IMPACT OF FARMING SYSTEMS ON LANDSCAPE HETEROGENEITY IN SOUTHERN SASKATCHEWAN CROPLAND

by

Wenjie Xu

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Dalhousie University is located in Mi'kma'ki, the

ancestral and unceded territory of the Mi'kmaq.

We are all Treaty people.

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ABSTRACT

Organic farms have been recognized to have higher biodiversity than conventional farms, but it is unclear if organic farms are conserving more perennial habitat in their fields than conventional farms under large scale Prairie cropping systems. This study aims to determine whether landscape heterogeneity differs between organically managed cropland and conventionally managed cropland in the Canadian Province of Saskatchewan. A total of 71 pairs of adjacent organic and conventional fields were selected. Mixed Perennial Vegetation, Shelterbelts, Cultivated Lowland and Cultivated Upland were digitized using aerial photos from 2008, 2012 and 2017 to quantify landscape heterogeneity. Overall, a higher average area of Mixed Perennial Vegetation in organic (9.31%) fields compared with conventional (6.06%) fields, and was related to a larger mean patch size on organic (1.82 ha) compared to conventional (1.50 ha) fields. This study highlighted the importance of organic farming in maintaining agricultural landscape heterogeneity, but differences were ecoregion-dependent.

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Chapter 1: Introduction

The Food and Agriculture Organization (FAO) has warned that agriculture has become the main factor in land degradation and pollution (Mateo-Sagasta et al., 2017). Studies have shown that intensive farming practices have caused significant declines in biodiversity (Geiger et al., 2010). Although conventional agriculture, which is characterized by its intensive farming practices and various chemical inputs (Corwin et al., 2019), produces significantly more food to feed the growing population (Conway, 1997), its negative impact on the environment has drawn society's attention and driven researchers to find better ways to feed the world.

The organic agriculture movement was introduced in response to these concerns where its concept was officially defined in the beginning of this century (IFOAM, 2005; IFOAM, 2008). After years of exploring and development in both production and marketing, organic agriculture is no longer accounting for a small proportion of agricultural production. As reported by the Canada Organic Trade Association (Canada Organic Trade Association, 2020), organic operations have increased by 19% from 2015 to 2020, and where the number of organic crop producers has grown by 23% in Saskatchewan, Canada. Despite a lower productivity (Connor, 2008; Kremen et al., 2012), organic agriculture has demonstrated a greater effectiveness in maintaining soil organic carbon (SOC) in the topsoil (Marriott & Wander, 2006), reducing nutrient losses (Bender et al., 2015), removing chemical inputs out of fields (McErlich & Boydston, 2013; Pretty & Bharucha, 2015), and conserving biodiversity (Gabriel et al., 2013; Marja et al., 2014; Schneider et al., 2014).

Landscape heterogeneity refers to the diversity and spatial patterns of different landscape structures (Fahrig & Nuttle 2005). Higher landscape heterogeneity would have a greater variety of land covers and/or more complex spatial arrangement of those covers (Fahrig et al., 2011). Heterogeneous landscapes can support higher biodiversity than simplified landscapes. This is because (1) a greater number of land cover types are associated with a greater number of habitats and ecological niches for species as well as resources needed for different life stages (Pope et al., 2000; Bianchi et al., 2006; Brown, 2009); and (2) a more complex spatial arrangement of land cover types offers more opportunities for organisms to travel through or to have better access to the habitats and benefit from 'edge effect' (Batary & Baldi, 2010).

Despite their critical ecological role in biodiversity conservation, non-production perennial vegetations have been removed from fields in the past few decades. For example, barriers in the landscape, such as fence lines, wetlands, and shelterbelts encumber field operations will force equipment to circle around the barriers. Their existence in the fields results in lost efficiency and repetition of the application of inputs, leading to the increasing tendencies of farmers to remove these "barriers" to simplify field operations (Westmacott and Worthington, 1984; Benton et al., 2003). Some farmers convert non-production perennial vegetation to arable fields (Matson et al., 1997; Tilman et al., 2002) while others merge smaller fields together (Tscharntke et al., 2005). These types of intensive farming practices have caused severe declines in bird (Donald et al., 2001), insect and spider (Sotherton, 1998) populations on farmlands. To offset landscape simplification caused by intensive farming development, many countries, such as the United States of America (EPA, 2008), Germany (BMUB, 2010), and South Africa (DEA&DP, 2007) have proposed plans to compensate or maintain landscape structures. These countries failed to meet their biodiversity conservation goals, Switzerland, however, has seen an increased biodiversity of plants, arthropods, and small mammals by its unique local conservation approach (Herzog et al., 2005; Aschwanden et al., 2007; Albrecht et al., 2010). The success of the Swiss landscape compensation policy demonstrates the potential to counteract the impacts of landscape simplification via the maintenance of landscape heterogeneity in its original location. Despite the effectiveness of the Swiss policies, their benefits may not be instructive when applied to the Canadian agricultural landscape because of different political factors as well as different growing environments.

Understanding the importance of landscape structures and the serious consequences of landscape simplification, Environment and Climate Change Canada in a report, “2020 Biodiversity Goals and Targets for Canada,” highlighted that wetlands and many other landscape structures in the agricultural landscape should be preserved for ecosystem services and biodiversity. Despite the critical function of landscape heterogeneity, the preservation of non-production perennial vegetation was not required in the Canadian Organic Standards and Regulation when this study began. Therefore, the main objective of this study was to determine whether organic agriculture practices could maintain a higher landscape heterogeneity than conventional agricultural in the absence of regulatory policies.

Chapter 2: Background

This chapter will begin by describing the difference between organic and conventional farming systems particularly in relation to biodiversity. Then the components of landscape heterogeneity are described in the context of landscape simplification. Landscape metrics are subsequently explained because they are the quantitative indicators that are used to assess the landscape heterogeneity. Lastly, Saskatchewan, a province from Prairie Canada, with its unique landscape and agriculture production is summarized.

