current biodiversity monitoring efforts at the UBC Farm.

Species group	Currently monitored?	Frequency	Responsible person/group	Protocol exists?	Data/methods relevant for current plan?
Soil microbes	No	—	—	—	—
Soil arthropods	**Yes**	Annually (Sep/Nov)	Dr. Sean Smukler (APBI 260)	Yes	Yes
Aboveground arthropods	**Yes**	Annually (Sep/Nov)	Dr. Sean Smukler (APBI 260)	Yes	Yes
Pests	**Yes**	Sporadic	Farm staff	No	No
Pollinators	No	—	—	—	—
Weeds	**Yes**	Sporadic	Farm staff	No	No
Hedgerow plants	**Yes**	Irregular	Mel Sylvestre (UBC Farm), Dr. Sean Smukler (APBI 260)	Yes	Yes
Trees	No	Completed in past	Prof. Stephen Mitchell	Yes	Yes
Crops	**Yes**	Annually	Farm staff	Yes	Yes
Forest fungi	**Yes**	Annually (Sep-Nov)	Dr. Richard Hamelin (FRST 307)	No	Yes
Mammals	**Yes**	Annually (Sep/Nov)	Dr. Sean Smukler (APBI 260)	No	Yes
Birds	**Yes**	Monthly (from 2007)	Nature Vancouver	Yes	Yes
Bats	No	—	—	—	—

Soil Biota - Microbes: So far very little is known about the microbial community in the production potion of the farm. Most other research stations have collected microbial data, as the microbial community is essential for nutrient cycling and the uptake of nitrogen in some plants. While the microbial community has not been sampled in the past, the APBI 402/SOIL 502 Sustainable Soil Management class taught by Dr. Maja Krzic and Dr. Sandra Brown has been monitoring soil nutrients since 2004 at several sites across the farm landscape. This data has been uploaded to the UBC Farm database.

Soil Biota – Arthropods: Some current monitoring of arthropods is performed by Dr. Sean Smukler's APBI 260 class during the fall. This data is collected by deploying pitfall traps throughout the farm and collecting arthropods once a week from September through November. Collected arthropods are later identified to broad functional groups.

Pollinators: While no systematic monitoring of pollinators is currently happening at the farm, there is growing interest in monitoring these species at the UBC Farm, including from Dr. Smukler. One of his students, Marika van Reeuyk, completed a study on bee diversity in the farm hedgerows in 2017. The nearby UBC Botanical Garden also has an active citizen science pollinator monitoring program led by the Environmental Youth Alliance (EYA). Thus, there is the potential for collaboration with the Botanical Garden in establishing a joint pollinator monitoring program. There has also been an effort on the part of the UBC Botanical Garden and the Beaty Biodiversity Museum to characterize the historical biodiversity of bees at UBC and estimate what changes in species diversity have occurred.

Pests & Weeds: Currently, monitoring of pests and weeds is conducted by farm staff. It appears that monitoring is haphazard where any recording of the appearance of pests and weeds only occurs if some sort of treatment needs to be applied to control an outbreak. There are some records of pests present on the farm from 2013 in the farm database.

Hedgerow Plants: Currently the four hedgerows present at the UBC Farm were surveyed in 2010 to describe the plant species present. These maps are stored on the UBC Farm hard drive. However, some faculty members are skeptical at the accuracy of these maps. In the summer of 2017, SEED interns began to update the maps, and new interns completed this mapping during the summer of 2018. Dr. Sean Smukler's APBI 260 class also collects some data on vascular plant diversity in a limited number of the hedgerows each fall. In addition to the hedgerows planted by UBC Farm staff, the Indigenous gardens have their own hedgerows that have not yet been surveyed.

Trees: All tree data collection at the UBC Farm has been conducted by Dr. Stephen Mitchell's classes, but this has not occurred recently. This data was collected from 2011 and 2012 when the entirety of the forested area of UBC Farm was divided into sections to be surveyed. This survey determined species presence across the farm, and measured the health and age of the trees.

Crop Diversity: The farm currently records the variety of each crop grown on the farm, and saves seeds from a small number of crops. Much of this data is in the form of crop maps and it appears that the data on which crops are grown each year and the seeded/harvested area of each is not consistently recorded from year-to-year.

Forest Fungi: Currently, monitoring occurring with regards to forest fungal diversity is performed by Dr. Richard Hamelin's FRST 307 class during the fall semester. They sample throughout the forested areas of the UBC Farm and identify both macro- and microfungal species that grow in the area. Attempts were made by Dr. Hamelin and Natalie Westwood to identify potential areas for standardized fungal sampling throughout the 2017, however due to unforeseen dry conditions, they were unable to identify areas that have a variety of fungal species.

Mammals: Some current monitoring of mammals is performed by Dr. Sean Smukler's APBI 260 class during the fall. Using camera traps at a number of sampling locations throughout the farm, students identify different types of mammals (and other species).

Birds: Currently, Nature Vancouver conducts a bird survey once a month on the third Sunday of each month. They have nine established observation stations across the farm where bird sightings and bird calls are recorded. This data has been collected since 2007. All the data is then uploaded to the eBird database. While the eBird dataset does not record the specific station at which each bird was observed, this data has been provided by Nature Vancouver and will be added to the UBC Farm server. In addition, Dr. Smukler's APBI 260 class monitors bird diversity throughout the farm during the fall semester. He has collected data on bird diversity for a number of years and may still have this data stored and available. This data has been collected during the first six weeks of each fall term.

Bats: No current monitoring of bats is currently occurring on the farm. A representative from the South Coast Bat Conservation Society approached the farm in 2017 in the hopes of collecting bat guano to identify what insects they were consuming. However, funding for this work was uncertain and the possibility of this work happening is unclear.

Table 3. Historical biodiversity monitoring efforts at the UBC Farm.

Species Group	**Years Monitored**											
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Soil microbes												
Soil arthropods									?			
Pollinators												
Aboveground arthropods									?			
Pests							Sporadic					
Forest plants												
Weeds				Sporadic								
Hedgerow plants												
Crops												
Forest fungi										?		
Mammals									?			
Birds												
Bats												

4. Biodiversity indicators for the UBC Farm

4.1. Indicator selection approach

4.1.1. Criteria for indicator selection

Indicators are "measurements that reflect the status of a system, for example an oil pressure gauge on an engine or the number of owls in a forest"[39]. Numerous types of diversity (ecosystem, species, genetic) and species groups are present at the UBC Farm and contribute to ecosystem services and socioecological outcomes on the farm. Due to the multifaceted nature of biodiversity, multiple indicators are required to adequately monitor biodiversity.

Ideally, these indicators will be relatively simple to quantify, will respond to changes in environmental conditions on farms that reflect changes in on-farm management practices, and reflect critical components of the fundamental science research programs of UBC Farm affiliated researchers. In addition, certain species groups are more important to the critical functions at the farm (e.g., food production) or will be easier to incorporate into a monitoring program due to current assessment activities at the farm.

The criteria considered when selecting individual biodiversity indicators[40] for the UBC Farm monitoring plan, from highest priority to lowest priority, include:

- Biodiversity relevant (indicators should address key properties of biodiversity related to status, pressures, responses, use, or capacity);
- Scientifically sound (based on clearly defined, verifiable, and scientifically acceptable data collected using standard methods of known accuracy and precision);
- Of interest and relevance to the current research interests and activities of UBC Farm affiliated faculty;
- Relevant to farm operations and the farm's socio-ecological outcomes;
- Sensitive to environmental and farm management changes;
- Measure a unique aspect of biodiversity (i.e., minimizes overlap across indicators);
- Cost effective and logistically feasible; and
- Potential usefulness for teaching and outreach.

These criteria were used to select biodiversity indicators at three levels – landscape/habitat, species, and crop for the monitoring plan. Indicators were then categorized into three groups to identify the most critical indicators for inclusion in the monitoring program. These three categories include:

- *Core indicators*: The indicators that should form the core of the biodiversity monitoring program and be prioritized for assessment each year of the program. These are indicators that meet most of the selection criteria described above.
- *Secondary indicators*: These are indicators that could be monitored during the program if logistics/funding allows. These indicators meet some of the selection criteria and could contribute additional data to the monitoring program.

- *Peripheral indicators*: These are indicators that should only be monitored if there is specific interest from researchers or students. These are indicators that meet few of the selection criteria, but could be the basis of directed research projects, pilot studies, or new research questions/programs.

4.1.2. UBC community participation in indicator selection

A variety of experts across UBC and the UBC Farm, as well as some outside the immediate university community were consulted about indicator selection and monitoring methods. In addition, a number of wider meetings and presentation to UBC faculty and UBC Farm staff took place during 2017 and 2018. For details on these experts and meetings, please see Appendix 2.

4.2. Landscape/Habitat diversity indicators

4.2.1. Landscape/Habitat diversity overview

Landscape structure includes the types and amounts of different land cover that are present (landscape composition), the spatial arrangement of these land cover types (landscape configuration), and the degree to which a landscape facilitates the movement of organisms and matter (landscape connectivity). Changes in landscape structure across an agricultural landscape largely reflect human activities that occur for agricultural management[41]. This includes cropland expansion and loss of natural habitat[42], amalgamation of fields and increasing field sizes[43], changes to the types and amounts of crops grown[44], and the maintenance or addition of hedgerows, prairie strips, and riparian areas[45]. Change to landscape structure is likely to alter patterns of biodiversity across landscapes as it changes the amount of habitat available to a particular species, or changes how species can move across the landscape and access different habitats and resources[46-48]. In agricultural landscapes, pests are a particular group of interest, and it has been widely observed that landscape structure, and in particular "landscape complexity," has strong effects on pest and predator abundance and diversity[19].

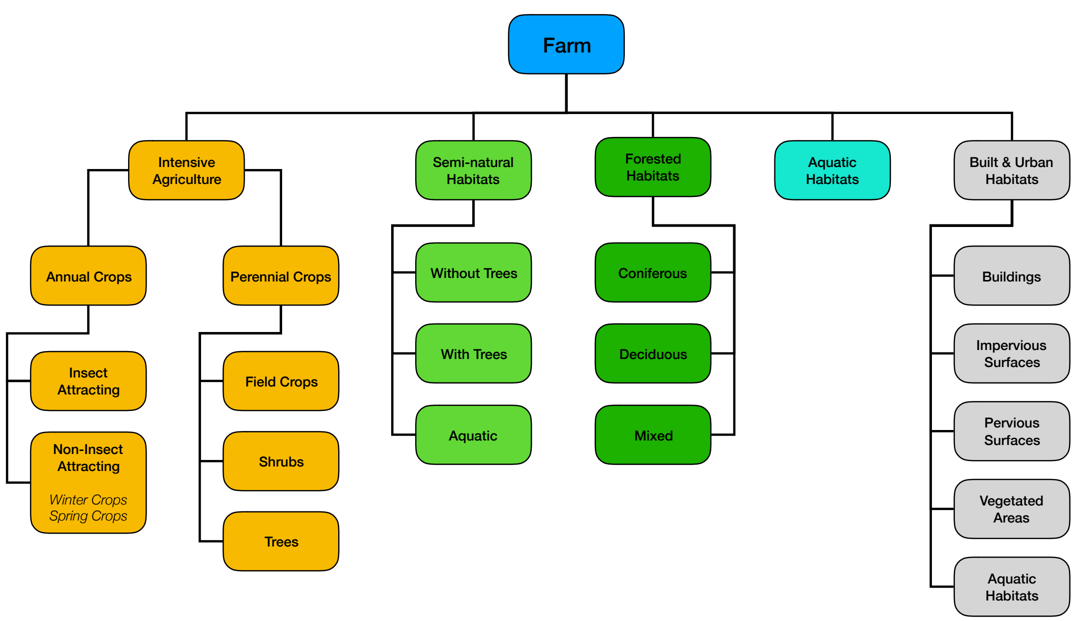
4.2.2. Habitat Categories

To track changes in land use/land cover (LU/LC) change across the UBC Farm and quantify landscape structure on and around the farm, a modified version of the BioBio and EBONE habitat classification system is proposed. LU/LC will be mapped across the farm and around the farm within a 500 m buffer using digital imagery and field sampling (Table 4 & Figure 3). The goal of this system is to assess current conditions and track changes in both the production and non-production areas of the farm, as well as the immediate surroundings that may affect biodiversity on the farm. A detailed protocol for this is currently being developed through the Masters in Geomatics and Environmental Management program in the Faculty of Forestry. This plan and an updated LU/LC map for the farm is expected to be complete by April 2019.

Table 4. Land use/land cover habitat categories, sub-categories and examples.

Habitat category	Sub-category	Examples
Intensive agriculture	Annual crops	
	Non-insect attracting	Winter: oats, barley, wheat, rye, triticale, beans Spring: oats, barley, wheat, lettuce, peas, beans, kale
	Insect attracting	Oilseed rape, sunflower, maize, soya, cucumber, squash, tomatoes, potatoes, strawberries
	Perennial	
	Field crops	Fodder crops, alfalfa, asparagus
	Shrubs	Blueberries, grapevines
	Trees	Apples, orchards, oak plantation
Semi-natural	Without trees	Grasslands, meadows, grassy field margins
	With trees	Hedgerows, tree plantations, arboretums
	Aquatic	Drainage ditches, artificial ponds
Natural Aquatic		Streams, ponds, marshes, wetlands
Forested	Coniferous	Douglas-fir, western red cedar, western hemlock
	Deciduous	Bigleaf maple, red alder, cottonwood, cherry, cascara
	Mixed	Mixed coniferous and deciduous tree species
Built Infrastructure & Urban	Buildings	Condominiums, apartments, farm buildings, greenhouses
	Impervious surfaces	Paved roads, sidewalks, paved lots
	Pervious surfaces	Gravel roads, unsealed lots, playgrounds
	Vegetated	Gardens, mowed grass, recreational fields
	Aquatic	Artificial ponds and watercourses in parks

Figure 3. Land use/land cover classification for the UBC Farm.



4.2.3. Selected landscape/habitat indicators

Using the LU/LC mapping and categories described above, a number of different indicators of landscape structure and diversity will be calculated and mapped across the UBC Farm at different spatial resolutions (Table 5). Ideally, these indicators should be calculated for the entire farm, as well as finer spatial scales such as 50 × 50 m or 100 × 100 m. The most appropriate scale to calculate and map these indicators will need to be assessed in the future once the new LU/LC mapping is complete. It is also anticipated that a separate analysis for the areas outside the farm boundaries will occur with slightly different indicators (see below). More details on the selected indicators can be found in Appendix 3.