2.1 Farming Systems

2.1.1 Conventional Agriculture

Conventional agriculture is a type of large-scale, industrialized, agricultural production system in general. The definition to conventional agriculture may vary from country to country, but their practices share many common characteristics. Conventional agriculture relies on resource inputs, such as fertilizers (FAO, 2007; Hawkesford, 2014), and pesticides (Lamichhane et al., 2016). Compared with other agricultural production system, conventional management significantly enhances productivity; for example, cereal yields doubled from 1961 to 1985 while rice, maize, and wheat yields increased steadily (Conway, 1997). It is reasonable to speculate that there would have been greater famine without conventional agriculture as the population grew from 1.65 billion to 6 billion during the 20th century alone (Worldometers, 2020).

However, the benefits of conventional management practices and intensified farming practices using these approaches do not compensate for the overall decline in ecosystem services and biodiversity. While supporting higher production, the intensification of agricultural management coupled with monocultures of high-yielding crop types with increased chemical inputs, has led to negative impacts on agricultural environment (Stoate et al., 2009) and biodiversity (Firbank et al., 2008). Studies have shown that agriculture has replaced industries and settlements as the main factor in water degradation (Yermiyahu et al., 2007), decline in biodiversity (Seufer & Ramankutty, 2017), degradation of ecosystem services (Landis, 2017), and causing threat to human health (Criss & Davisson, 2004). For example, conventional agriculture has led to serious declines in bird populations (Siriwardena et al., 1998) while agricultural intensification has led to decreased populations of soil microbial biomass (Wardle et al., 1999) and arthropods (Attwood et al., 2008). Furthermore, conventional agriculture was reported to negatively impact abiotic factors through environmental contamination due to the application of pesticides (Baker et al., 2010; Blair et al., 2015; Hakeem et al., 2016), chemical fertilizers (Basso et al., 2005; Gomiero et al., 2011), and herbicides (Bennett et al., 2004). These chemical inputs may further affect human health through run-off and chemical leaching (Sabarwal et al., 2018).

2.1.2 Organic Agriculture

In contrast to applying synthetic inputs in conventional systems, organic management relies on ecological processes, biodiversity, and life cycles. Food and Agriculture Organization of United Nations defined organic agriculture as follows:

> "*Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasises the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system.*" (FAO, 1999).

The International Federal of Organic Agriculture Movements refined the organic agriculture definition as follows:

"*Organic Agriculture is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved.*" (IFOAM, 2008).

The Principles of Health, Ecology, Fairness, and Care for organic agriculture are the foundation, which instruct the directions of development of organic management (IFOAM, 2005). The Principal of Health indicates that organic agriculture should restore and support the health of both biotic and abiotic factors; the Principal of Ecology indicates that organic agriculture should be managed with the operation and cycles of living ecological systems, and help sustain them; the Principal of Fairness indicates that organic agriculture should make sure the fairness among life opportunities and the common environment; and the Principal of Care indicates that organic agriculture should protect the well-being of current and future generations and environment.

Agricultural production is a systematic process, organic production is even more holistic and sophisticated. In order to distinguish organic production from conventional production, organic agriculture needs regulatory standards to restrict its input and farming behaviors. Canadian General Standards Board has published serial publications for Canadian organic agriculture production since 2006 (https://publications.gc.ca). This national organic standard specified frequently used terms in organic agriculture, organic plan and detailed clause for crop production, livestock production.

2.1.3 Comparison between Organic and Conventional Agriculture

2.3.1.1 Ecosystem Services

Organic agriculture delineates a generally better performance than conventional agriculture in many aspects of ecosystem services (Seufert & Ramankutty, 2017), such as soil organic carbon concentration, nutrient cycling, and greenhouse gas emissions (Macrae et al., 2010; Scialabba & Muller-Lindenlauf, 2010; Henneron et al., 2015). Soil organic carbon (SOC), an important factor for enhancing soil physical structure (Fernandez et al., 2016; Reeve et al., 2016), was found to be higher after organic conversion (Gattinger et al., 2012) and in the topsoil on organic fields than conventional fields (Marriott & Wander, 2006). Organic agriculture has also been found to reduce nutrient losses by leaching and runoff (Anglade et al., 2015), especially where cover crops are used (Vincent-Caboud et al., 2017).

The reliance on pesticides on conventional fields is well-known (Geiger et al., 2010; Mortensen et al., 2012; Pretty & Bharucha, 2015). However, the intensive use of anthropogenic inputs in conventional agriculture have resulted in consequences, such as water pollution, biodiversity decline, and increased resistance to pesticides (Mortensen et al., 2012; Menalled et al., 2016). Unlike the heavy reliance on anthropogenic inputs in conventional agriculture, organic agriculture generally relies on ecosystem services, which makes it distinctive from other farming systems. Contrary to conventional agriculture, organic agriculture has many limitations on their inputs (Canadian General Standards Board, 2015); hence, the management of organic agriculture depends on the ecosystem services provided by biological processes (Altieri, 1999). Taking pest management as an example, organic agriculture relies on nonchemical methods of control (Zehnder et al., 2007) whereby arthropods and insectivorous birds hunt pest insects as food sources; in other words, the food chain is used to control pests instead of pesticides in organic agriculture (Tscharntke et al. 2005). In addition, organic farming was also proved to lessen the reliance on pesticides and promote human health by lowering dietary risks (Benbrook et al., 2021).

2.3.1.2 Biodiversity

Organic agriculture benefitted tremendously from multilayered relationship with biodiversity through three different levels – genetic diversity, species diversity and ecosystem diversity (Bengtsson et al., 2010; Fitter, 2012). Genetic diversity enhances primary productivity, interspecific competition, and fluxes of energy and nutrients (Hughes, et al., 2010) as well as contributing to a greater resiliency and adaption of crop quality (Fielder, et al., 2015), improved disease resistance (He et al., 2010), and higher carbon sequestration (Hajjar et al., 2008). Species diversity contributes to species complementarity, making resources more evenly distributed and building up more complicated food chains by the occupation of more ecological niches within a landscape (Tilman et al, 2002; Tscharntke et al., 2005). The organic agroecosystem is a semi-natural agriculture production system that relies more on nature. Therefore, the organic agroecosystem relies on ecological processes and diversity in order to respond to disturbances and stressors (Peterson et al., 1998; Elmqvist et al., 2003; Schmidt et al., 2005; Bianchi et al., 2006).

The magnitude of ecosystem services from biodiversity may be influenced by the management of landscape heterogeneity (Boutin et al., 2011; Winqvist et al., 2012). In heterogeneous landscape, perennial vegetation may already support biodiversity, which may not be further promoted by organic management (Batary et al., 2013); in simple landscapes however, organic management may support higher biodiversity than neighboring conventional fields (Gabriel et al., 2013). Moreover, the abundance of species may react to the level of landscape heterogeneity instead of types of farming systems; for example, carabids showed no response to differences of farming system (Winqvist et al., 2012), and the diversity of spiders increased mainly with landscape heterogeneity instead of farming system (Schmidt et al., 2005). In general, organic agriculture could be an important approach to protecting biodiversity, but alone, it may not provide sufficient benefits to all species (Emmerson et al., 2016). The degree to which the impact of landscape heterogeneity can override the impact of different farming systems on biodiversity remained an important question (Tscharntke et al., 2005). Therefore, understanding what landscape heterogeneity is, how it links to biodiversity and ecosystem services, and how farming systems would affect it would be necessary.

2.2 Landscape Heterogeneity

Agricultural landscapes are extensively cultivated with ephemeral crops with inclusions of non-production perennial vegetation, such as wetlands or stony land (Landis & Marino, 1995). Less intensive farming practices can bolster ecosystem services like pollination to some extent but not sufficiently if there is a lack of natural habitat in the surrounding area (Kremen & Miles, 2012). As indicated in Canada's biodiversity strategy (Environment and Climate Change Canada, 2016), protecting non-production perennial vegetation is critical for the conservation of biodiversity as they provide shelter and food in agricultural landscapes (Morandin & Winston, 2006; Walz & Syrbe, 2013). For example, the abundance and richness of pollinators have shown to be higher on organic fields and associated with variety of landscape structures (Deguines et al., 2014); diverse wildflower strips enhance resource availability and increase bee abundance (Balzan et al., 2014). Ecosystem services and biodiversity are also related to the spatial pattern of landscape structures; for example, isolation from natural landscape structures is associated with a decline in pollination services (Carvalheiro et al, 2010). In pest management, the spatial configuration of, and access to, perennial vegetation all positively support natural enemies of pests (Ekroos et al., 2010; Gaigher & Samways et al., 2014; Puech et al., 2015).

Landscape heterogeneity has two aspects: compositional heterogeneity and configurational heterogeneity. Compositional heterogeneity describes the diversity of landscape structures while configurational heterogeneity describes the spatial pattern of landscape structures (Fahrig & Nuttle 2005; Fahrig et al., 2011). In general, a heterogeneous landscape has a large variety of landscape structures (higher compositional heterogeneity) and/or an intricate spatial pattern of those landscape structures (higher configurational heterogeneity; Fig. 1).

2.2.1 Compositional Heterogeneity

Compositional heterogeneity measures the types of landscape structure present on landscape and how much there is of each type. Landscape structures in an agricultural landscape refers to non-production perennial vegetation that is able to serve as a habitat or provide resources (Fischer et al., 2006; Brown, 2009). This classification includes habitat features such as: perennial grassland, shrubland, forest, wetlands, hedgerows and some other non-production perennial vegetation. Annual cropping systems are subject to cultivation, planting, pest management and harvesting during relatively short growing season. Consequently, crop fields under frequent management are not suitable as habitat for many species like ducks (Durham & Afton, 2008) and invertebrates (Meek et al., 2002). The rare exception is some species of harvesters (Arachnida: Opiliones) which prefer living in cropland and are capable of traveling through the fields (Wissinger, 1997).

Different types of non-production perennial vegetation (NPPV) serve as different habitats (Tscharntke et al., 2005) which are required by different organism. As many species rely on the food, shelter, and microclimate provided by non-crop habitats, The non-production perennial vegetation within the agricultural landscape acts as a reservoir of agricultural biodiversity (Bianchi et al., 2006). Numerous researchers have confirmed that field margins, hedgerows, wetlands, and other NPPV and semi-natural patches support agricultural bird species (Bellamy, 2000; Cerezo et al., 2011; Hiron et al., 2015), arthropods (Perfecto & Vandermeer, 2002; Duelli & Obrist, 2003), and insects (Sjödin et al., 2010; Holzschuh et al., 2010). In general, having more types of habitats or landscape structures in each landscape can lead to a higher level of biodiversity in the agricultural landscape.

In addition to the biodiversity directly related to habitats, compositional heterogeneity can support biodiversity through landscape complementation. Landscape complementation occurs when a new land cover type is added to a given landscape, biodiversity is expected to increase through an accumulation of species associated with that distinct cover type or newly created habitats (Fuller et al., 1997; Ouin & Burel, 2002), especially in agricultural landscape (Tscharntke et al., 2005; Billeter et al., 2008). Furthermore, the increased biodiversity is not necessarily linear as it depends on the responses of the different species to the combination of resources provided by these cover types. One critical benefit from different land cover types is linked to an organism's lifecycle where different land cover types are required at different life stages (Tscharntke et al., 2005; Fahrig et al., 2011). For example, many amphibians need both aquatic and terrestrial habitats at different life stages; hence, they are more likely to occur in an area containing both of them (Pope et al., 2000). As a result, landscapes that include multiple habitats or land cover types could have higher overall biodiversity than one would predict from merely adding the species associated with each cover type individually.

2.2.2 Configurational Heterogeneity

Configurational heterogeneity refers to the spatial pattern of the landscape; it describes how different categories of land covers are spatially distributed as patches in a landscape.

Configurational heterogeneity measures physical characteristics of landscape structures, such as shape and spatial aggregation of landscape structures.

Configurational heterogeneity can maintain or enhance biodiversity in three significant ways: (1) reducing the mean patch size of crop fields (Fahrig et al., 2015; Šálek et al., 2018); (2) increasing shape complexity to enhance ecological ‘edge effect’ (Magura, 2002); and (3) increasing juxtaposition/interspersion of different patch types (Brotons et al., 2005; Fahrig et al., 2011), creating more access to each landscape structure. Moreover, measurements for physical characteristics and spatial pattern are correlated with each other. For example, different land cover patches with more complex shapes not only increases the edge length but also increases the interspersion index, improving the flow of ecological processes between two potentially complementary landscape structures (Brotons et al., 2005).