Table 5. Selected landscape/habitat indicators, definitions, and rationale

Indicator Group	Indicator	Definition & Rationale
Core Indicators	Habitat richness	Total number of habitat types present. Direct indicator of habitat richness.
	Habitat diversity	Shannon diversity index based on proportion cover of each LU/LC category. Indicator of richness and dominance of habitats.
	Average size of habitat patches	Indicator of fragmentation of habitat patches and spatial scale of landscape heterogeneity across the farm
	Length of linear elements	Length of grassy field margins, ditches, and hedgerows. Measure of potential connectivity across the farm
	Crop richness	Number of crops present. Measure of diversity of 'planned' biodiversity on the farm.
	Shrub cover	Proportion of farm covered by shrubs. Indicator of vegetation complexity in production fields, potential bird and spider habitat
	Tree cover	Proportion of farm covered by trees. Indicator of vegetation complexity in production fields, bird habitat
	Semi-natural habitat cover	Proportion of farm covered by semi-natural habitat. Indicator of potential of farm to provide habitat for wildlife species.
	Built infrastructure cover	Proportion of farm and surrounding area covered in built infrastructure. Indicator of loss of habitat for wildlife and urbanization.
Secondary Indicators	Tree density	Number of trees per hectare. Indicator of intensification of orchards and plantations.
	Non-crop plant cover on arable fields	Proportion of fields covered by weeds and non-crop plant species. Indicates potential habitat for arthropod pests and predators
	Ratio of non-flowering to flowering crops	Ratio of non-flowering to flowering crop area. Indicator of relative amount of pollinator resources present in production area

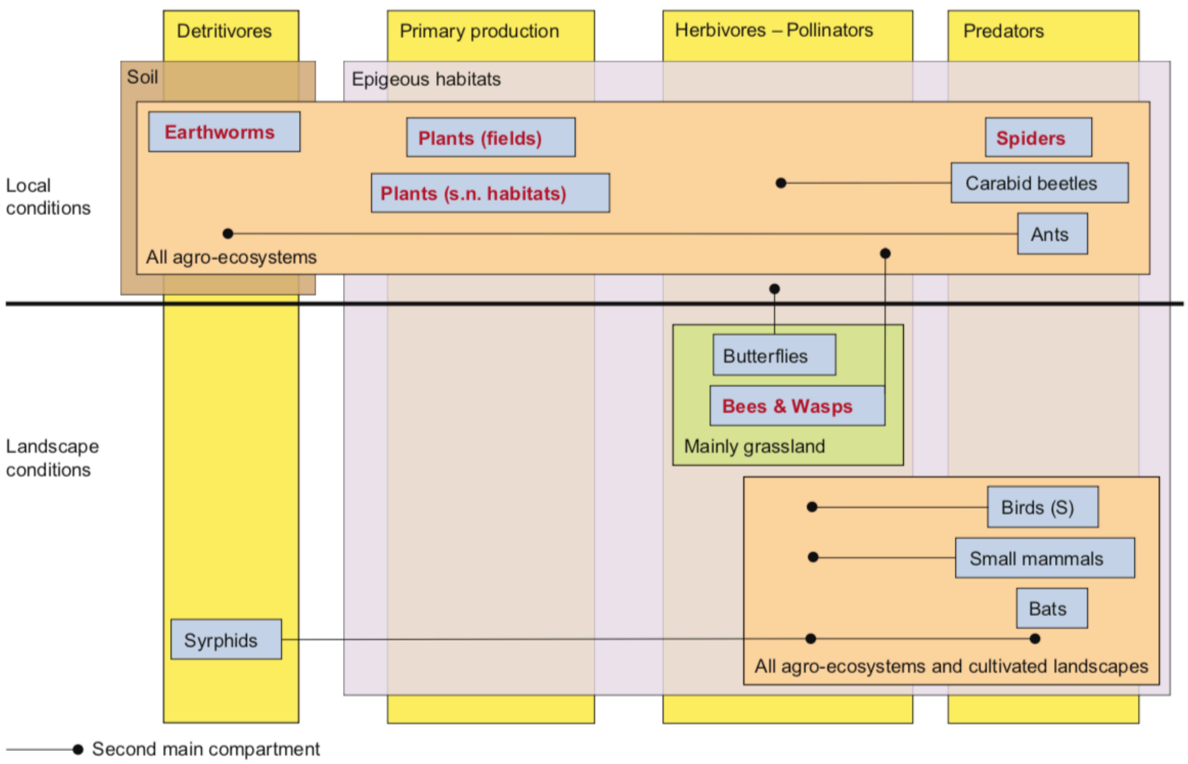
4.3. Species Diversity Indicators

4.3.1. Species diversity overview

Species diversity is a core and most common indicator of biodiversity. However, other than for some groups like mammals and birds, collecting and identifying individuals to the species-level can be difficult, time-consuming, and costly[49]. Therefore, only select groups of species are usually monitored in biodiversity monitoring plans. Ideally, these groups will span trophic levels and spatial scale (Figure 4).

Diversity includes a large number of potential measures and metrics[50]. Thus, besides choosing a subset of species groups to monitor, there are additional decisions around which diversity metrics to calculate. In addition to determining the total number of species present in an area, other measures assess the distribution of individuals across species (dominance and evenness) or the turn-over in species identity across sites or through time. Importantly, having a greater number of species does not always equate to an increase in the functions those species perform or an increase in genetic diversity[51]. If the species fulfill similar ecological roles (e.g., all species are pollinators or decomposers) or are phylogenetically related (e.g., all come from genera that are closely related), then functional or phylogenetic diversity may not match well with species diversity. A select number of metrics have been chosen for the UBC Farm monitoring plan and are described below.

Figure 4. Position in food chain and scale of spatial distribution/response to environmental conditions for select biodiversity indicators.



**BioBio selected indicators are in red.*

4.3.2. Selected indicator species groups

The selected indicator species groups and rationales for their selection are described below and in Table 6. There are six core species groups, six secondary groups, and four peripheral indicators.

Table 6. Selected landscape/habitat indicators, definitions, and rationale

Indicator Group	Indicator	Rationale
Core	Wild bees and bumblebees	Important for crop pollination. Sensitive to agricultural practices, landscape and crop diversity, and environmental conditions. Relatively easy to identify. Public concern for health.
	Agricultural vascular plants and weeds	Essential to primary production. Strong impact on crop production. Indicator of presence of invasive and exotic species. Sensitive to local conditions.
	Forest vascular plants	Key for forest habitat structure and carbon storage. Relatively long-lived and indicator of slow dynamics. Easy to identify.
	Earthworms	Critical for soil structure and quality and detritus processing. Relatively easy to sample and identify functional groups.
	Birds	Charismatic and of interest to farm visitors. Already being monitored by Nature Vancouver. Sensitive to wider landscape changes and development.
	Mammals	Charismatic and of interest to farm visitors. Potential indicator for future human-wildlife conflict. Sensitive to wider landscape changes and development
Secondary	Spiders	Important predator/beneficial species group. Indicators of habitat complexity and pest presence. More difficult to sample and identify.
	Soil arthropods	Key to soil structure and functioning, soil quality, etc. Relatively simple to sample for, but require much lab time to identify.
	Arthropod pests	Critical indicator of crop damage and source of significant financial loss. Require much laboratory work.
	Butterflies	Relatively easy to sample and of interest to farm visitors. Indicator of grassland/floral conditions. Sampling weather dependent.
	Carabid beetles	Important biocontrol species group and highly investigated in agricultural landscapes. Require much laboratory work.
	Bats	Difficult to sample and direct sampling requires night work and vaccinations. Possibility of using bat detectors to monitor species and abundance.
Peripheral	Soil microbes	Critical to soil functioning and quality, decomposition. Uncertainty as to link between taxonomic groups and ecosystem function. Expensive to process samples and identify groups.
	Forest fungi	Important indicators of forest health. Limited understanding of impacts on agricultural production.
	Ants	Important for a number of functions (ecosystem engineering, biocontrol, soil properties). Require much laboratory work.
	Diptera, Syrphidae	Biocontrol agents. Relatively easy to sample but difficult to identify and require much laboratory work.

Agricultural vascular plants: As the dominant primary producers in terrestrial ecosystems, vascular plants are the foundation of most terrestrial food webs[52]. They also provide habitat, breeding sites, shelter, and refuge for many species of birds, arthropods, amphibians, and mammals, making vascular plant diversity a proxy for overall biodiversity[53-55].

While vascular plants fulfil most of our indicator criteria, a large sampling effort will be necessary to capture the amount of diversity across the farm[52]. Focusing monitoring efforts on specific habitat types or species groups, such as hedgerows and weed species, can help overcome this challenge[52].

Hedgerows are associated with several ecosystem services, including carbon sequestration, water filtration, and soil erosion prevention[56]. As semi-natural habitats, they also provide resources for natural enemies and pollinators[57]. While hedgerows provide many beneficial services, they may also serve as corridors for weeds and agricultural pests[58]. Monitoring long-term plant diversity of hedgerows can help stakeholders determine how hedgerow plant species contribute to these ecosystem services and other processes occurring on the farm.

Weed species respond readily to changes in agricultural management, making them a useful biodiversity indicator[59]. Weeds are of particular interest to farm managers, as they influence farm production by competing with crops for nutrients, light, water, and other resources[59]. Long-term monitoring of weed species can improve knowledge of which species have the greatest impact on crop yield, and provide insight on how farm management impacts the distribution and abundance of weeds throughout the farm.

Forest vascular plants: Forest plants cover half of the UBC Farm and provide a variety of important ecosystem services, including carbon storage, rainfall interception, microclimate regulation and opportunities for recreation[60,61]. As mentioned above, they also provide habitat, breeding sites, shelter, and refuge for many species of birds, arthropods, amphibians, and mammals[53-55]. Spillover of organisms from forested areas to agricultural fields (e.g., arthropod pest and predators) can also be an important process that affects pest regulation and crop damage in agroecosystems[62,63]. Understanding how the forest is changing through time, which often occurs at slower rates than in agricultural fields, is critical to improving our knowledge of agricultural landscapes.

Additionally, there is already a substantial amount of baseline data on forest diversity and structure present for the UBC Farm through Dr. Stephen Mitchell and the UBC Faculty of Forestry. This baseline data and the ability to have Forestry students complete species diversity, forest structure, and timber measurements for the monitoring plan means that including forest plants in the monitoring plan is a priority.

Wild bees and bumblebees: Wild bees and bumblebees pollinate many agricultural crops and wild plant species. While domesticated honeybees are the most common pollinators used in agricultural systems worldwide, disease and population crashes of domesticated bees are making wild bees increasingly important for insect-pollinated crops[64-66]. Additionally, wild bees pollinate many crops more effectively than domesticated species[66], particularly when diverse assemblages of pollinators are present[16,67]. Fields with diverse bee communities have been found to have higher flower visitation rates, improving crop quantity and quality through increased seed set and fruit size[68]. The resilience of pollinator services also increases with bee diversity, as species respond differently to climate and land-use change leading to yearly variation in community composition[16].

Although the benefits of wild pollinators is well recognized, habitat loss from agricultural intensification is a major contributor to the global decline of wild bee and bumblebee populations[64]. Field studies have contributed to understanding the impacts of agriculture on wild pollinator abundance and diversity, and long-term monitoring programs are needed to assess how wild bees respond to changes in management practices[66].

Earthworms: Earthworms are among the most important detritivores in soil ecosystems and can substantially alter the soil environment. There are three ecological classifications of earthworms based on where they occur in the soil profile and how they influence soil processes. Epigeic species live in the litter layer and produce casts on the soil surface; endogeic species make temporary, horizontal burrows in topsoil or subsoil; and anecic species are found in deep, permanent burrows that vertically connect the soil surface with lower horizons[69].

Through burrowing and releasing casts, earthworms influence physical, chemical, and biological soil processes and contribute to many ecosystem services. Specifically, they impact soil drainage, carbon sequestration, nutrient cycling, and plant productivity by increasing porosity, stabilizing aggregates, transforming soil organic matter, stimulating microbial activity, and increasing nutrient availability[69-72].

Earthworm communities with a combination of different ecological types are thought to improve the provision of ecosystem services, as burrowing patterns, food preferences, and earthworm density influence nutrient cycling and plant nutrient uptake[72,73]. Species richness, abundance, and population dynamics are sensitive to changes in the soil environment, making earthworms a suitable indicator for assessing the impact of agricultural management on biodiversity[74].

Birds: Metro Vancouver is home to a wide diversity of birds, with over 250 species that are sighted annually (birding.bc.ca). Ecological roles vary considerably between species, and diets range from predators of small vertebrates or insects, to granivores that feed on seeds and grains.

Birds are sensitive to changes in their environment, and the intensification of agriculture in recent decades coincides with a decline in farmland bird diversity [75,76]. The relationship between agriculture and birds has been well studied, as birds contribute to both regulating and cultural ecosystem services on the farm [77]. Recent studies suggest that excluding birds from agricultural systems leads to a combination of increased pest damage, higher pest abundance, and reduced yields [78]. While foraging has the potential to regulate agricultural pests, such as insects and rodents, birds can also negatively impact farm production by consuming or damaging crops prior to harvest[79]. While the trade-off between pest regulation and crop damage caused by birds in agricultural systems is complex, the general public tends to value birds, as they are both visually and vocally appealing[77].

Birds are useful indicators of biodiversity because they are sensitive to changes in agricultural practices, contribute to regulatory services, and attract public interest[77]. Additionally, they are one of the most well studied taxonomic groups, and species identification guides are readily available[77]. Monitoring bird diversity can contribute to a better understanding of how management and changes to the farmscape impact bird populations over time.

Mammals: Mammals have important functions, both positive and negative, in agricultural landscapes, as well as being the source of much interest from people. Mammals, especially rodents and deer, can be important crop pests[80], while individuals from higher trophic levels (e.g., coyotes) can help control these populations{Newsome:1990bu}. Mammals are also often the source of significant human-wildlife conflicts in peri-urban and agricultural landscapes{Treves:2007in}, especially larger mammals such as coyotes or racoons[81]. At the same time, wildlife viewing and the opportunity to observe and photograph mammals is often of significant appeal{Fennell:1997io}. At the UBC Farm, there is a need to understand how the farm facilitates mammal movement and how farm management affects this. While mammal monitoring can be labour intensive if trapping is undertaken, recent developments in remote camera trapping have made it easier to comprehensively monitor mammals[82].

4.3.3. Selected species diversity indicators

A variety of species diversity indicators have been chosen as core and secondary indicators. Selection is based on the information each provides, the ease of calculation, and ability to communicate information to a diverse audience. Core indicators focus on species richness, while secondary indicators focus on turnover in species identify and species evenness (Table 7). More details on the selected indicators and methods to calculate them can be found in Appendix 3.

Table 7. Selected species diversity indicators, definitions, and rationale

Indicator Group	Indicator	Definition & Rationale
Core	Gamma diversity	Total number of species on farm. Measure of total species richness present across farm or specific habitat.
	Alpha diversity	Average number of species per plot/sample/habitat. Measure of species richness likely present at a single location and time.
	Area weighted diversity	Number of species weighted by habitat area. Adjusts total species richness to take into consideration relative amount of habitat present.
	Chao estimated richness	Extrapolated/estimated number of species. Partially corrects for sampling effort and species that weren't encountered in sampling.
	Individual species abundance	Number or density of individuals. Finer scale measure of changes in specific groups or species through time or space.
Secondary	Beta diversity	Species turnover across plots or habitats. A measure of the heterogeneity of species diversity across the farm.
	Species evenness	Species equitability across plots or habitats. Partial measure of species composition and dominance across community of interest.
Peripheral	Functional diversity	The diversity of traits in the community. Provides added information about the potential functions or niches present in a community and how this is changing across space or time.
	Phylogenetic diversity	The amount of phylogenetic difference present in a community. Provides information about the phylogenetic relatedness or common ancestry present in a community.