2.2.3 Landscape Simplification

Despite the important ecological meaning of both compositional and configurational heterogeneity of non-production perennial vegetation, they are difficult to manage in practice (Fahrig et al, 2011). In other words, while farmers have options to either maintain perennial vegetation or move them out of fields, they cannot determine the spatial occurrence of these natural landscape structures; for example, wetlands usually need a lower topography to accumulate more water. Therefore, the overall trend of agricultural landscape management has resulted in the loss of perennial vegetation and other natural landscape structures in the fields. This process is called ‘landscape simplification’, which leads to landscape homogeneity—the opposite of landscape heterogeneity. Landscape simplification is mainly caused by two specific practices: fragmentation and/or removal of landscape structures; and amalgamation of small fields into a big one (Tscharntke et al., 2005). From 1961 to 1996, the production of food doubled; yet the area of arable land only increased 10% globally (Tilman, 2014), indicating a large possibility that farmers simplified their fields to favour more cropland in their existing fields by trading perennial vegetation for crop fields (Lambin et al., 2001). Landscape simplification happens at different spatial scale. Within fields, monocultures took place of polycultures to favor higher productivity and effective weed control (Landis, 2017). At the landscape scale, economic forces drove regional specialization on crops and farm consolidation, leading to the simplified mixture of crop and non-production perennial vegetation (MacDonald et al., 2013).

To maximize profit, farmers may remove some landscape features located in the center of their cropland to enlarge their cropland area and enhance efficiency (Benton et al., 2003) while other farmers have converted NPPV to arable fields (Matson et al., 1997; Tilman et al., 2002; Swift et al., 2004). For example, natural forest patches and semi-natural grassland (Vandermeer et al., 1998) can be removed, small and wetlands can be drained (Whilde, 1993). Some edge habitats like hedgerows and field boundaries were removed to allow efficient use of large machinery across fields (Westmacott and Worthington, 1984).

2.2.4 Ecological Compensation Area (ECA)

Ecological compensation is an extensive concept that encompasses methods that address the adverse ecological impacts of landscape homogeneity. It implies the creation, restoration, or enhancement of natural or semi-natural landscape structures to counterbalance landscape simplification (Wildlife and Traffic, 2003; Evert et al., 2010; Conway et al., 2013). Many countries have implemented ecological compensation programs at national-scales, such as the U.S. (EPA, 2008) and Germany (BMUB, 2010); or provincial-scale, such as in South Africa

(DEA&DP, 2007) and Australia (DNR&E, 2002), to address the loss of biodiversity and ecosystem services. As the forerunner in the ecological conservation, Swiss farmers are only provided access to government subsidy if they set aside 7% of their cropland as ecological compensation area (ECA) since 1999 (Herzog et al., 2001). The common characteristic or the essence of measures, like "Wetland Banking" in the U.S., "BushBroker" in the Australia and "Compensation Pools" in Germany, are to rebuild the lost non-production perennial vegetation somewhere else. This type of ecological compensation policy is likely to be bought-in by farmers or developers to get planning permission (Wildlife and Traffic, 2003). It turned out that their ecological policy goals were hardly met because of the lack of integration with landscape planning and commensurability of ecosystem functions in the countries mentioned above. Regardless, the replacement of wetlands has been slowly improving in recent studies (Hill et al., 2013). Unlike other countries, Switzerland maintains ecological compensation areas in their field by local farmers who attempted to be qualified to payments and additional incentives. Interestingly, farmer participation is particularly high (Herzog et al., 2001). Studies have shown that Swiss standard of keeping 7% of cropland as ecological compensation area is an effective approach to restore and/or increase biodiversity of plants, arthropods and small mammals (Herzog et al., 2005; Aschwanden et al., 2007; Albrecht et al., 2010).

2.4 Landscape Metrics

Landscape heterogeneity is used as a surrogate for biodiversity and landscape metrics are used as a proxy of species richness in some landscape ecology studies (Rossi and van Halder, 2010; Walz, 2011; García-Llamas et al., 2018). In order to quantify the landscape heterogeneity, landscape metrics are used to analyze landscape patterns to assess the level of landscape heterogeneity. Landscape metrics are used to quantify the landscape composition (e.g., the variety, richness or abundance of land cover types) and landscape configuration (e.g., the spatial arrangement, position of land covers within the quarter section) of landscape structures (McGarigal, 2014; McGarigal, 2015). Researchers can generate information on the physical characteristics and ecological relationships of landscapes with landscape metrics. While ecologists have already d.0eveloped many different metrics to represent this, more landscape metrics continually get proposed (Uuemaa et al., 2009).

Among the many software packages that calculate landscape metrics (McGarigal & Marks, 1995), Fragstats is one the most frequently used due to its comprehensive choice of landscape metrics and intuitive operating interface. Fragstats is a spatial pattern analysis program for quantifying the compositional and configurational heterogeneity (McGarigal, 2015). In addition to its convenience, Fragstats only quantifies spatial patterns and does not interpret the results and define the landscape automatically.

Landscape metrics can only represent the landscape pattern after researchers define two scaling factors - the spatial and thematic scale. Because the landscape is hierarchically comprised of patch mosaics, boundaries are needed to distinguish one patch type with another (McGarigal, 2015). Except for natural boundaries, patch boundaries in landscape studies can also be imposed by purpose and only have actual meaning when particular spatial and/or thematic scales are referenced to (Rossi and van Halder, 2010; García-Llamas et al., 2018).

Many researchers have proposed core sets of metrics or universal combinations of landscape metrics describing the general nature of a given landscape (Riitters et al., 1995; Herzog et al., 2001; Cushman et al., 2008; Schindler et al., 2008). With different study topic, those selection of landscape metrics are not universally applicable. It is researchers' responsibility to create the basis for depicting landscape structures and the scale for defining the landscape in order to answer their study objectives. In the following review, levels of landscape metrics, types of landscape metrics, scaling factors and common issues that may affect the interpretation of these metrics are covered.