4.4. Crop diversity indicators

4.4.1. Dimensions of crop diversity

The planned diversity of crops (either perennial or annual) in agricultural ecosystems, like other aspects of biodiversity, can enhance ecological functioning and services in and around the farm. Crop diversity can be in terms of species (e.g. polycultures), or within species genetic diversity (e.g. several varieties of the same crop). Moreover, diversity can be achieved spatially through mixed cropping systems or inter-cropping, or temporally through a seasonal or annual crop rotation. With increased diversity of species and varietals of crops, there is an increase in the possible variation in responses to change and stressors, providing a resilience-enhancing buffer to the system. In particular, crop genetic diversity has been shown to enhance pest and disease management as well as pollination services[83,84].

4.4.2. Selected crop diversity indicators

Core crop diversity indicators focus on crop types/varieties as this information is largely already available through the farm database and farm staff (Table 8). The main challenge is mapping this diversity spatially across the farm to better understand spatial patterns of 'planned' diversity and how this varies through time. Other indicators focused more on functional, genetic, and phylogenetic diversity of crops on the farm have been included as peripheral indicators due to the added complexity of measuring traits or assessing genetic diversity. Specific details on the selected indicators can be found in Appendix 3.

Table 8. Selected crop diversity indicators, definitions, and rationale

Indicator Group	Indicator	Definition & Rationale
Core	Number of different varieties	Total number of crop types and varieties present. Measure of the richness of the "planned" diversity on the farm. Relatively easy to measure and assess.
	Crop alpha diversity	Average number of crop types or varieties across fields or fixed spatial areas (e.g., 50 × 50 m)
	Crop beta diversity	Turnover in crop types or varieties across fields or fixed spatial areas (e.g., 50 × 50 m)
Peripheral	Crop functional diversity	The diversity of traits across crops present at the farm. Provides information on potential functions crops are providing.
	Pedigree-based genetic diversity	Measure of genetic relatedness of crop types and varieties. Requires information on selection and breeding processes.
	Genetic diversity index of crops	Molecular-based measure of genetic relatedness of crop types and varieties. Requires specialized analysis tools.

4.5. Farm management indicators

4.5.1. Linking farm management with biodiversity

Farm management directly affects farm biodiversity, most obviously through changes to the 'planned' biodiversity of crop types and varieties, but also through the influence of these management decisions on the wild diversity present in agricultural landscapes. Decisions about which crops are grown and where; the consumption of energy and external inputs; and the amount and timing of tillage, seeding, watering, pesticide use, fertilizer use, and field operations can all affect the biodiversity present[85-87].

4.5.2. Selected farm management indicators

A number of potential farm management indicators are possible for the UBC Farm. For the purposes of this document, we list them here (Table 9) without going into detail about how they should be assessed or measured. In general, these indicators provide information about the intensity of management on the farm and should be assessed through the current record-keeping protocols at the farm.

Table 9. Potential farm management indicators, definitions, and rationale

Indicator Group	Indicator	Definition & Rationale
Core	Total direct and indirect energy input	Gj ha^{-1} for the utilized agricultural area. Measure of agricultural intensification and mechanization
	Expenditures on fuel, pesticides, fertilizer	$ ha^{-1}. Additional measure of agricultural intensification and amount of external inputs to production system.
	Area with use of organic N fertilizer	Proportion of utilized agricultural area. N inputs drive crop production but also affect other species such as weeds and pests. Also important for soil quality and water runoff.
	Total N input	kgN ha^{-1}. N inputs drive crop production but also affect other species such as weeds and pests. Also important for soil quality and water runoff.
	Number of field operations	Indicator of disturbance with mechanized equipment. Includes number of cuts, timing of first cut, and tillage (% area tilled)
	Organic pesticide use	Number and rate of application of herbicides, insecticides, and fungicides. Pesticides can have large effects on non-target biota, especially plants and arthropods.
Secondary	Irrigation	% of utilized agricultural area irrigated. Potentially can influence soil community and weed presence in production fields, increase runoff as well.
	Soil cultivation	% of utilized agricultural area with no-till. A measure of the prevalence of no-till methods and potential impacts to soil biota.

5. Biodiversity Monitoring Sampling Plan

5.1. Landscape/habitat diversity

A detailed protocol for classifying LU/LC at the farm is currently being developed through the Masters in Geomatics and Environmental Management (MGEM) program in the Faculty of Forestry. In brief, a LU/LC classification will be performed using 5 m resolution SPOT satellite imagery, LiDAR elevation surface feature, building and vegetation height data, and field surveys. This plan and an updated LU/LC map for the farm is expected to be complete by April 2019. From this data, landscape and habitat diversity metrics will be calculated at a variety of spatial scales using GIS software and the FragStats program.

5.2. Species diversity

5.2.1. Rationale and sampling principles

A significant challenge with long-term biodiversity monitoring is dealing with changes to crop types and farm landscape structure over time. These changes occur both seasonally (intra-annual variation as crops flower, are harvested or are planted), and annually (inter-annual variation as crops are rotated, program goals change, or market demands shift). Because of this variability, the sampling design below recommends a combination of 'fixed' and 'floating' sampling locations (plots, transects, quadrats, etc.). The former will allow a consistent comparison of indicators at a specific location on the farm over time and can tell us something about how that indicator changes as its surroundings and management change, whereas the latter will provide insight into how indicators in the same immediate surrounding (next to or within a given crop type) are changing. In both cases, data about surrounding conditions and crop types will be used to control for this variation.

The sampling design for the biodiversity monitoring plan aims to provide a rigorous, scientifically-defendable, and cost-effective plan for sampling key biodiversity groups across the diverse land covers of the farm in a way that provides a consistent foundation for monitoring but that is also flexible enough to accommodate the future changes to land use, land cover, and management techniques that will occur on the farm. The specific principles that informed the sampling design include:

- Scientifically sound and based on accepted or current methods utilized in the scientific literature or citizen-science initiatives;
- Ensuring that major land cover types on the farm (e.g., annual crops, perennial crops, hedgerows, gardens, and forest) are consistently sampled;
- Adequate replication of measurements in each land cover for statistical analysis;
- A flexible design that can accommodate the different dimensions of the habitats present (e.g., hedgerows versus production fields), ecological properties (e.g., production fields versus forested areas), and future changes at the farm;
- Where possible measuring multiple biodiversity indicators in the same location so that relationships between groups can be assessed; and
- Cost effective and logistically feasible.

5.2.2. Sampling locations and plan

A stratified sampling plan will be used, with sampling intensity proportional to the area of each land cover. The sampling intensity goal will be two sampling locations per hectare in the farm/production area (production fields, non-production fields, orchards, plantation forests, field margins, hedgerows) and one sampling location per hectare in the second-growth forest areas, although this may vary due to logistical constraints. Within the second-growth forest area of the farm (12 ha or 50% of the farm) this will mean around 12 permanent sampling locations. Within the production areas, fields, plantation forests, and gardens (10 ha or 42% of the farm) this equates to about 20 permanent sampling locations. Permanent sampling locations will also be located for land covers less than 1 ha in area (e.g., indigenous garden, staff garden, Mayan garden, plantation forests) that represent distinct land covers/uses within the farm. In addition, a number of floating sampling locations (number to be determined in the future) will be added each year to ensure adequate coverage of the production areas of the farm.

Sampling locations within the forest will be located along a gradient from forest edge, with the forested area of the farm split into distance-from-edge bands at 25 m intervals (0-25, 25-50, 50-75, and 75-100 m from edge) and equal numbers of sampling plots located within each of these bands. Within the agricultural area of the farm, permanent plots will be located in field centers (~6 plots), field margins/hedgerows (~10 plots), and the center of plantation forests (~5 plots).

To select sampling locations, a 25 x 25 m grid of points will first be overlaid across the entire farm property. These points will then be stratified into the different land cover and distance to forest edge categories using a GIS. Next, a random sample of points in each category/edge distance category will be chosen, with the stipulation that no two points in the same strata be within 50 m of each other. Points will be selected until the required sampling intensity is met. Within the production area of the farm, these points are proposed to be permanent and high-accuracy GPS location information will need to be recorded. In the forested portion of the farm, to reduce the effects of trampling from repeated monitoring visits, it is proposed that monitoring rotates through a set of sample points every 4 years (12 locations from a total sample of 48 are monitored each year). Any land cover categories that haven't already been included in the sampling scheme (e.g., field margins, hedgerows, small gardens) will be allocated additional sampling locations manually.

At each sampling location the following core samples will be collected (Table 10), with detailed protocols described in Appendix 4. Below, we briefly outline the sampling methods.

In production fields pollinator pan traps and mammal camera traps will be placed directly at each sampling location. Between the adjacent crop rows, a single 50 m pollinator transect will be performed, and two 50 m arthropod pest/predator transects will be completed within the nearest two adjacent crop rows. Along a random azimuth and random distance less than 10 m from the plot center, four 2 × 2 m (4 m^2) vegetation plots will be located. A similar procedure will be used to place three earthworm/microbe soil sample plots (Figure 5).

In linear features (field margins, hedgerows) similar procedures for pan/camera traps and the pollinator transect (oriented parallel to the field edge or hedgerow) will be performed. However, the vascular plant plots and earthworm/microbe plots will instead be located at random distances along the pollinator transect. The pest/predator transects will not be performed in linear features.

Table 10. Core samples to be collected at each sampling location.

Locations	Species Group	Sampling Method	Data Collected
Field centers, margins, and hedgerows	Pollinators	Pan traps (3 pan traps of different colours)	Pollinator species abundance and species identity
		One pollinator visual transect (50 m)	Bumblebee and wild bee abundance and species identity
	Vascular plants/weeds	Four plant cover quadrats (4 m^2 plots)	Vascular plant and weed percent cover and species identity
	Earthworms	Earthworm sampling plots (30 × 30 × 20 cm plots)	Earthworm abundance and functional group identity
	Soil microbiome	Soil core (5 × 5 × 30 cm or similar)	Soil microbiome samples for future analysis
	Arthropod pests and predators	Two crop pest and predator scouting surveys along crop rows (50 m) (**only within production fields)	Pest and predator abundance and species identity, crop damage
	Mammals	Camera traps (from S. Smukler) rotated through sampling locations	Mammal abundance and species identity
	Birds	Nature Vancouver monthly surveys	Bird abundance and species identity
Second-growth and plantation forest	Pollinators	Pan traps (3 pan traps of different colours)	Pollinator species abundance and species identity
		One pollinator visual transect (50 m)	Bumblebee and wild bee abundance and species identity
	Vascular plants	Nested 4, 25, 50, and 100 m^2 vegetation plots for herbs, shrubs, and trees	Percent cover, species identity, vertical structure, diameter at breast height, tree health
	Earthworms	Earthworm sampling plots (30 × 30 × 20 cm plots)	Earthworm abundance and functional group identity
	Soil microbiome	Soil core (5 × 5 × 30 cm or similar)	Soil microbiome samples for future analysis
	Mammals	Camera traps (from S. Smukler) rotated through sampling locations	Mammal abundance and species identity
	Birds	Nature Vancouver monthly surveys	Bird abundance and species identity

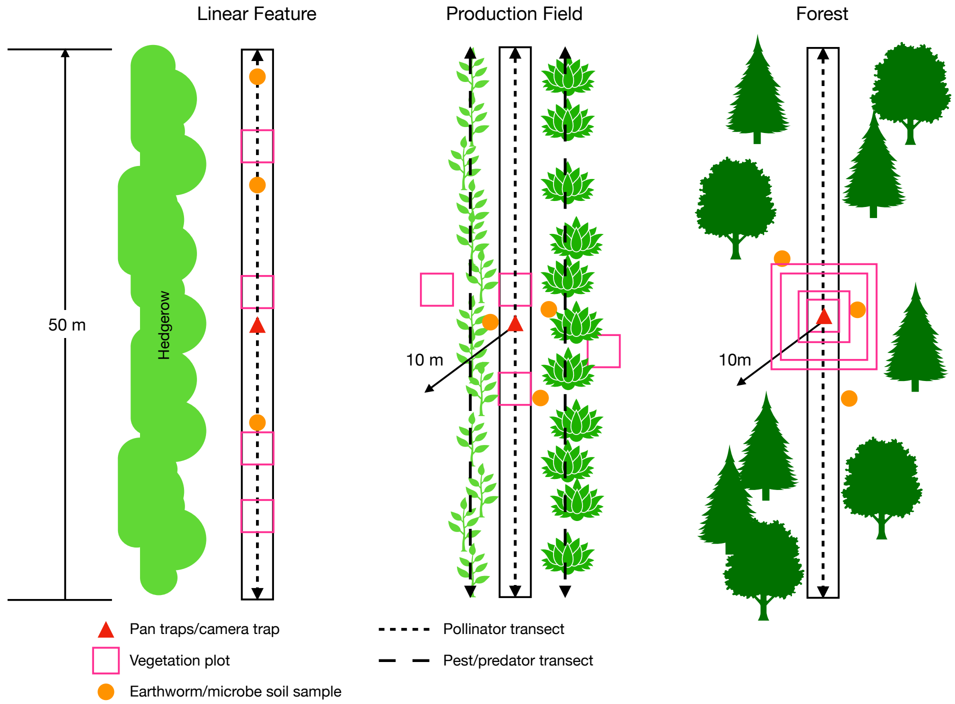
In forest habitats similar methods for pan/camera traps, pollinator transect, and earthworm/microbe plots will be used, with the pollinator transect oriented parallel to the nearest forest edge. No pest/predator transects will occur. For vascular plants, nested 4 m^2, 25 m^2, 50 m^2, and 100 m^2 plots will be used for different plant types (e.g., bryophytes, herbaceous plants, shrubs, and trees). An overview of the sampling methods for each species groups and sampling type are presented below.

5.2.3. Sampling methods overview

This section provides a brief overview of the sampling methods for each group. Detailed protocols for each are provided in Appendix 4.

Pollinators: Pollinators will be primarily be assessed using walking transects and pan traps. With walking transects, observers will walk 50 m transects for a set amount of time and record all bumblebee (*Bombus* species) individuals within 2 m of either side of the transect. Bumblebee identification training will be provided by the Environmental Youth Alliance (EYA) and observers will utilize bumblebee guides

Figure 5. Biodiversity sampling scheme in linear habitats, production fields, and forest habitats.



**Adapted from Herzog et al. 2012.*

that exist specifically for the lower Fraser Valley (Appendix 6). Data from this monitoring will be contributed to the Pacific Northwest Bumble Bee Atlas citizen science initiative.

Visual transects will be supplemented with pollinator pan traps. In this method, pans or cups of different colours (white, yellow, and blue) filled with a solution of water and dish soap are placed in the field to attract pollinators. Individuals collect in the liquid and can then be placed in alcohol for later identification. This method is used extensively in pollinator studies[88,89] and allows for the sampling of species difficult to spot and identify on the wing (e.g., cuckoo bees) and allows for a more complete sampling of pollinators than visual transects. Net trapping of pollinators may also occur for specific species if required.

Vascular plants/weeds: Vascular plant and weed sampling will occur in production fields, field margins, and forest habitats, with a custom sampling scheme for each.

In production fields four 2 × 2 m quadrats will be randomly placed within 10 m of the central plot location and between the crop rows. Within each quadrat, all plant species present will be identified and their percent cover visually estimated. Similarly, in linear habitats like field margins, the four quadrats will be placed at random locations along the 50 m pollinator transect, and plant species identity and percent cover recorded.

In hedgerows, a similar setup as the field margins will be used for understorey and herbaceous species using four 4 m^2 quadrats. For woody shrubs and trees, percent cover for each species will be estimated in three vertical layers along the entire length of the hedgerow. Hedgerow maximum height will also be recorded along the hedgerow, and the diameter and height of all large woody trees will be collected.

For forest habitats, nested plots of increasing size will be used. The smallest plot (4 m^2) will be used mosses and an assessment of woody tree regeneration, the next larger plot (25 m^2) for herbaceous species, the 50 m^2 plot for woody shrub species, and the largest (100 m^2) for trees. Within each plot, all plant species will be identified and percent cover estimated. In addition, for trees, their height and diameter will be measured, along with measures of health, decay class, and canopy extent.

Earthworms: Earthworms will be sampled by adding a solution of dissolved mustard powder and water to the soil within a 0.3 × 0.3 m quadrat. This causes earthworms to move to the soil surface where they can then be identified and collected. Earthworms will be sorted into juveniles and adults and functional groups following the NatureWatch Canada WormWatch protocols and then placed in alcohol for later identification. Alternatively, if using a mustard solution is not effective, the soil within the quadrat will be excavated and worms collected manually from the soil. All earthworm data will be contributed to the WormWatch citizen science project of Nature Canada.

Soil microbiome: A small 2 ml sample of soil will be taken from an amalgamated soil sample (0-30 cm depth) at each of the earthworm sampling locations. These samples will then be stored in a -80° freezer until later genomic sequencing and taxonomic unit identification when funding allows.

Arthropod pests/predators: As the diversity of insect pests and predators is large and can vary significantly from year to year and depending on the crop present, a scouting survey approach will be taken. Observers will walk two 50 m transects of crop rows in the production fields, closely examining plants and noting the presence of any pests or predators, as well as crop damage. Observers will use a simplified rating system to assess the abundance of the different pests and predators, and will quantify crop damage (e.g., number of leaves damaged, etc.).

Mammals: Mammals will be sampled using remote camera traps (provided by S. Smukler) that use infrared sensors to detect movement and take a photo when animals pass by the viewing area of the camera. Cameras will be placed at the central sample locations for one-month periods to assess the presence of mammals in all habitats at the farm. Due to the cost of these cameras, it will not be possible for every sampling location to have a camera at the same time. Instead, cameras will be rotated across the sampling locations on a monthly basis.

Birds: Birds diversity data will continue to be collected by Nature Vancouver volunteers on a monthly basis. There may also be the potential to supplement this data using passive monitoring and placing a number of remote microphones around the farm to collect bird song data to identify the presence and abundance of different bird species.

5.2.4. Species diversity sampling schedule

The majority of sampling for species diversity will take place during the summer months (April-September) with sample processing and subsequent identification taking place during the winter months when personnel are available. Landscape diversity and LU/LC classification will also take place during the winter for the previous growing season. Crop diversity measures will be taken at the beginning of the growing season as crops are planted, while farm management indicators will be gathered throughout the growing season by farm staff. A proposed typical summer sampling schedule is presented In Table 11.

Table 11. Potential summer sampling schedule for UBC Farm Biodiversity Monitoring Plan

Task	**Sample #**	**April**				**May**				**June**				**July**				**August**				**September**			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Landscape diversity																									
LU/LC classification	1																								
Species diversity																									
Plot setup	—																								
Pollinator transects	3-4																								
Earthworm sampling	3																								
Soil microbiome	3																								
Weed cover	3																								
Arthropods/crop damage	4																								
Plant surveys	1																								
Camera traps	1																								
Bird surveys	6																								
Crop diversity																									
Crops/varieties grown	1																								
Farm management																									
Indicator collection	1																								

**orange* indicates sampling not currently occurring, *green* indicates sampling that could be performed by Sean Smukler's APBI 260 class, *yellow* indicates sampling performed by Nature Vancouver, and *blue* indicates data collection that could be performed by farm staff.

5.2.5. *Potential automated species diversity monitoring options*

Automated monitoring of biodiversity is advancing rapidly and offering new methods of assessing biodiversity levels without intensive field sampling. Examples include remote camera trap monitoring of mammal species[90] and the audio recording of amphibians[91] bird calls[92] and bat echolocation calls[93]. Additionally, remote cameras can provide valuable phenological data[94] (e.g., the timing of plant life cycle events like leaf-out, flowering, and leaf-fall) that is affected by changes in climate and can have important effects on biodiversity[95].

With machine learning analyses and well-developed libraries of the audio calls of different species, these methods can provide a cost-effective way to collect biodiversity data at spatial and temporal scales unfeasible with traditional techniques[82,96]. They can also capture species that are unlikely to be collected through conventional techniques or capture information at times (e.g., nighttime, poor weather) when people are unlikely to be conducting fieldwork.

We have included a potential package for remotely sensing biodiversity at the UBC Farm. This includes remote camera traps, automated microphones for birds and bats, and an automated camera system to record and monitor changes in plant phenology at the farm. There are two main costs with respect to this package. The first is a monetary cost as remote cameras and microphones are expensive and there are a number of up-front costs to purchase the equipment and setup a remote system. The second cost is developing a library of bird calls and bat echolocations so that species identification can be automated. Going through camera trap photos to identify animals can also be tedious and time-intensive. We have focused on providing some basic information about how these systems could be setup at the UBC farm as well as rough costs for such a system (see Section 7).

Mammal Camera Traps: Remote cameras should be placed across the farm, both in production areas and the forested portion of the farm to capture different species of mammals. Cameras should be placed on trees or fenceposts at heights likely to capture the movement of animals of interest (coyotes, skunks, squirrels, etc.). Cameras should be regularly inspected for battery life, memory use, and rotated across sampling points every few weeks or monthly. To prevent theft, cameras also need to be locked using cable locks and placed within armoured cases. Once photos have been downloaded and assessed for animal presence, species richness and animal density measures can be estimated[97,98].

Automated Bird/Bat Microphones: Audible and ultrasonic microphones paired with battery-operated can provide estimates of bird distributions, abundances, and diversity[99]. Single-microphone units can sample species richness and composition, while stereo-microphones and pinpoint the location of sound sources to identify individual birds. Automated microphones can also readily measure changes in bird phenology and responses to disturbance[99].

For the UBC Farm, we propose that two automated bird microphones and two automated bat microphones be placed at the farm, focused on sampling birds and bats in the production and forested areas of the farm. Exact sampling locations and timing should be developed in collaboration with UBC experts and potentially Nature Vancouver. Once calls are recorded, automated detection of calls and then expert-based identification of the calls will be required. This could be done in collaboration with UBC students and faculty, Nature Vancouver members, or potentially through an online citizen-science initiative.

Plant Phenology Camera: Tracking plant phenology (timing of leaf-out, leaf-fall, and flowering) in plants can help track changes in climate and vegetation responses to these changes[94,100]. Digital cameras can be setup to track vegetation phenology using time-lapse images of a fixed area over time (months or years) and then use image analysis methods to examine the greenness of vegetation. A number of networks have been setup for this purpose, including PhenoCam, the USA National Phenology Network, and EuroPhen.

A single automate phenology camera could be setup at the UBC Farm for a reasonable price to monitor changes in vegetation phenology, likely of hedgerows or the forested portion of the farm. PhenoCam provides detailed instructions around purchasing and setting up a camera, how to analyze images using open-source and free software based on the Python or R statistical programs. Data from the farm could then be contributed to the wider PhenoCam network of 400 global cameras to help track changes in phenology worldwide. Camera data could also be supplemented with volunteer or citizen-science events focused on quantifying plant phenology in additional areas of the farm that the camera cannot sample.

5.3. Crop diversity

Currently, total crop diversity is recorded at the UBC Farm, therefore the first core indicator can be collected via current record-keeping mechanisms. However, crop areas, crop origins, and genetic diversity measures of crops are currently not known or recorded. A minimum first step to track crop diversity spatially across the farm would be to map the crop areas each year.

The UBC Farm is undergoing an assessment of a new database/application to facilitate the tracking and entry of farm management and production. The possibility of spatially delineating fields, rows, and beds, and using the software to track crop and variety-specific plantings would be of particular use to track crop diversity across the farm and calculate the core indicators of crop diversity described here. In addition, locations such as the Mayan garden, Indigenous garden, staff gardens, and flower production fields, with their high crop diversity, will likely require interviews with farm staff and detailed field surveys.

5.4. Farm management

Similar to the crop diversity methods described above, the new UBC farm database/application should ensure that all major farm management activities that occur in each field are recorded over each year. For the biodiversity monitoring plan, this should include measures of energy use, fertilizer use, pesticide application, monetary expenditures, and field operations (tilling, weeding, etc.).

6. Data Management

Key to the biodiversity monitoring plan is a database and data management plan to ensure that all of the biodiversity observations are recorded and stored in a secure and easily accessible way. Additionally, it will be important that the biodiversity data can be linked smoothly with other data collected at the farm (e.g., farm management and production data), can be connected to other external databases such as those for functional traits, is available in a format that enables analysis, facilitates data input from varied staff and interns, and can facilitate presentation of monitoring results online through a dedicated monitoring program website. It is also critical that the database be able to incorporate a variety of data formats, including ecological, land use/land cover mapping, farm management, digital photo, digital sound recording, and GIS data.

Since the UBC Farm is in the process of defining the key management and production data that needs to be collected going forward and as part of this is choosing a new data management system, it is somewhat uncertain what form the biodiversity monitoring database should or will take. Here, we focus on key attributes that the database should have and outline some considerations specific to the monitoring program. Key features that the database should have include:

- Be a relational database to ensure that different data types can be linked through plot locations or other characteristics;
- Easily accommodate multiple data formats (numeric data, GIS and remotely sensed data, digital photographs, digital sound recordings, etc.);
- Enable linkages with other external databases such as functional trait databases, biodiversity occurrence databases, etc.;
- Facilitate open-access functionality so that researchers and the public can eventually easily access the biodiversity monitoring data;
- Allow for an easy-to-use Graphical User Interface (GUI) to facilitate data entry by farm staff, researchers, students, volunteers, and biodiversity interns, potentially across different platforms (smartphones, tablets, PC and Mac operating systems);
- Facilitate data export to a diversity of formats for statistical analysis and allow easy communication between the database and statistical analysis program to facilitate analysis and dynamic presentation of results in, for example, a web application;
- Can be easily linked to online websites to provide dynamic communication of biodiversity monitoring activities and results (e.g., daily activities, numbers of organisms observed, etc.); and
- Is flexible and can be modified easily (e.g., without a high amount of specialized technical knowledge) as new data needs to be incorporated and the monitoring program evolves.

The initial setup and testing of a database for the biodiversity monitoring plan will be a key step, and one that is likely to require some specialized computer science skills. Connecting with the UBC Department of Computer Science to engage with undergraduate students who could help design and build the initial database and user interface could be a useful approach. The database should also take into account wider UBC initiatives to track biodiversity observations (e.g., CBIRD and SEEDS) and create an open-data policy for the university.

7. Costs & Budget

Below, we provide a cost breakdown for equipment and supplies for each component of the biodiversity monitoring program for the setup and first year of monitoring, focusing on the core samples of priority indicators (Table 12). These are potential maximum costs, without consideration of the possibility of borrowing equipment from UBC researchers, which may be possible in some cases. The total equipment costs for these components is approximately $5,428. Personnel costs are not included here, as it is assumed that these can be covered by existing farm internship positions, UBC courses, and farm volunteers. Estimated equipment and supply costs for subsequent years of biodiversity monitoring after initial setup are estimated at approximately $500/year.

Table 12. Equipment costs and budget for the core biodiversity monitoring plan.

Component	Equipment	No. items	Unit Price (CAD)	Cost (CAD)
GENERAL SUPPLIES	Permanent markers (5 pcs)[1]	2	$5.97	$11.94
	Mechanical pencils (12 pcs)[1]	2	$5.99	$11.98
	Clipboard[1]	4	$4.47	$17.88
	Measuring tape (50 m)[1]	2	$41.11	$82.22
	iPad (128 GB w AppleCare)[2]	1	$628.00	$628.00
	Otterbox iPad case[3]	1	$119.28	$119.28
	DSLR Camera[1]	1	$599.00	$599.00
	Ethanol dropper bottle (10 pcs)[1]	1	$4.19	$4.19
	Rite in the rain paper (200 sheets)[1]	4	$32.95	$131.80
	Cooler[1]	1	$29.97	$29.97
	Stake flags (100 pcs)[4]	1	$12.04	$12.04
	Survey stakes (plastic, orange)[4]	75	$5.83	$437.25
	Wooden stakes (50 pcs)[4]	2	$51.27	$102.54
	Flagging (wood fibre-enviro)[4]	10	$4.24	$42.40
	TOTAL			**$2,230.49**
VASCULAR PLANTS				
General supplies	Plant ID book[1]	1	$27.06	$27.06
	Plant press[6]	1	$67.70	$67.70
	Laser Hypsometer[4]	1	$529.21	$529.21
	Clinometer[4]	1	$180.28	$180.28
	Diameter tape[4]	2	$50.61	$101.22
	Subtotal			*$905.47*
1 m² quadrats	¾” x 20’ PVC pipe[5]	4	$6.19	$24.76
	¾” PVC elbow connector[5]	8	$1.09	$8.72
	¾” PVC T-junction[5]	8	$1.79	$14.32
	¾” PVC cross junction[5]	2	$2.79	$5.58
	PVC cement[5]	2	$3.79	$7.58
	Subtotal			*$60.96*
	TOTAL			**$966.43**
BEES				
General supplies	Dissecting microscope[1]	1	$215.99	$215.99
	Petri Dishes (20 pcs)[6]	2	$7.28	$14.56
	Probes for petri dish[6]	4	$1.05	$4.20
	Forceps[6]	4	$25.00	$100.00
	Subtotal			*$334.75*
Pan trapping	Blue bowls*	25	$0.75	$18.75
	Yellow bowls*	25	$0.75	$18.75
	White bowls*	25	$0.75	$18.75
	Dish soap[1]	5	$1.77	$8.85

	4L milk jug (water container)	2	$0.00	$0.00
	Collection jars (500 pcs)[7]	1	$165.09	$165.09
	Sieves (4 pcs)[6]	4	$9.90	$39.60
	Featherweight forceps[6]	2	$7.53	$15.06
	100% ethanol (1L)[8]	10	$6.54	$65.40
	Metal stakes (2 pcs)[5]	20	$3.99	$79.80
	4” hose clamps (6 pcs)[5]	20	$9.89	$197.80
	Micro hose clamps (25 pcs)[5]	10	$24.99	$249.90
	Subtotal			*$877.75*
Net Sampling	Insect nets[6]	2	$21.29	$42.58
	100% ethanol (1L)[8]	3	$6.54	$19.62
	Aspirator[6]	2	$11.31	$22.62
	Subtotal			*$84.82*
	TOTAL			**$1,297.32**
EARTHWORMS	Watering can[5]	2	$12.39	$24.78
	Mustard powder (450g)[1]	25	$7.19	$179.75
	Shovel[5]	2	$43.99	$87.98
	16” diameter PVC pipe[1]	2	$65.74	$131.48
	Small trowel[5]	2	$13.99	$27.98
	100% ethanol (per L)[8]	10	$6.54	$65.40
	TOTAL			**$517.37**
SOIL MICROBIOME	Soil corer[9]	2	$125.19	$250.38
	Eppendorf tubes (1.5ml-500 pcs)[10]	2	$63.00	$126.00
	100% ethanol (per L)[8]	2	$6.54	$13.08
	Latex gloves (100pcs)[5]	1	$26.66	$26.66
	TOTAL			**$416.12**
GRAND TOTAL				***$5,427.73***

Sources: [1]Amazon.ca, [2]Apple.ca, [3]Otterbox.com, [4]Forestry Suppliers, [5]Rona.ca, [6]BioQuip, [7]VWR Canada, [8]UBC, [9]AMS, [10]Eppendorf.ca

We have also included the costs to remotely monitor birds, mammals, bats, and plant phenology at the farm (Table 13). This includes all of the remote cameras and microphones required, assuming placement of four additional dedicated remote cameras across the farm, two bird and bat recorders each, and one plant phenology camera, as well as required accessories (batteries, memory cards, locks, cables, software, etc.). The total cost for this component is $10,160. A cheaper option, where only two remote camera traps and one bird and bat recorder each are purchased for the farm would cost $5,850. Ongoing costs for future years would be minimal, except for an annual software license fee of approximately $400. Costs for analysing the subsequent data (sound recording and photos) are not included here.