2.4.1 Levels of Landscape Metrics

2.4.1.1 Patch Metrics

The landscape is composed of a mosaic of patches, which is usually referred to as the basic units that make up a landscape. The definition of a patch is dependent on researchers' interests or research topics. If the impact of climate on landscape heterogeneity is investigated, each natural land cover would be a targeted patch in one landscape. If the research question relates to identifying how farming practices affect landscape heterogeneity, then there is no need to calculate the changes that happened within natural perennial vegetation. In this case, the natural 'patches' mentioned in the first condition would be aggregated artificially to one large 'patch' to address the different research questions. In other words, patch boundaries are defined by researchers and are only meaningful concerning a particular spatial scale and thematic scale. For example, a naturally occurring wetland could include multiple vegetation types along the slope/water gradient in an arable landscape. From the centre of a wetland and moving outwards, one might discover distinct zones of open water, shallow aquatic plants, cattails, wetland grasses, shrubs, trees, and finally cultivated annual crops. Depending on the goal of the researcher, each of these vegetation features could be mapped independently or grouped together. Otherwise, patches are dynamic and occur at multiple scales (McGarigal & Marks, 1995). In Fragstats 4.2 (McGarigal, 2015), there are many metrics that can be calculated at the patch level. Patch metrics assess spatial characteristics for every patch in the landscape regardless of their land cover/land use types. Patch metrics are less used in landscape studies because researchers seldom need details about each patch; however, they have two primary applications: (1) they can serve as the fundamental metrics contributing to further calculations (Pôças et al., 2011); and (2) they can measure each patch and support better understanding of the ecological interpretation of land use and land cover (Crews-Meyer, 2004).

2.4.1.2 Class Metrics

Unlike the patch level metrics, which calculate properties such as the number and average size of each patch within a landscape, class level metrics represent the aggregate properties of the patches belonging to a single class or patch type. For example, for a class of wetlands, one may calculate the total number of wetland patches in each area, their mean size and percentage of the study area they occupy. Most patch level metrics have counterparts at the class and landscape levels. For example, many of the metrics at class level (e.g., mean shape index) represent the same basic information as the corresponding patch metrics (e.g., patch shape index). Still, instead of considering a single patch, they consider all patches of a single type simultaneously. In class level metrics, compositional metrics are frequently used; specifically, the metrics that calculate the number of types of patches within a given landscape and the percentage the landscape comprised of the corresponding patch type are only available under class level. Since different species occupy different ecological niche and habitats (Tscharntke et al., 2005), it is reasonable to use the class level compositional metrics to assess the relevant biodiversity (Foster et al., 1997; Fauth et al., 2000; Kumar et al., 2006; Kumar et al., 2009). Some researchers have combined some compositional metrics to form a new index in order to represent better farm-scale biodiversity (Quinn et al., 2013). Configurational metrics are commonly used in studies that investigate spatial or temporal changes of land use/land cover (Hietala-Koivu, 1999; Zhang et al., 2004; Brown & Schulte, 2011; Lamine et al., 2017) or global tendency, for example, the impact of urbanization on landscape heterogeneity (Herold et al., 2002; Burton & Samuelson, 2008; Geri et al., 2010; Li et al., 2017).

2.4.1.3 Landscape Level Metrics

Landscape level metrics are computed for the entire landscape, where many of these indices are derived similarly as patch or class metrics. Therefore, many class and metrics at the landscape level are calculated from patch and class metrics by simply summing and averaging over all patches or classes (McGarigal, 2015). Meanwhile, it is important to recognize that not all metrics may be calculated at all three levels; for example, diversity metrics are only available at the landscape level. Metrics at landscape level are popular in landscape ecology studies, such as evaluating land cover/land-use changes (Fu et al., 2006; Burton & Samuelson, 2008; Brown & Schulte, 2011) and biodiversity (Kumar et al., 2006; Kumar et al., 2009; Belfrage et al., 2015), because only metrics at landscape level can quantify the characteristics of studied landscape.

Despite the many metrics from different levels representing the same structural information, the methods for calculating the parameters differ. Class level metrics quantify the spatial pattern within a landscape of a single patch type, whereas metrics at landscape level calculate the spatial patterns of the entire landscape pattern. Thus, they have different meanings and interpretations. Most metrics at class level can be explained as 'fragmentation indices' because they measure the configuration of a particular patch type. In contrast, most of the metrics at landscape level can be interpreted as landscape heterogeneity indices as they represent the overall landscape pattern (McGarigal & Marks, 1995).

2.4.2 Types of Landscape Metrics

Landscape metrics are classified by the aspects of landscape they quantify. In this review, area and edge metrics, shape metrics, and aggregation metrics were covered in detail; core area metrics, contrast metrics, and diversity metrics could be further referred in 'Fragstats. 4.2 Help' (McGarigal, 2015).

2.4.2.1 Area and Edge Metrics

This group of metrics quantifies the size of patches and the amount of edge created by patches. Patch size metrics are the most basic and useful information embedded in the landscape and are most frequently used (McGarigal, 2014). Because patch size metrics are structural indices that provide the fundamental knowledge of a landscape like representing the dynamics of landscape heterogeneity. For example, Percentage of Landscape is the proportion of each class relative to the entire landscape; therefore, it is sensitive to any changes happened in landscape composition. It is extensively calculated in studies of detecting landscape heterogeneity changes (Hietala-Koivu, 1999; Fu et al., 2006; Brown & Schulte, 2011; Lamine et al., 2017). In addition, patch size metrics could explain biodiversity level and ecosystem services by patch occupancy, species richness, and distribution. For example, Percentage of Landscape is a metric that is strongly correlated with the abundance of female cowbirds and indigo buntings (Fauth et al., 2000); Mean Patch Size is a metric that significantly associated with deer vulnerability to harvest (Foster et al., 1997) and the count of Yellow-bellied Glider (McAlpine et al., 2002). Mean Patch Size is also proved to be critical for representing geometry and arrangement of patches (Herzog & Lausch, 2001). Both Mean Patch Index and Largest Patch Index are used to examine the interaction between landscape heterogeneity and carbon stocks (Ren et al., 2013).