Table 13. Equipment costs and budget for autonomous biodiversity monitoring option.

Component	Equipment	No. items	Unit Price (CAD)	Cost (CAD)
General	Analysis software (1 yr license)[1]	1	$394.68	$394.68
	Battery charger[1]	2	$145.73	$291.46
			Subtotal	*$686.14*
Birds	D4I rechargeable batteries (4 pcs)[1]	4	$100.32	$401.28
	64 GB SDXC flash card[1]	4	$47.52	$190.08
	Cable lock[1]	2	$50.16	$100.32
	Pad lock[1]	2	$10.56	$21.12
	Armour[1]	2	$236.28	$472.56
	Bird Song Meter SM4[1]	2	$1,120.68	$2,241.36
			Subtotal	*$3,426.72*

Bats	D4I rechargeable batteries (4 pcs)[1]	4	$100.32	$401.28
	64 GB SDXC flash card[1]	4	$47.52	$190.08
	Cable lock[1]	2	$50.16	$100.32
	Pad lock[1]	2	$10.56	$21.12
	Armour[1]	2	$236.28	$472.56
	Bat Song Meter SM4BAT FS[1]	2	$1,318.68	$2,637.36
			Subtotal	*$3,822.72*
Mammals	Browning camera set (4-pack)[2]	1	$768.32	$768.32
	Security case + lock[2]	4	$68.85	$275.40
	Masterlock padlock[2]	4	$42.33	$169.32
	Rechargeable AA batteries (12 pcs)[2]	4	$39.68	$158.72
	Battery charger[8]	1	$66.33	$66.33
			Subtotal	*$1,438.09*
Phenology Monitoring	StarDot NetCam SC (1.3IR model)[3]	1	$532.42	$532.42
	Power over ethernet adapter[4]	1	$15.99	$15.99
	Wifi range extender[4]	1	$39.99	$39.99
	Ethernet surge protector[4]	1	$32.62	$32.62
	Ethernet cables[4]	1	$115.00	$115.00
	Ventech camera enclosure[4]	1	$50.00	$50.00
			Subtotal	*$786.02*
			TOTAL	**$10,159.69**

Sources: [1]Wildlife Acoustics, [2]Trailcampro, [3]B&H Photo and Video, [4]Amazon.ca

8. Opportunities for Collaboration

8.1. Researchers

Given the size of UBC and that the number of researchers, including faculty, postdoctoral fellows, and graduate students is so large, a full list of potential researchers/research projects that could potentially contribute to the UBC Farm biodiversity monitoring plan has not been compiled at this time. However, such a list should be created, in addition to a mechanism to communicate the presence of a biodiversity monitoring plan to researchers and identify possible links and opportunities for collaboration. This should occur both through outreach by the UBC Farm, but also when researchers approach the farm to conduct new research projects. One source for some of this information could be the SEED/CBIRD initiative to map all of the biodiversity expertise across UBC. A formal mechanism to ensure that any biodiversity research that occurs at the farm contributes to the wider monitoring program and that data is shared in a common format, is a critical component moving forward.

8.2. UBC courses

A large number of courses at UBC could contribute to biodiversity monitoring at the UBC Farm. Currently, only three courses that we know of are monitoring biodiversity. This includes APBI 260 – Agroecology I, FRST 307 – Forest Biotic Disturbances, and LFS 496 – Land and Food Systems Internship. This last course incorporates specific internship opportunities including the farm's Biodiversity Internship program.

Numerous courses with laboratory components have the potential to incorporate biodiversity monitoring activities at the farm in their curricula. Based on our initial analysis, these courses cover the entire spectrum of biodiversity present at the farm (Table 14). In particular, APBI 497 – Sustainable Agriculture and Food Systems, BIOL 230 – Fundamentals of Ecology, BIOL 306 – Advanced Ecology, BIOL 404 – Ecological Methodology, and LFS 496 – Land and Food Systems Internship all have the potential to contribute to the monitoring of large number of species groups. A large number of other courses could help monitor select groups of species.

It should also be highlighted that UBC farm interns could perform a large amount of the biodiversity monitoring work each year, with minimal costs. For example, two interns each summer would be roughly equivalent to one full time employee (20 hrs/week each), and could perform the vast majority of monitoring activities over the growing season. Supplemented with future field courses, additional courses during the spring and fall, and citizen-science initiatives, this could be a feasible way to monitor biodiversity at the farm over the long-term.

A full list of the potential courses, brief descriptions of their curricula, relevance to the biodiversity monitoring plan, and instructor contact information is available in Appendix X.

8.3. Other UBC initiatives and groups

A select number of UBC groups could contribute to biodiversity monitoring at the UBC Farm. This includes:

- *Beaty Biodiversity Museum*: The collections at the Beaty Biodiversity Museum could provide insight on past biodiversity at the UBC Farm and allow for the estimation of historical changes

Table 14. Current and potential UBC courses that could contribute to biodiversity monitoring.

	Hedgerow vascular plants	Weeds	Wild bees and bumblebees	Spiders	Earthworms	Birds	Soil invertebrates	Forest vascular plants	Butterflies	Carabid beetles	Soil microbes	Forest fungi	Ants	Diptera, Syrphidae, Hoverflies	Bats	Mammals	Crop diversity	Land Use Land Cover Change	**Total**
APBI 200					P		P				P								**3**
APBI 210	P	P						P											**3**
APBI 222																	P		**1**
APBI 260	C				C	C	C			C				C		C			**7**
APBI 327			P						P	P			P	P					**5**
APBI 328		P																	**1**
APBI 342					P		P				P								**3**
APBI 417																	P		**1**
APBI 497	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	**18**
BIOL 210	P	P						P											**3**
BIOL 230			P	P	P	P	P	P	P	P			P	P	P	P		P	**13**
BIOL 306			P	P	P	P	P	P	P	P			P	P	P	P		P	**13**
BIOL 317		P																	**1**
BIOL 323												P							**1**
BIOL 324	P	P						P											**3**
BIOL 326			P	P	P		P		P	P			P	P					**8**
BIOL 327			P	P					P	P			P	P					**6**
BIOL 404	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P			**16**
BIOL 406	P	P						P											**3**
BIOL 411			P						P	P			P	P					**5**
FRST 201								P											**1**
FRST 211								P											**1**
FRST 239								P											**1**
FRST 305								H											**1**
FRST 307												C							**1**
FRST 310					P		P				P	P							**4**
FRST 395						P										P			**2**
FRST 556																		P	**1**
FRST 557								P										P	**2**
LFS 496	C	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	C	P	**18**
Total	**8**	**9**	**9**	**7**	**10**	**7**	**10**	**14**	**9**	**10**	**6**	**6**	**9**	**10**	**5**	**7**	**4**	**6**	

Currently monitoring · Historic monitoring · Potential to contribute in biodiversity. Collaborating with the Beaty Museum could also help facilitate contributions of the biodiversity monitoring to the Global Biodiversity Information Facility (GBIF).

- *Botany Enthusiasts Club (BEC)*: This UBC Alma Mater Society club is dedicated to botany, gardening and sustainability and could assist in the monitoring of plant species at the farm.
- *Pacific Regional Society of Soil Science (PRSSS)*: The PRSSS connects students, researchers, consultants, and professionals who study or work in the field of soil science and land resource management. Connections through this society may be able to provide expertise around monitoring soil invertebrates, earthworms, and soil microbes.
- *SEEDS Sustainability Program*: SEEDS creates partnerships between UBC students, faculty, staff, and community partners to develop innovative research projects that advance sustainability. Partnering with SEEDS through their internship program has the potential to contribute to multiple components of the monitoring plan, including direct biodiversity monitoring, communication of results to the UBC community, and integration of biodiversity monitoring into UBC planning and policies.
- *The Wildlife Society (TWS)*: TWS is an international organization dedicated to excellence in wildlife science and education with a UBC student chapter. Members of this chapter may be interested in helping monitor animal and bird species on the farm.
- *UBC Botanical Garden*: The UBC Botanical Garden has the mandate to assemble, curate, and maintain a documented collection of temperate plants for research, conservation, education, and community outreach. There is the potential to establish joint monitoring programs for pollinators, birds, and weeds between the garden and farm. Currently, the garden is developing a citizen-science based pollinator monitoring program and also has monthly bird surveys conducted by Nature Vancouver.

A comprehensive list of these groups, including contact information can be found in Appendix X.

8.4. Community groups and organizations

Outside the direct UBC community, the following groups and organizations are either currently contributing to biodiversity monitoring on the farm or could help in this capacity in the future:

- *BioBlitz Canada*: BioBlitz is a national partnership of leading conservation, education, and research organizations with the goal to document Canada's biodiversity by connecting the public with nature via scientist-led participatory surveys. Connections with BioBlitz Canada could be developed to conduct regular or annual citizen-science biodiversity surveys at the UBC Farm.
- *Environmental Youth Alliance (EYA)*: A non-profit that cultivates transformative nature experiences for children and youth in urban environments to foster community connectedness, build ecological leadership skills, and enhance their well-being. EYA has already agreed to provide bumblebee identification training at the UBC Farm and could provide additional training and monitoring expertise.
- *Nature Vancouver*: Nature Vancouver is a Vancouver-based organization with a focus on education and outdoor activities. In addition to the current monthly bird surveys that occur at the farm, Nature Vancouver might also be able to provide plant and moss identification expertise.

- *South Coast Bat Conservation Society (SCBats)*: This society promotes bat conservation on the south coast of British Columbia. SCBats has expressed past interest in setting up a bot monitoring station at the UBC Farm, and this possibility could be further explored in the future.

A comprehensive list of these groups, including contact information can be found in Appendix X.

8.5. Opportunities for citizen-science events

A key task to explore with the different UBC and community groups listed above is the feasibility of creating citizen-science initiatives or UBC campus "bio-blitzes" in the future to monitor biodiversity at the UBC Farm and UBC campus. There should be the real possibility to organize events across campus where students and the public can assess biodiversity and contribute data to the farm's biodiversity monitoring plan, and even fill gaps in assessment that would otherwise remain empty. This could include activities to count native bees or bumblebees, assess weed presence in production fields, count earthworms, scout for pest damage in crops, inspect camera trap photos for animals, or count flowers and leaves to assess plant phenology. In coordination with groups like the Beaty Biodiversity Museum and UBC Botanical Garden, it may also be possible to organize events to quantify biodiversity across the campus each year in an annual event, and ensure that the necessary scientific expertise is available to ensure a reasonable level of data quality. Examples of similar activities and initiatives that could serve as models, contribute methods, or where data from the biodiversity monitoring program could be submitted, include:

- Bumble Bee Watch – tracks bumble bee sightings in North America. Users can upload photos, have bee identifications verified by experts, and help researchers determine the conservation status of bumble bees.

- Audubon Christmas Bird Count – citizen-led bird census activities that occur between December 14 and January 5 each year. The CBC started in 1900 and now occurs at 2,585 sites across the western hemisphere and 463 in Canada.

- eButterfly – users can submit butterfly sightings and locations, organize and share photos, and explore dynamics range maps.

- EEDMapS – compiles sightings of invasive species and provides web-based maps of invasive species distributions. A smartphone app is also available for the project.

- iNaturalist – an online social network of naturalists, citizen scientists, and biologists. Species sightings (photos) can be shared using a mobile application, with species identification provided through an automated tool and verified by experts. Currently has over 88,000 users that have contributed nearly 16 million observation.

- National Moth Week – week in July every year where moth observation and identification events occur. Data can be submitted to the NMW website to help track and map moth distribution.

- FrogWatch – part of the NatureWatch Canada suite of citizen science projects. Provides frog identification guides for each province. Participants identify frog and toad calls and data can be submitted to the NatureWatch Canada website.

- PlantWatch – part of the NatureWatch Canada suite of citizen science projects. Provides plant identification guides for each province. Participants identify plants and data can be submitted to the NatureWatch Canada website.
- WormWatch – part of the NatureWatch Canada suite of citizen science projects. Provides worm identification guides for each province. Participants identify worms and data can be submitted to the NatureWatch Canada website.
- NestWatch – participants provide information on the nesting success of birds (nests, clutches, broods, and fledglings). There is also a mobile application and users can contribute their data to a central database. Run through the Cornell Lab of Ornithology.
- eBird – an online database of bird observation from scientists, researchers, and amateur birders that also provides real-time data on bird distribution and abundance. An advanced web application is also part of the project. As of 2016, 330,000 users are part of eBird and have uploaded over 100 million checklists.
- BioBlitz Canada – a "national partnership of leading conservation, education and research organizations with a goal to document Canada's biodiversity by connecting the public with nature in a scientist-led participatory survey of life and make sure this information can be useful to current and future science."

9. Communication and outreach

Communication of the results of the biodiversity monitoring program will be essential to ensure that the project contributes to the educational mandate of the CSFS and UBC Farm. It is important for all of the UBC community to understand how biodiversity is changing on campus, and what impacts this might have on their wellbeing and UBC. Effective communication also has the potential to help influence and change human behaviour in the direction of creating more sustainable food systems. An additional possible benefit of such communication includes ensuring interested students and volunteers are aware of the program and become involved in monitoring activities, as well as continued support for the program within the university and wider regional communities.

Below, a brief communication plan for the biodiversity monitoring program is outlined, focusing on different venues and audiences.

9.1. Informal Communication

Informal reporting of the biodiversity monitoring results should take place primarily to communicate results to UBC Farm staff and members of the CSFS. Opportunities for such communication could include monthly farm staff meetings, CSFS annual meetings, and other events that occur throughout the year. A regular email update on monitoring activities to farm staff could also be useful throughout the growing season to ensure that monitoring activities are announced and any conflicts identified and that farm staff are recording the farm management variables needed for the monitoring program.

Farm staff meetings will be especially important to communicate upcoming biodiversity monitoring activities and results of monitoring work during the growing season. At a minimum, these types of updates should happen at the beginning, middle, and end of each growing season (e.g., March/April, June, and September/October) and should focus on logistics, operational aspects of the monitoring with respect to a working farm (ensuring staff are aware of monitoring locations, monitoring activities won't conflict with farm activities), and communication of results that could have an impact on farm activities (insect pest and weed occurrences).