Patch size can also be characterized by its spatial extent or reach. This is known as Radius of Gyration, which measures how far across the landscape a patch extends its reach on average and is given by the mean distance between cells in a patch. In an ecological sense, the Radius of Gyration represents the average distance that an organism could travel across a landscape from a random start point. From a geometric perspective, when all other factors are equal and the area of the patch is held constant, the higher the Radius of Gyration, the further a patch is stretched out (McGarigal, 2015). As a measure of the extent of patches, Radius of Gyration is used in many biodiversity studies (Schindler et al., 2008; Nichol et al., 2017).

Edges are the boundaries between different categories of patches within the landscape. At a patch level, edge metrics measure the perimeter of each patch; at the class level and landscape level, edge metrics measure the total length of the edge of the targeted patch type or the entire landscape, respectively (McGarigal, 2014). As a measure of configurational heterogeneity, higher edge value in a landscape means the spatial pattern of the given landscape is more complex. Edge metrics are also ecologically important as metrics like Edge Density, the length of edge per unit area, is highly correlated with some bird species (Fauth et al., 2000) and insect species (Radeloff et al., 2000). Therefore, edge metrics are frequently used to assess biodiversity level (Bailey et al., 2007; Schindler et al., 2008; Ramezani et al., 2010 Clément et al., 2017; Nichol et al., 2017).

2.4.2.2 Shape Metrics

Shape metrics measure the geometry of the patches. It is difficult to appropriately represent the 'shape' of patches because the shape is morphologically random, and there are infinite possibilities of patch shapes (McGarigal, 2014). Generally, it is feasible to use a computer to calculate the shape as a morphological property; however, comparing unique shape or morphology is meaningless. Hence, the emphasis of shape is moved onto geometric complexity and its comparison among patches and landscapes (McGarigal, 2015).

Due to its simplicity, the Perimeter-Area Ratio is extensively applied in the early landscape ecology studies (Buechner, 1989; Helzer & Jelinski, 1999; Gabriel et al., 2005). As illustrated by Carlos (1998), the Perimeter-Area Ratio should not be used as the only metric in the fragmentation measurement. The problem with this metric as a measurement of shape complexity is that it changes unpredictably with the size of the patch. By measuring the complexity of patch shape compared to a standard shape (square) of the same size, the Fractal Dimension Index does not have the same drawback. Thus, the Fractal Dimension Index is widely applicable in landscape ecological research. In addition to the influence in small animal migration (Buechner, 1989) and woody plant colonization (Hardt and Forman, 1989), the primary usage of shape metrics concerns the 'edge effect' (Parker & Meretsky 2004; Zeng & Wu, 2005; Li et al., 2013). As shape metrics delineate the geometric complexity, it is natural that they are used to detect dynamics or quantify the changes of landscape heterogeneity (Herold et al., 2002; Fu et al., 2006; Brown & Schulte, 2011; Lee & Huang, 2018).

2.4.2.3 Aggregation Metrics

McGarigal (2015) uses aggregation metrics as an umbrella term to describe four closely related concepts that comprise of the landscape texture: 1) dispersion, 2) interspersion, 3) subdivision and 4) isolation. Both of those concepts are related to the aggregation but are slightly different from each other in meaningful ways.

Dispersion refers to the spatial distribution of a patch type without explicit reference to any other patch types—it explains how dispersed a patch type is. Interspersion explains how often each patch type is adjacent to each other patch type and not by the size, contiguity, or distribution of others. As patch types become more dispersed, they also tend to be more interspersed among other patch types. Interspersion is considered to be critical in terms of preserving or enhancing the quality of habitat because different patches provided by a high level of interspersion make it possible for creatures to find their ideal habitats during their various life stages, which contributes to landscape compensation (Tscharntke et al, 2005).

Subdivision refers to the degree to which patch types are broken up into individual patches. Isolation and aggregation are closely related concepts. Isolation exclusively deals with the degree to which patches are spatially isolated from each other, whereas subdivision does not address the distance between patches. Both subdivision and isolation would lead to habitat loss and fragmentation. These types of disaggregation may lead to reduced dispersal success and patch colonization rates, then further threaten the conservation of biodiversity (With, 1999), and eventually damage the dynamic balance of local ecosystems (Saunders et al.,1991).

Among the Aggregation Metrics, the most frequently used ones are Clumpiness Index, Interspersion and Juxtaposition Index, Aggregation Index, Number of Patches, Patch Density, Contagion, and Patch Cohesion Index. Aggregation metrics are widely used in ecological studies (Kumar, et al., 2006; Burton & Samuelson, 2008; Kumar et al., 2009; Ren et al., 2013), and landscape heterogeneity studies (Griffith et al., 2000; Li et al., 2001; Egbert et al., 2002; Zhou et al., 2008; Midha & Mathur, 2010; Li et al., 2017). With regards to isolation metrics, Euclidean Nearest Neighbor Distance is the simplest measure. It calculates the shortest distance between two patches to quantify patch isolation. Therefore, Euclidean Nearest Neighbor Distance is also widely used to assess fragmentation in landscape ecology studies (Foster et al., 1997; Kumar et al., 2006; Kumar et al., 2009; Geri et al., 2010; Ren et al., 2013).

2.4.2.4 Core Area Metrics

The core area refers to the interior area of patches after users define an edge buffer. The edge buffer stands for the distance at which the 'core area' would not get affected by the edge of the patch caused by interaction with adjacent patches (Millington et al., 2003; McGarigal, 2014). The core area has been found to be a much better indicator of habitat quality than patch area in some cases (Laurance & Yensen, 1991). Aside from evaluating the level of biodiversity (Foster et al., 1997), they are mainly used to calculate habitat loss and landscape fragmentation (Strittholt & Delasala, 2001; Millington et al., 2003; Geri et al., 2010; Pătru-Stupariu et al., 2017).