9.2. Formal Reporting

Formal reporting of biodiversity monitoring results should take place annually and should take three primary forms. The first should be an annual biodiversity monitoring report that will present a summary of the monitoring activities completed, the overall biodiversity results from the year, changes in biodiversity through time, and plans for the upcoming year. This report should be accessible to the entire UBC community, and therefore focus on non-technical language, easily-understood figures and graphics, an emphasis on broad trends in the amount and types of biodiversity that are present on the farm, and a comprehensive account of biodiversity and monitoring activities for the past year.

Secondly, key trends and results from the biodiversity monitoring report should be incorporated into the annual CSFS report as a new section to the report on par with the current "Food Cultivation" or "Gathering and Celebrating" sections. For this, a key number of biodiversity indicators and benchmarks should be developed or identified (e.g., number of species recorded, monitoring activities, citizen-science events, classes/people involved in monitoring) to communicate both the trends in biodiversity at the farm, as well as the research and education outcomes of the program.

Finally, peer-reviewed scientific papers should be a goal of the monitoring program as results and opportunities allow. This would help formally fulfill the goal of the biodiversity monitoring plan to enhance the research opportunities and outputs at the UBC Farm. Ideally, graduate students of CSFS faculty or CSFS postdoctoral research would lead these papers, with the potential for team publication also a real possibility. Once the annual monitoring report has been released an opportunity-scanning exercise with CSFS faculty should happen to identify potential research questions that could lead to scientific papers and the possible students or researchers that could lead these papers.

Other formal reporting venues to explore include developing a UBC Farm Sustainability report and incorporating the biodiversity monitoring results into the UBC-wide sustainability reports. For the UBC Farm sustainability report, key sustainability indicators from the biodiversity monitoring program and other farm activities and research (e.g., levels and changes in biodiversity, energy inputs, greenhouse gas emissions, water usage, land use/land cover changes) could be presented in a form similar to the existing UBC Farm Annual Report. Incorporating biodiversity indicators and trends in the UBC-wide sustainability reports is something that is currently being explored by the UBC Sustainability Office and SEEDS. As this develops, CSFS should look for opportunities for the UBC Farm and any biodiversity monitoring activities to contribute to this and highlight the innovative work being done at the farm.

9.3. Education Opportunities

A large number of educational programs occur at the UBC Farm each year. This includes the Farm Practicum program, Food Skills workshops, FarmWonders and FarmLeaders children programs, Intergenerational Landed Learning Project, and Think&EatGreen@School project. Each of these offer opportunities to communicate how biodiversity contributes to the food we eat, increase biodiversity literacy, and connect people with the biodiversity around them. As the biodiversity monitoring program develops, identifying opportunities for it to involve participants in each of these programs and develop curricula-specific modules or materials would be valuable.

9.4. Community Outreach

The UBC Farm and CSFS have developed a number of strong community partnerships and outreach venues that should be used to communicate the results of the biodiversity monitoring program. In particular, this includes the weekly Farm Markets, Joy of Feeding, UBC Farm Fall Fair, FarmAde concert, Long Table Dinner, and volunteer programs all help connect different community groups to the UBC Farm. These events and programs are valuable places to communicate how biodiversity helps maintain sustainable food production at the UBC Farm while highlighting the biodiversity monitoring program and engaging with the wider community with biodiversity conservation. At the simplest level, this could involve creating a culture where biodiversity at the farm and biodiversity monitoring results are always included when describing the farm. Biodiversity tours of the farm could also be considered as the program develops and knowledge of the species at the farm grows. At a more formal level, biodiversity-specific materials could be developed (pamphlets, posters, etc.) to help communicate what biodiversity is present at the farm, how it is changing, and how it contributes to food production.

9.5. Social Media and Internet

A strong social media and internet presence for the biodiversity monitoring program will be an essential way to communicate results to a wide audience and ensure that both the UBC and wider communities are aware of the program and become involved in citizen-science events. At a minimum, a strong social media presence for the program should include Twitter, Facebook and Instagram accounts with regular updates (ideally daily) during the growing season highlighting the monitoring activities that are occurring and information on the species encountered in the field. In addition to the actual monitoring activities, this type of outreach should be a formal responsibility of biodiversity interns, with time scheduled each day to complete.

In addition to a social media presence, a simple, interactive website for the biodiversity monitoring program should be developed. This would include current information on levels of biodiversity recorded during the growing season through counters and simple figures (e.g., numbers of pollinators, birds recorded, plots completed, etc.), access to past reports and monitoring protocols, a calendar of upcoming monitoring events and how to get involved, and information on key species or species groups that are present at the farm and how they contribute to food production and ecosystem services. Eventually, it might even be possible to include videos of animals from camera traps, plant phenology videos, and recordings of birds from remote microphones. Citizen-science could also be integrated into the website, allowing visitors to contribute to the monitoring through the identification of animals on camera trap photos, bird calls on recordings, or assessment of crop damage from photos taken in the field.

9.6. Data Sharing and Citizen-Science

To ensure that the data collected by the biodiversity monitoring program contributes to wider biodiversity monitoring activities, avenues for sharing this data with existing repositories should be explored and key databases identified. In particular, contributing the Global Biodiversity Information Facility (GBIF) should be a priority as this can be done through the iNaturalist smartphone app. GBIF incorporates all scientific collections of specimens, and citizen-science records from iNaturalist and eBird and currently has over 1 billion species occurrence records worldwide. A schedule for contribute the biodiversity data to these external databases should also be created. Key databases to explore contributions to include:

- NatureWatch Canada (PlantWatch, FrogWatch, and WormWatch databases)
- Pacific Northwest Bumble Bee Atlas
- iNaturalist
- eBird
- Canadian Biodiversity Information Facility
- Global Biodiversity Information Facility

10. References

1. MA. *Ecosystems and human well-being: synthesis*. **5,** (Island Press Washington, DC, 2005).
2. Moonen, A.-C. C. & Barberi, P. Functional biodiversity: An agroecosystem approach. *Agr Ecosyst Environ* **127,** 7–21 (2008).
3. Power, A. G. G. Ecosystem services and agriculture: tradeoffs and synergies. *Philos T R Soc B* **365,** 2959–2971 (2010).
4. Thrupp, L. A. Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. *Int Aff* **76,** 265–281 (2000).
5. Lin, B. B., Philpott, S. M. & Jha, S. The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. *Basic and Applied Ecology* **16,** 189–201 (2015).
6. FAO. What is Agrobiodiversity? (2004). Available at: http://www.fao.org/docrep/007/y5609e/y5609e01.htm#bm1. (Accessed: 19 November 2018)
7. Altieri, M. The ecological role of biodiversity in agroecosystems. *Agr Ecosyst Environ* **74,** 19–31 (1999).
8. Duru, M. *et al.* How to implement biodiversity-based agriculture to enhance ecosystem services: a review. *Agron. Sustain. Dev.* **35,** 1259–1281 (2015).
9. Forman, R. T. & Godron, M. Patches and structural components for a landscape ecology. *BioScience* **31,** 733–740 (1981).
10. Benton, T. G., Vickery, J. A. & Wilson, J. D. Farmland biodiversity: is habitat heterogeneity the key? *Trends In Ecology & Evolution* **18,** 182–188 (2003).
11. Barrios, E. Soil biota, ecosystem services and land productivity. *Ecological Economics* **64,** 269–285 (2007).
12. Kremen, C. *et al.* Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. *Ecol Lett* **10,** 299–314 (2007).
13. Hooper, D. *et al.* Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecol Monogr* **75,** 3–35 (2005).
14. Tscharntke, T., Klein, A.-M., Kruess, A., Steffan-Dewenter, I. & Thies, C. Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. *Ecol Lett* **8,** 857–874 (2005).
15. Allan, E. *et al.* Land use intensification alters ecosystem multifunctionality via loss of biodiversity and changes to functional composition. *Ecol Lett* **18,** 834–843 (2015).
16. Kremen, C., Williams, N. M. & Thorp, R. W. Crop pollination from native bees at risk from agricultural intensification. *Proc. Natl. Acad. Sci. U.S.A.* **99,** 16812–16816 (2002).
17. Hoehn, P., Tscharntke, T., Tylianakis, J. M. & Steffan-Dewenter, I. Functional group diversity of bee pollinators increases crop yield. *Proceedings of the Royal Society of London Series B-Biological Sciences* **275,** 2283–2291 (2008).

18. Letourneau, D. K. *et al.* Does plant diversity benefit agroecosystems? A synthetic review. *Ecol Appl* **21,** 9–21 (2011).

19. Gardiner, M. M. *et al.* Landscape diversity enhances biological control of an introduced crop pest in the north-central USA. *Ecol Appl* **19,** 143–154 (2009).

20. Foran, T. *et al.* Taking Complexity in Food Systems Seriously: An Interdisciplinary Analysis. *World Development* **61,** 85–101 (2014).

21. Garibaldi, L. A. *et al.* Farming Approaches for Greater Biodiversity, Livelihoods, and Food Security. *Trends In Ecology & Evolution* **32,** 68–80 (2017).

22. CSFS. *Centre for Sustainable Food Systems Strategic Plan.* 1–4 (Centre for Sustainable Food Systems, 2016).

23. SCAPC. *Cultivating Place.* 1–16 (South Campus Academic Planning Committee, 2010).

24. McGeoch, M. A. The selection, testing and application of terrestrial insects as bioindicators. *Biol Rev* **73,** 181–201 (1998).

25. Duelli, P. & Obrist, M. K. Biodiversity indicators: the choice of values and measures. *Agr Ecosyst Environ* **98,** 87–98 (2003).

26. Duelli, P. Biodiversity evaluation in agricultural landscapes: An approach at two different scales. *Agr Ecosyst Environ* **62,** 81–91 (1997).

27. Duelli, P. & Obrist, M. K. In search of the best correlates for local organismal biodiversity in cultivated areas. *Biodiversity and Conservation* **7,** 297–309 (1998).

28. Pearson, D. L. & Cassola, F. World-Wide Species Richness Patterns of Tiger Beetles (Coleoptera: Cicindelidae): Indicator Taxon for Biodiversity and Conservation Studies. *Conserv. Biol.* **6,** 376–391 (1992).

29. Billeter, R. *et al.* Indicators for biodiversity in agricultural landscapes: a pan-European study. *Journal of Applied Ecology* **45,** 141–150 (2007).

30. HENDRICKX, F. *et al.* How landscape structure, land-use intensity and habitat diversity affect components of total arthropod diversity in agricultural landscapes. *Journal of Applied Ecology* **44,** 340–351 (2007).

31. Schweiger, O. *et al.* Quantifying the impact of environmental factors on arthropod communities in agricultural landscapes across organizational levels and spatial scales. *Journal of Applied Ecology* **42,** 1129–1139 (2005).

32. Sauberer, N. *et al.* Surrogate taxa for biodiversity in agricultural landscapes of eastern Austria. *BIOC* **117,** 181–190 (2004).

33. Collette, L. Indicators of Agricultural Genetic Resources: FAO's contribution to monitoring agricultural biodiversity. in 1–15 (2002).

34. OECD. *OECD compendium of agri-environmental indicators.* (OECD Publishing, 2013). doi:10.1787/9789264186217-en

35. van Dijk, G. Biodiversity indicators in agriculture: a combination of species and habitat approaches. in 1–19 (2002).

36. *Targets and indicators for biodiversity for food and agriculture.* 1–7 (FAO, 2013).

37. EEA. *Streamlining European biodiversity indicators 2020: Building a future on lessons learnt from the SEBI 2010 process*. 1–50 (European Environment Agency, 2013).

38. Petersen, J.-E. *Integration of environment into EU agriculture policy — the IRENA indicator-based assessment report*. 1–64 (European Environment Agency, 2006).

39. Alexandra, J., Haffenden, S., White, T. & McKenzie, J. *Listening to the land: a directory of community environmental monitoring groups in Australia.* (Australian Conservation Foundation, 1996).

40. Dale, V. H. & Beyeler, S. C. Challenges in the development and use of ecological indicators. *Ecological Indicators* **1,** 3–10 (2001).

41. Foley, J. A. *et al.* Global consequences of land use. *Science* **309,** 570–574 (2005).

42. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478,** 337–342 (2011).

43. Baessler, C. & Klotz, S. Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agr Ecosyst Environ* **115,** 43–50 (2006).

44. Aguilar, J. *et al.* Crop Species Diversity Changes in the United States: 1978–2012. *Plos One* **10,** e0136580 (2015).

45. Holzschuh, A., Steffan-Dewenter, I. & Tscharntke, T. Grass strip corridors in agricultural landscapes enhance nest-site colonization by solitary wasps. *Ecol Appl* **19,** 123–132 (2009).

46. Leibold, M. A. *et al.* The metacommunity concept: a framework for multi-scale community ecology. *Ecol Lett* **7,** 601–613 (2004).

47. Fahrig, L. Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution, and Systematics* **34,** 487–515 (2003).

48. Fahrig, L. *et al.* Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecol Lett* **14,** 101–112 (2011).

49. Chiarucci, A., Bacaro, G. & Scheiner, S. M. M. Old and new challenges in using species diversity for assessing biodiversity. *Philos T R Soc B* **366,** 2426–2437 (2011).

50. Magurran, A. E. *Ecological Diversity and Its Measurement.* (Princeton University Press, 1988).

51. Cadotte, M. W., Carscadden, K. & Mirotchnick, N. Beyond species: functional diversity and the maintenance of ecological processes and services. *Journal of Applied Ecology* no–no (2011). doi:10.1111/j.1365-2664.2011.02048.x

52. Dennis, P. *et al. Conceptual foundations for biodiversity indicator selection for organic and low-input farming systems*. 1–184 (BioBio, 2010).

53. Jetz, W., Kreft, H., Ceballos, G. & Mutke, J. Global associations between terrestrial producer and vertebrate consumer diversity. *Proceedings of the Royal Society B: Biological Sciences* **276,** 269–278 (2009).

54. Qian, H. & Kissling, W. D. Spatial scale and cross-taxon congruence of terrestrial vertebrate and vascular plant species richness in China. *Ecology* **91,** 1172–1183 (2010).

55. Castagneyrol, B. & Jactel, H. Unraveling plant-animal diversity relationships: a meta-regression analysis. *Ecology* **93,** 2115–2124 (2012).

56. Thiel, B., Smukler, S., Krzic, M., Gergel, S. & Terpsma, C. Using hedgerow biodiversity to enhance the carbon storage of farmland in the Fraser River delta of British Columbia. *Journal of Soil and Water Conservation* **70,** 247–256 (2015).

57. Van Vooren Laura *et al.* Ecosystem service delivery of agri-environment measures: A synthesis for hedgerows and grass strips on arable land. *Agr Ecosyst Environ* **244,** 32–51 (2017).

58. Mazzi, D. & Dorn, S. Movement of insect pests in agricultural landscapes. *Annals of Applied Biology* **160,** 97–113 (2012).

59. Bagavathiannan, M. V. & Davis, A. S. An ecological perspective on managing weeds during the great selection for herbicide resistance. *Pest Management Science* **74,** 2277–2286 (2018).

60. Gamfeldt, L. *et al.* Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* **4,** 1340 (2013).

61. Sutherland, I. J., Bennett, E. M. & Gergel, S. E. Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting. *Forest Ecology and Management* **374,** 61–70 (2016).

62. Rand, T. A., Tylianakis, J. M. & Tscharntke, T. Spillover edge effects: the dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. *Ecol Lett* **9,** 603–614 (2006).

63. Blitzer, E. J. *et al.* Spillover of functionally important organisms between managed and natural habitats. *Agr Ecosyst Environ* **146,** 34–43 (2012).

64. Winfree, R., Aguilar, R., Vazquez, D. P., LeBuhn, G. & Aizen, M. A. A. A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology* **90,** 2068–2076 (2009).

65. Stokstad, E. Entomology. The case of the empty hives. *Science* **316,** 970–972 (2007).

66. Garibaldi, L. A. *et al.* From research to action: enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment* **12,** 439–447 (2014).

67. Russo, L., Park, M. G., Blitzer, E. J. & Danforth, B. N. Flower handling behavior and abundance determine the relative contribution of pollinators to seed set in apple orchards. *Agr Ecosyst Environ* **246,** 102–108 (2017).

68. Martins, K. T., Gonzalez, A. & Lechowicz, M. J. Pollination services are mediated by bee functional diversity and landscape context. *Agr Ecosyst Environ* **200,** 12–20 (2015).

69. Blouin, M. *et al.* A review of earthworm impact on soil function and ecosystem services. *European Journal of Soil Science* **64,** 161–182 (2013).

70. Bertrand, M. *et al.* Earthworm services for cropping systems. A review. *Agron. Sustain. Dev.* **35,** 553–567 (2015).

71. Hoeffner, K., Monard, C., Santonja, M. & Cluzeau, D. Feeding behaviour of epi-anecic earthworm species and their impacts on soil microbial communities. *Soil Biol Biochem* **125,** 1–9 (2018).

72. Xiao, Z. *et al.* Earthworms affect plant growth and resistance against herbivores: A meta-analysis. *Funct Ecol* **32,** 150–160 (2018).

73. Andriuzzi, W. S., Schmidt, O., Brussaard, L., Faber, J. H. & Bolger, T. Earthworm functional traits and interspecific interactions affect plant nitrogen acquisition and primary production. *Appl Soil Ecol* **104,** 148–156 (2016).

74. Lüscher, G. *et al.* Responses of plants, earthworms, spiders and bees to geographic location, agricultural management and surrounding landscape in European arable fields. *Agr Ecosyst Environ* **186,** 124–134 (2014).

75. Gregory, R. D., NOBLE, D. G. & CUSTANCE, J. The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom. *Ibis* **146,** 1–13 (2004).

76. Flynn, D. F. B. *et al.* Loss of functional diversity under land use intensification across multiple taxa. *Ecol Lett* **12,** 22–33 (2009).

77. Ormerod, S. J. & Watkinson, A. R. Editors' Introduction: Birds and Agriculture. *Journal of Applied Ecology* **37,** 699–705 (2000).

78. Gaston, K. J. *et al.* Population Abundance and Ecosystem Service Provision: The Case of Birds. *BioScience* **68,** 264–272 (2018).

79. Elser, J. L. *et al.* Economic impacts of bird damage and management in U.S. sweet cherry production. *Crop Protection* **83,** 9–14 (2016).

80. Zhang, W., Ricketts, T. H., Kremen, C., Carney, K. & Swinton, S. M. Ecosystem services and dis-services to agriculture. *Ecological Economics* **64,** 253–260 (2007).

81. Poessel, S. A. *et al.* Patterns of human–coyote conflicts in the Denver Metropolitan Area. *J Wildlife Manage* **77,** 297–305 (2013).

82. De Bondi, N., White, J. G., Stevens, M. & Cooke, R. A comparison of the effectiveness of camera trapping and live trapping for sampling terrestrial small-mammal communities. *Wildlife Res* **37,** 456–465 (2010).

83. Kremen, C., Iles, A. & Bacon, C. Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture. *Ecology and Society* **17,** art44–19 (2012).

84. International, B. *Mainstreaming Agrobiodiversity in Sustainable Food Systems.* (bioversityinternational.org, 2017).

85. Ekroos, J., Heliola, J. & Kuussaari, M. Homogenization of lepidopteran communities in intensively cultivated agricultural landscapes. *Journal of Applied Ecology* **47,** 459–467 (2010).

86. Tuck, S. L. *et al.* Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. *Journal of Applied Ecology* **51,** 746–755 (2014).

87. Weibull, A.-C., Östman, Ö. & Granqvist, Å. Species richness in agroecosystems: the effect of landscape, habitat and farm management. *Biodiversity and Conservation* **12,** 1335–1355 (2003).

88. Krewenka, K. M., Holzschuh, A., Tscharntke, T. & Dormann, C. F. Landscape elements as potential barriers and corridors for bees, wasps and parasitoids. **144,** 1816–1825 (2011).

89. Kennedy, C. M. *et al.* A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecol Lett* **16,** 584–599 (2013).

90. Tobler, M. W., Percastegui, S. E. C., Pitman, R. L., Mares, R. & Powell, G. An evaluation of camera traps for inventorying large- and medium-sized terrestrial rainforest mammals. *Anim Conserv* **11,** 169–178 (2008).

91. ACEVEDO, M. A. & RIVERA, L. J. V. From the Field: Using Automated Digital Recording Systems as Effective Tools for the Monitoring of Birds and Amphibians. *Wildlife Soc B* **34,** 211–214 (2006).

92. Gasc, A., Sueur, J., Pavoine, S., Pellens, R. & Grandcolas, P. Biodiversity Sampling Using a Global Acoustic Approach: Contrasting Sites with Microendemics in New Caledonia. *Plos One* **8,** e65311 (2013).

93. MacSwiney, M. C., Clarke, F. M. & Racey, P. A. What you see is not what you get: the role of ultrasonic detectors in increasing inventory completeness in Neotropical bat assemblages. *Journal of Applied Ecology* **45,** 1364–1371 (2008).

94. GRAHAM, E. A., RIORDAN, E. C., YUEN, E. M., ESTRIN, D. & RUNDEL, P. W. Public Internet-connected cameras used as a cross-continental ground-based plant phenology monitoring system. *Global Change Biology* no–no (2010). doi:10.1111/j.1365-2486.2010.02164.x

95. Khanduri, V. P., Sharma, C. M. & Singh, S. P. The effects of climate change on plant phenology. *Environmentalist* **28,** 143–147 (2008).

96. Lemckert, PenmanMahony. A cost-benefit analysis of automated call recorders. *Applied Herpetology* **2,** 389–400 (2005).

97. Royle, J. A., Nichols, J. D., Karanth, K. U. & Gopalaswamy, A. M. A hierarchical model for estimating density in camera-trap studies. *Journal of Applied Ecology* **46,** 118–127 (2009).

98. Gardner, B., Reppucci, J., Lucherini, M. & Royle, J. A. Spatially explicit inference for open populations: estimating demographic parameters from camera-trap studies. *Ecology* **91,** 3376–3383 (2010).

99. Blumstein, D. T. *et al.* Acoustic monitoring in terrestrial environments using microphone arrays: applications, technological considerations and prospectus. *Journal of Applied Ecology* **48,** 758–767 (2011).

100. Crimmins, M. A. & Crimmins, T. M. Monitoring Plant Phenology Using Digital Repeat Photography. *Environmental Management* **41,** 949–958 (2008).

101. Gotelli, N. J. & Colwell, R. K. in *Biological Diversity Frontiers in Measurement and Assessment* (eds. Magurran, A. E. & McGill, B. J.) 39–54 (Oxford University Press, 2010).

102. McCune, B. & Grace, J. B. *Analysis of Ecological Communities*. (MjM Software Design, 2002).

103. Villéger, S., Mason, N. W. H. & Mouillot, D. New multidimensional functional diversity indices for a multifaceted framework in functional ecology. *Ecology* **89,** 2290–2301 (2008).

104. Cadotte, M. W. *et al.* Phylogenetic diversity metrics for ecological communities: integrating species richness, abundance and evolutionary history. *Ecol Lett* **13,** 96–105 (2010).

Appendices

1. Details of biodiversity monitoring at other research farms and networks
2. Detailed descriptions of selected biodiversity indicators
3. Detailed biodiversity monitoring protocols
4. Key contact information
5. List of known species at the UBC Farm and surrounding area
6. Bumblebee species guide
7. Earthworm species guide
8. Weed species guide
9. Nature Vancouver bird survey data

Appendix 1 – Details of Biodiversity Monitoring at Other Research Farms and Networks

Russell Ranch, University of California Davis

Russell Ranch is a 120 hectare farm focused on irrigated and dry-land Mediterranean agriculture. It hosts The Century Experiment, which is a 100-year study investigating the long-term impacts of crop rotation, farming systems (conventional, organic, and mixed) and inputs of water, nitrogen, and carbon on agricultural sustainability.

Monitoring for biodiversity in the past has focused mainly on weed communities, soil biological (microbial and faunal) communities, and beneficial and pest insect communities. For example, a study by Minoshima et al. (2007) examined how nematode, fungal, and bacterial populations were affected by farming systems and tillage. However, monitoring of most of these different indicators has not been conducted on a regular schedule.

In 2012 a new research plan for Russell Ranch was proposed, which included additional long-term monitoring of aboveground diversity and projects focused on the biodiversity and ecosystem service impacts of hedgerows (e.g., pollination, pest and weed pressure, soil carbon storage, enhanced water holding capacity, erosion control, N sequestration) and testing wildflower mixes for their bee and pest attractiveness. In 2018, above- and belowground biodiversity research has been initiated. Aboveground this includes investigating how increasing biodiversity along farm edges, by planting vegetated swales, canals, and hedgerows can influence pollinators and runoff water quality. Belowground, research focuses on linking farm management actions (e.g., organic vs. conventional, standard vs. no-till practices) with soil diversity, and how soil microbes respond to fertilizer application.

Kellogg Biological Station, Michigan State University

Kellogg Biological Station (KBS) is a 1,300 ha research station that includes a bird sanctuary, farm, research facilities, conference center, and a nearby experimental forest. Within KBS, the Kellogg Farm incorporates 530 ha of agricultural lands and includes a Long-Term Ecological Research (LTER) site, the KBS LTER. Long-term experiments associated with the LTER station include evaluations of cropping systems, crop diversity gradients, nitrogen and water constraints, pest control methods, integrated farming systems, biofuel cropping systems, and tillage x fertilizer interactions.

Biodiversity research at Kellogg Biological Station focuses on plants, insects, and soil microbes. This includes studies investigating how beneficial insects and parasites can act as pest control for soybean aphid. Other consistent monitoring has focused on soil biota: both microbes and invertebrates. The Kellogg Biological Station has also monitored multiple aspects of plant diversity and has examined the effects of crop diversity on weed populations and identified plant species diversity in hedgerows. KBS also has a long term seed bank collection, collected every 3-6 years. Many of the monitoring protocols for these programs are available online.

Rothamsted Research Station

Rothamsted Research Station is the longest running agricultural research station in the world, and has investigated crop production research questions for 175 years. Like Russell Ranch, work directly performed by Rothamsted has not focused on biodiversity monitoring or research. The only species group where monitoring is focused is insects; two surveys are conducted each year, one focused on aphids and one that identifies moth species.

However, Rothamsted is part of the Environmental Change Network (ECN), which is a multi-agency programme, initiated in 1992, that measures and monitors environmental change across the United Kingdom. Relevant to biodiversity, these include species-level data for bats, birds, frogs, rabbits, deer, butterflies, moths, carabid beetles, spittle bugs, and plants, as well as composite indicators (multiple species combined into a single measure) for butterflies, moths, and ground predators.

Looking forward, Rothamsted's five-year plan (2017-2020) identifies five Institute Strategic Programmes, of which one includes consideration of biodiversity and ecosystem services. "Future Agri-Food Systems" aims to achieve sustainable agricultural systems and endeavours to understand the importance of biodiversity for agricultural production and ecosystem services.

McGill University - Emile A. Lods Agronomy Research Centre

McGill's research farm, located west of Montreal, incorporates intensive crop fields into a peri-urban area. Similar to other institutes, very little biodiversity research has occurred here. However, some research on symbioses between plants and microbes (i.e., nitrogen-fixing bacteria) has occurred, as well as soil biodiversity studies focused on earthworms and soil microbes and their effects on nutrient cycling and crop productivity.

University of Alberta - Rangeland Research Institute (RRI)

The RRI focuses on rangeland agriculture instead of crop agriculture, and includes two large research ranches, each ~5000 ha in size. Like other research stations, RRI has conducted research on how soil biodiversity affects plant growth and carbon storage. There has also been an effort to monitor rangeland ecosystem functions to create a long-term dataset. Other research has looked at mammal and songbird diversity and how different ranching management actions impact biodiversity. One final project monitors native bee populations around both the RRI and Alberta.

National Ecology Observatory Network (NEON)

NEON is a continental-scale network of ecological monitoring stations whose goal is to evaluate how ecosystems in the US are changing through time. A variety of data types are gathered at each NEON site, including airborne remote sensing, aquatic hydrologic and organismal measures, flux tower data, soil measurements, and terrestrial organismal sampling. NEON includes a number of agricultural monitoring sites, including Santa Rita Experimental Range (Arizona), Central Plains Experimental Range (Colorado), Blandy Experimental Farm (Virginia), Klemme Range Research Station (Oklahoma), LBJ National Grassland (Texas), and San Joaquin Experimental Range (California). As part of NEON, standardized sampling of indicator species takes place at each location. This includes diversity and abundance measures for plants, soil microbes, small mammals, mosquitoes, birds, and ground beetles. All data is free and publicly available via the NEON website.

Long-term Agroecosystem Research Network (LTAR)

The LTAR is a new research strategy involving 18 institutions across the United States. Its goal is to better understand how agroecosystems function at multiple scales and provide knowledge to improve agricultural sustainability and delivery of ecosystem services (Walbridge & Schaefer 2011). While this network is still in the preliminary stages of organization (it was founded in 2014), it plans on monitoring soil microbial diversity, weed indicators, and other general biodiversity indicators.

TomKat Ranch

TomKat Ranch Educational Foundation (TKREF) is located on an eighteen hundred acre working cattle ranch in Pescadero, California. Their mission is to provide healthy food on working lands in a way that sustains the planet and inspires others to action, and to serve as a learning laboratory for animal agriculture on working lands focusing on climate stability, nature's benefits, healthy food, biodiversity, and vibrant community. They have been monitoring biodiversity and other ecological indicators on the ranch since 2010 (in partnership with Point Blue Conservation Science), including bird, soil, stream, vegetation and weather data.

Appendix 2 – Key Contact Information

This section summarizes the various people that were either interviewed or contacted about this project. Each entry summarizes the person's contact information and what the discussion focused on.

Veronik Campbell
Email: veronik.campbell@ubc.ca
Role: CSFS Academic Program Manager
Summary: In May and June 2017, NW and VC communicated via email. Veronik sent a file containing which classes had recently used UBC Farm.