2.4.2.5 Contrast Metrics

Contrast refers to the relative difference of land covers among patch types. For example, in an agricultural landscape, the edge contrast between a patch of woodlot and a patch of forest is smaller than the one between a patch of cropland and a patch of anthropogenic landscape like oil wells. The boundary between patches can function as a barrier to some species traveling but is permeable for other species (Wiens et al. 1989, Hansen & Castri 1995). Some species, like the owl (Species epithet from Dunning) prefers patch types with highly contrasting edges (Dunning et al., 1992). Compared with other metrics, contrast metrics are less used in landscape heterogeneity studies.

2.4.2.6 Diversity Metrics

Diversity metrics are a set of compositional metrics that calculate richness and evenness at the same time. Richness represents how many patch types are within a landscape; evenness calculates the relative abundance of different patch types, typically emphasizing the spatial dominance. The two most extensively used metrics are Shannon’s Diversity and Simpson’s

Diversity. Some studies that investigate geo-diversity prefer Shannon's diversity over Simpson's Diversity because Shannon's Diversity is more sensitive to the presence of rare landscape habitats (Burton & Samuelson, 2008; Belfrage et al., 2015; Li et al., 2017). In some studies that assess biodiversity, Simpson's Diversity is preferred to avoid rare habitats that may not provide biodiversity (Kumar et al., 2006; Kumar et al., 2009). In some cases, Simpson's Diversity and Shannon's Diversity are used at the same time (Schindler et al., 2008).

2.4.3 Scaling Factors

Scaling factors refer to spatial scale and thematic of studied landscape. Some studies focused on the influences of disturbances on the landscape within a broader landscape scale (Lloret et al., 2002; Miller & Thode, 2007), other studies, however, may look at how individual species respond to farming practices within a smaller local scale (Bajgai et al., 2015; Zhao et al., 2015). The scale of observation depends on the objective of the study (Turner & Gardner, 2015). Since it is impossible to find a generally suitable set of metrics to address all research questions (Riitters et al., 1995; Herzog & Lausch, 2001; Schindler et al., 2008), metrics should be selected with reference to the research objectives and study questions. The researcher must define their landscape, including the spatial scale of the landscape and thematic scale of the landscape, prior to metrics selection and calculation. Using an inappropriate combination of spatial and thematic scale could result in misinterpretation of the landscape metrics and eventually wrong conclusions (Símová & Gdulová, 2012).

2.4.3.1 Spatial Scale of the Landscape

Spatial scale encompasses grain and extent (McGarigal, 2015). In defining a landscape to address specific study questions, the grain is the smallest unit of spatial scale possible within a given data set. From an organism-centered/ ecological perspective, the grain is the level of the resolution where the patch size becomes so subtle that the individual or species stops responding to it (McGarigal & Marks, 1995), representing "individual units of observation" (Wiens, 1989). Extent refers to the overall size or range of the study area under consideration (Turner & Gardner, 2015). Extent and grain define the upper and lower limits of resolution of a study (Wiens, 1989). However, the real landscape pattern cannot be concluded by assessing every square foot of studied landscape. Therefore, extrapolating the status of whole landscape from the sampled area is a common approach in landscape studies. Unfortunately, there is a good chance of reaching erroneous conclusions (McGarigal, 2015).

2.4.3.2 Thematic Scale of the Landscape

Thematic scale refers to the number of classes of landscape structures in a landscape. Thematic content refers to landscape structures encompassed in a landscape, which is defined by researchers. The underlying reason for defining the landscape structures is because the landscape is hierarchically comprised of patch mosaics. The boundaries that distinguish one patch type with others are imposed artificially. The essence of defining the thematic scale of a landscape is to determine the boundaries that separate targeted landscape structures. Although a natural boundary can be found between patches, the patches that are defined naturally might not be qualified to address the particular study questions. For example, the boundaries among patches inside agricultural landscape would be ignored if the impact of urbanization on agricultural landscape is investigated. Because of different study objectives, researchers should use different classification strategies to address their study questions. A small alteration in the number of classes or the categorizations of landscape structures could have extensive impacts on metrics calculations and eventually could result in the inappropriate interpretation of landscape metrics (Bailey et al., 2007; Buyantuyev & Wu, 2007).

2.4.4 Common Issues in the Use and Interpretation of Metrics

2.4.4.1 Landscape Metrics Redundancy

There is seldom a direct relationship between landscape metric and characteristics. Although there is a wealth of metrics depicting landscape heterogeneity, landscape heterogeneity only has two components – composition and configuration, and each component has a few aspects. In the landscape metrics proposed by researchers so far, there are only a few primary measurements, such as area, perimeter, and number of patches, that can be generated from a landscape directly, many other metrics are then derived from those basic indicators like patch size and perimeter. Some metrics are alternate ways of representing the same information (e.g., mean patch size and patch density); hence, inherent redundancy is generated. Those metrics are called empirically redundant metrics (McGarigal & Marks, 1995). Researchers may also end up with redundant metrics when the parameters they selected are statistically related. Because their study areas share some spatial properties, for example, all study area are held consistently, different aspects of landscape pattern would have the same statistic meaning (e.g., total edge and edge density).

To address landscape metrics redundancy, a core suite of metrics was attempted to be created or used to assess or predict landscape heterogeneity from considerable landscape metrics (Herzog & Lausch, 2001; Cushman et al., 2008; Schindler et al., 2008; Stefan et al., 2008). For example, a multivariate factor analysis was used (Riitters et al., 1995) to identify a small set of metrics which can depict the critical dimensions of landscape pattern. Their results showed 6 univariate landscape metrics which were average perimeter-area ratio, contagion, standardized patch shape, patch perimeter-area scaling, number of attribute classes, and large-patch density-area scaling, explain 87% of the variation among 55 tested landscape metrics. However, different studies came up with different conclusions in terms of a universal set of landscape metrics. Taking the fast-growing number of metrics into consideration, it is less likely that the researcher can find a set of metrics that can be applied in all studies. Ultimately, the choice of metrics relies on each research topic or researcher's interests (McGarigal, 2015).