Dr. Juli Carillo
Email: juli.carrillo@ubc.ca
Position: Assistant Professor, Land and Food Systems
Summary: MM met with in April and July 2018 to discuss ideas for biodiversity monitoring on the UBC Farm, potential to monitor pests and arthropods, and how to connect with students in her lab. Potential for courses she teaches to contribute to monitoring was also discussed.

Tim Carter
Email: tim.carter@ubc.ca
Position: Field Manager; UBC Farm
Summary: NW met with in May 2017. Discussed seed saving, hedgerows, weed and pest monitoring, and anything he felt would be important to monitor from his perspective.

Dancing Water
Email: unknown
Position: Tu'wusht Garden Coordinator; UBC Farm
Summary: NW met with in July 2017. Briefly discussed the possibility of doing some sort of monitoring in the Tu'wusht garden. Dancing Water seemed unsure if there was any relevant collaboration between the project and her program.

Seth Friedman
Email: seth.friedman@ubc.ca
Position: Practicum Coordinator, UBC Farm
Summary: MM met with Seth June 2018 to discuss possibility of practicum students monitoring pest biodiversity at the UBC Farm and how to integrate the practicum program into the biodiversity monitoring program.

Dr. Leonard Foster
Email: foster@msl.ubc.ca
Position: Associate Professor, Biochemistry and Molecular Biology
Summary: MM met with Leonard in April 2017 to discuss bee microbiome research and monitoring and potential for biodiversity monitoring to contribute to this work.

David Gill
Email: david.gill@ubc.ca
Position: Program and Policy Planner, Campus & Community Planning
Summary: MM has had multiple meetings with David around the wider biodiversity initiatives on campus, including biodiversity monitoring on campus, the creation of biodiversity signage and a common signage standard for UBC, and the creation of a biodiversity database across the UBC campus.

Dr. Richard Hamelin
Email: richard.hamelin@ubc.ca
Position: Professor, Department of Forestry
Summary: NW started communicating with him via email in July 2017 and met in July and August 2017 to discuss potential collaboration between his undergraduate forest fungal class and UBC Farm biodiversity monitoring. May have data collected from past classes that have not been added to the Farm database. Dr. Hamelin is willing to develop more consistent monitoring sites and developing a program that would bridge undergraduate knowledge of fungal species to the public and children to enable them to identify fungal species. We met in August to choose these sites, but unfortunately most of the fungi was dormant due to dry conditions and we were not able to choose sites.

Dr. Cara Haney
Email: cara.haney@msl.ubc.ca
Position: Assistant Professor; Michael Smith Laboratories
Summary: MM met with in March 2018. Discussed possibility of monitoring soil microbiome at the UBC Farm, how to collaborate on this, and potential to use some common facilities. Also discussed costs of analysis and DNA barcoding.

Katherine Hastie
Email: khastie@mail.ubc.ca
Position: Outreach and Volunteer Coordinator; UBC Farm
Summary: NW met with in June 2017. Discussed the volunteer program at UBC Farm and the possibility to integrate biodiversity monitoring in any of the volunteer groups or potentially creating a volunteer group specifically for biodiversity monitoring. It seems that there is not a clear group that would work well for monitoring biodiversity, but there may be a possibility of creating a new group specifically for this purpose.

Kailee Hirsche
Email: kailee.hirsche@ubc.ca
Position: Children's Program Coordinator; UBC Farm
Summary: NW spoke with in May 2017 and then periodically throughout July. Discussed the potential role of children's programs in biodiversity monitoring. She recommended talking to Stacy Friedman (program manager of Landed Learning (stacy.friedman@ubc.ca)) and Raelene Hodgson(coordinator of CRUW (Culturally Relevant Urban Wellness).

Trevor Jones
Email: trevor.jones@ubc.ca
Position: Coordinator - MGEM Program

Summary: MM met with to discuss the possibility of volunteers from the Masters of Geomatics and Environmental Management (MGEM) to update land cover/land use of the UBC Farm and create protocol to monitor this into the future.

Dr. Douglas Justice
Email: douglas.justice@ubc.ca
Position: Associate Director, Horticulture & Collections, UBC Botanical Garden
Summary: MM met with in September 2018 to explore the unofficial arboretum at the farm, identify tree species present, and discuss management options and priorities for the site.

Dr. Maja Krzic
Email: maja.krzic@ubc.ca
Position: Associate Professor, Applied Biology/Forest and Conservation Sciences
Summary: NW talked with her about what work her students had done on the farm with Dr. Sandra Brown. She said that each year her class samples the soil of different areas of fields at the Farm to determine nutrient levels, but has never collected any biodiversity measures. Dr. Brown believes that Tim Work should have all the data collected by the class.

John Madden
Email: j.madden@ubc.ca
Position: Director, Sustainability & Engineering, Campus and Community Planning
Summary: MM met with John in September 2018 to discuss the UBC Farm's role with respect to the UBC Urban Forest Management plan, and how this could connect with biodiversity monitoring on the farm.

Wilson Mendes
Email: wilson.mendes@ubc.ca
Position: xʷc̓ic̓əsəm Garden Coordinator
Summary: NW met with in July 2017. Briefly discussed the possibility of doing some sort of monitoring in the xʷc̓ic̓əsəm garden. Wilson seemed to be open to potential collaboration in the future.

Dr. Stephen Mitchell
Email: stephen.mitchell@ubc.ca
Position: Professor Emeritus, Forest and Conservation Sciences Department
Summary: MM met with Steve in May 2018. Discussed all of the forest inventory and diversity work performed at the farm in the past, and arranged to have all of this data transferred to the farm server.

Dr. Tara Moreau
Email: tara.moreau@ubc.ca
Position: Associate Director of Sustainability and Community Programs, UBC Botanical Gardens
Summary: MM met with Tara in April 2018 to discuss potential to coordinate with pollinator and weed monitoring between the UBC Farm and Botanical Gardens. Shared weed presence data and continue to discuss potential to collaborate.

Liska Richer
Email: liska.richer@ubc.ca
Position: Manager, SEEDS Sustainability Program

Summary: MM met with in October 2018. Discussed potential to connect SEEDS with biodiversity monitoring at the farm, whether the farm could take advantage of the SEEDS program, how biodiversity monitoring at the farm can connect with other sustainability initiatives on campus.

Dr. Suzanne Simard
Email: suzanne.simard@ubc.ca
Position: Professor, Faculty of Forestry
Summary: NW met in July 2017. Discussed potential for projects at UBC Farm with regards to soil microbial communities. Dr. Simard suggested several methods to sample soil microbes in agricultural systems.

Dr. Sean Smukler
Email: sean.smukler@ubc.ca
Position: Assistant Professor Faculty of Land and Food Systems
Summary: NW met in June of 2017. Discussed what monitoring his class has done, sampling protocols and locations. Was willing to make adjustments to his sampling protocols and locations to better assist the farm in monitoring biodiversity. He also has records of the data he has collected in the past that should be transferred to the farm database. MM met with Sean April 2018 to discuss biodiversity monitoring on the farm, use of remote camera traps, and collaborating with Sean's agroecology class.

Dr. Roland Stull
Email: rstull@eoas.ubc.ca
Role: Professor; Director, Geophysical Disaster Computational Fluid Dynamics Center
Summary: NW met with in May 2017 and continued to communicate via email in June 2017. Originally met to discuss weather stations to monitor temperature, wind speed, and precipitation. Agreed to installing a monitoring station at UBC Farm and continued to develop the possibility before Dr. Hannah Wittman took over.

Mel Sylvestre
Email: sylvestre.melanie@ubc.ca
Position: Perennial, Biodiversity, and Seed Hub Coordinator; UBC Farm
Summary: NW met with Mel May 2017. Discussed seed saving, hedgerows, weed and pest monitoring, and anything she felt would be important to monitor from her perspective. MM met with Mel February 2018 to discuss biodiversity monitoring and the hedgerows on the farm. MM met with Mel September 2018 to discuss hedgerow and weed monitoring on the farm and land use/land cover mapping with Mel's Biodiversity Intern.

Dr. Mahesh Upadhyaya
Email: mahesh.upadhyaya@ubc.ca
Position: Professor, Plant Science
Summary: MM met with in April 2018 to discuss the potential to monitor weeds at the UBC Farm and how best to do this. Discussed difficulties in monitoring weeds and seed bank and implications for crop production.

Marika van Reeuyk
Email: marika@eya.ca
Position: Program Coordinator, Environmental Youth Alliance

Summary: MM met with Marika in September 2018 to explore potential for using EYA pollinator monitoring protocols at the UBC Farm and ability of EYA to provide training to interns/staff. Also explored possibility of EYA using the UBC Farm for a pollinator experiment involving different vegetation management strategies.

Appendix 2 – Detailed Descriptions of Selected Biodiversity Indicators

Landscape/habitat diversity indicators

- Core Indicators
  - *Habitat richness*: the total number of habitat types across the entire farm or smaller area, as well as the total number of habitat types per hectare. Within this indicator, richness of cultivated crops and semi-natural habitats is also possible.
  - *Habitat diversity*: the value of the Shannon diversity index:

    $H' = \sum_{i=1}^{R} p_i \cdot \ln p_i$

    Where p_i is the proportion of the farm that a particular LU/LC covers, summed across all of the different LU/LC classes present on the farm. Shannon diversity incorporates measures of both the richness of LU/LC across an area as well as the evenness of LU/LC (i.e., does one category dominate the landscape or are there a relatively equal distribution of areas across the different LU/LC categories).
  - *Average size of habitat patches*: the average size of habitat patches across all LU/LC categories in hectares, as well as for each LU/LC category. This provides a measure of fragmentation for each LU/LC category.
  - *Length of linear elements*: the length of grassy field margins, hedgerows, drainage ditches, roads, or trails in meters per hectare. Linear elements can be important for connectivity across agricultural landscapes and maintenance of biodiversity.
  - *Crop richness*: the number of crop types or varieties per hectare. A measure of "planned" species diversity.
  - *Shrub cover*: the proportion (%) covered by shrubs. This can be calculated as the share of cultivated areas with shrubs (e.g., blueberries), the share of semi-natural areas with shrubs, or share of total area with shrubs.
  - *Tree cover*: the proportion (%) covered by trees. This can be calculated as the share of cultivated areas with trees (e.g., orchards), the share of semi-natural areas with trees, or share of total area with trees.
  - *Semi-natural habitat cover*: the proportion (%) of farmland covered by semi-natural habitats. Can also calculate the proportion of semi-natural habitat with trees or shrubs.
  - *Built infrastructure*: the proportion (%) covered by built infrastructure (buildings, impervious surfaces, gardens, etc.). This can also be calculated separately for the immediate farm lands and the surrounding area, as well as separately for each sub-category within "Built infrastructure."
- Secondary Indicators: these indicators give measures of landscape diversity, but are either of secondary importance, or require additional information from other components of the biodiversity monitoring plan (e.g., forest tree surveys, weed surveys) to calculate.
  - *Tree density*: the number of trees per hectare in an area. To calculate this information from the forest plant and hedgerow surveys will be required.

- *Non-crop plant cover on arable fields*: the proportion of production fields (%) covered by weeds and other non-crop plants. Will require information from the weed surveys.
- *Ratio of non-flowering to flowering crops*: ratio of the area of production fields with non-flowering crops to those with flowering crops. This gives a measure of the relative amount of pollinator and arthropod resources available on the farm.

Species diversity indicators

- Core Indicators
  - *Gamma diversity*: The total number of species aggregated across the farm and all habitats present. This indicator can also be calculated for each habitat type separately. Comparison of gamma diversity over time gives a measure of total species richness change but may not capture changes in composition where species richness stays the same (i.e., substitution of species through time). Both total species richness and the Shannon index (H') can be calculated:

$$H' = \sum_{i=1}^{R} p_i \cdot \ln p_i$$

    Where p_i is the proportion of individuals belonging to species *i*. The Shannon index gives a measure of the diversity of species across the farm, considering both species richness and the evenness of species abundances.

  - *Alpha diversity*: The average number of species over the sample habitats or plots. This gives a measure of the mean number of species encountered in each location. Both average species richness and Shannon index can be calculated.
  - *Area weighted diversity (SA_{est})*: The total number of species across all of the habitats weighted by the proportional area of each habitat across the farm:

$$SA_{est} = \sum_{i=1}^{A} S_i \cdot P_i$$

    Where S_i is the total number of observed species present in habitat *i*, and P_i is the proportional area of habitat *i* across the entire farm.
  - *Estimated species richness*: the estimated/extrapolated number of species that are present in a habitat or across the farm based on the accumulated number of species found in the plots or samples. This measure partially corrects for incomplete sampling of the entire number of species present in a location. Two estimates can be calculated, the Chao2 estimator[101]:

$$S_{Chao2} = S_{obs} + \left(\frac{m-1}{m}\right)\frac{q1(q1-1)}{2(q2+1)}$$

    Where S_{obs} is the total number of species observed in a set of samples, *m* is the total number of samples, *q1* is the number of unique species across the samples, and *q2* is the number of duplicate species.

And the first-order Jackknife estimator[101]:

$$S_{jackknife1} = S_{obs} + \frac{q1(m-1)}{m}$$

- *Individual species abundance*: The number or density of individuals of each species or species group across the farm or in each habitat type.

- Secondary indicators
  - *Beta diversity*: the amount of species turnover/change or compositional change across samples. Measures of beta diversity can only be compared when sample number, size, and effort remain the same[102]. Beta diversity can be calculated using an estimator of the number of distinct communities (β_w):

$$\beta_w = \frac{S_c}{S} - 1$$

    Where S_c is the number of species in the composite sample and S is the average species richness in sample units[102].

  - *Species evenness*: the equitability of species across plots or habitats. This can be measured using Pielou's J:

$$J = \frac{H'}{logS}$$

    Where H' is the Shannon diversity measure and S is the average species richness across samples.

- Peripheral indicators
  - *Functional diversity*: measures of the difference in functional traits of species present on the farm. A variety of different measures are available and depend on measuring functional traits for species of interest or the availability of a database of functional traits for the species group. A description of some of the most commonly used indices, including functional richness, functional evenness, and functional divergence can be found in Villéger et al. [103].
  - *Phylogenetic diversity*: measures of the level of common ancestry between species within a sample. These measures incorporate information on the phylogenetic relatedness of species. A number of indices and measures are available and include measures of evenness, imbalance and evolutionary distinctiveness[104], among others.

Crop diversity indicators

- Core Indicators
    - *Number of different varieties:* the number of crop types or varieties on the farm. This gives a measure of crop diversity and potential changes in resources for species and differences in farm management.
    - *Crop alpha diversity:* the average number of crop types or varieties across production fields or at a fixed spatial resolution across the farm (e.g., 50×50 m). This gives a measure of the mean number of crop types present. Both average crop richness and Shannon index can be calculated.
    - *Crop beta diversity:* the amount of crop types turnover/change or compositional change across fields or a fixed spatial resolution across the farm (e.g., 50×50 m).
- Peripheral Indicators: the peripheral indicators are all measures of genetic or phenotypic diversity across crop types that require information on crop traits (from fieldwork or databases) or crop genetics. Both of these will require substantial fieldwork and/or laboratory analyses.
    - *Crop functional/phenotypic diversity*: diversity of functional traits across crop varieties and types
    - *Pedigree-based genetic diversity*: coefficient of parentage
    - *Genetic diversity index of crops*: genetic diversity index