2.4.4.2 Lack of framework for interpreting landscape metrics

The lack of framework for interpreting landscape metrics is an inherent problem in landscape studies involved with aerial photos and satellite images. The essence of both aerial photo and satellite image used in landscape studies is a snapshot of an area in a moment (McGarigal, 2015). Then the properties of landscape captured in the aerial photos and satellite images were used to extrapolate the overall characteristics of general landscape. (Rashford, et al, 2011; Mantyka-Pringle, et al., 2019; Whitfield et al, 2021). If the studied area is expanded to a broader scale or moved to another area within the landscape, findings often differ. The same logic applies to the temporal changes. The categories of landscape features may vary seasonally or with disturbance events, both natural and anthropogenic. For example, if the aerial photos that people used to quantify the landscape heterogeneity are taken during a natural disturbance like extremely high precipitation, it is not accurate to calculate landscape metrics based on this dataset to provide ecological recommendation. As aerial photos only capture a flash moment of landscape, and the landscape in that moment was used to deduce the landscape heterogeneity on a broader scale and more extended temporal period, a baseline framework for interpreting landscapes is needed. Therefore, it is logical to investigate the metrics that represent the underlying natural landscape heterogeneity. Then researchers can use it as baseline data, making a comparison between it with our calculated parameters by which a more meaningful interpretation would be produced (McGarigal, 2015). Failure to understand the behavior of the metrics can result to erroneous interpretations (Jaeger, 2000). Despite the recognition that a reference framework is needed, there is a relative lack of historical satellite imagery to inform empirical studies (McGarigal, 2014).

2.4 Saskatchewan

The agricultural region of Saskatchewan was selected for our study area for its unique landscape and its prosperous organic agricultural production. The following two sections covered characteristics of Saskatchewan agricultural landscape and agriculture production in Saskatchewan.

2.4.1 Landscape Characteristics in Prairies

Saskatchewan is a landlocked province of Canada, which is bordered on the west by Alberta, on the north by the Northwest Territories, on the east by Manitoba, and on the south by the United States (Fig. 2).

Saskatchewan is classified by four ecozones – Prairies, Boreal Plains, Boreal Shield, and Taiga Shield (Wiken, 1986). On a provincial scale, Saskatchewan is further classified by 12 ecoregions based on distinctive regional ecological factors, including vegetation, climate, and soils (Acton et al., 1998; Omernik, 2004). Four ecoregions dominate the agricultural landscapes of Saskatchewan: Boreal Transition, Aspen Parkland, Moist Mixed Grassland and Mixed Grassland (Fig. 3). The Boreal Transition is most unique as it is an ecological land classification under the ecozone of Boreal Plain, the other three ecoregions belong to the ecozone of Prairie, it marks the southern limit of closed boreal forest and northern advance of arable agriculture (Acton et al., 1998). It has the lowest average temperature and the most precipitation. From the Aspen Parkland in the northeast of the Prairies to Mixed Grassland in the southwest of Prairie, the average of both temperature and precipitation are higher. Table 1 summarizes the distinctive key features of each ecoregion in the south Saskatchewan (Action et al., 1998).

There are more than 10 types of surface expressions recorded in Saskatchewan, according to the provincial soil surveys found within the Canadian Soil Information Service. Among them, hummocky and undulating are especially important as they are the dominant surface expression in agricultural landscape in Saskatchewan (Fig. 4). Hummocky landscape is a complex and irregular cluster of steep slopes extending from knolls to somewhat rounded depressions; undulating landscape is regular sequence of gentle slopes extending from smooth rises to rounded concavities (Canadian Soil Information Service, 2013).

2.4.2 Agriculture

There are 459 urban municipalities, 296 rural municipalities, and 24 north municipalities (Saskatchewan Ministry of Municipal Relations, 2012). Restricted by landscape characteristics, the population and agricultural production mainly clustered in the southern half of Saskatchewan. According to the report, 'Saskatchewan remains the breadbasket of Canada' (Statistics Canada, 2017), field crops accounted for 90.7% of total cropland in Saskatchewan, it supports more than two-fifths of Canada's total field crop acreage with 36.7 million acres, more than Alberta and Manitoba combined. From 2011 to 2016, field crop production area rose by roughly 5 million acres. Oilseed and grain production accounts for more than 60% of all agricultural operation types. The leading field crop is canola, followed by spring wheat and lentils.

In addition to its irreplaceable agricultural production in general, Saskatchewan also had dominant organic production. Released in September 2019, report of 'Organic Agriculture in the

Prairies' illustrated irreplaceable position of Saskatchewan in organic agriculture production in Canada (Canada Organic Trade Association, 2020). Despite a slightly decrease in 2019, Saskatchewan still accounted for 60% of organic acres in the Prairie Canada, making it take 30% of Canada's total organic acreage. Other than its significant organic production area, it was also reported that the number of organic operations in Saskatchewan increased by 19% from 2015 to 2019; the number of organic crop producers grew by 23% from 2013 to 2018.

Compared to the Canadian Provinces of Ontario and Quebec, there are fewer published studies that have investigated the landscape ecology or sustainable agricultural studies in Saskatchewan and most studies are too old to be referred for the updated agricultural landscape (Pennock & Kessel, 1997; Jowkin & Schoenau; 1998; Fitzsimmons, 2003; McMaster et al., 2005), thus it is difficult to confirm if agricultural intensification happened in other agricultural production areas in Canada is the same case in Saskatchewan agricultural landscape. Despite the lack of relevant studies in this area, an increased average farm size and decreased the number of farms is reported in 2016 Census of Agriculture. Moreover, the Shelterbelts mapping study in Saskatchewan suggested that the lengthen of Shelterbelts remined stable in the period 2001-2009, but the order of Shelterbelts trees dramatically reduced (Amichev, et al., 2015). Under the big picture of global landscape simplification happened in agricultural landscape, the result of 2016 Census of Agriculture and the reduced order of Shelterbelts trees suggest the similar simplifying processes is happening on one of largest agricultural production area in Canada.

2.5 Research Gaps

Conventional agriculture has less dependence on landscape ecology as it receives many external inputs to boost field production (Ponisio & Kremen, 2016) and manage fields (Mortensen et al., 2012). Contrarily, under organic management, fields cannot be treated with synthetic pesticides, fertilizers like conventional agriculture does (McErlich & Boydston, 2013; Canadian General Standards Board, 2015). Organic agroecosystem, instead, is a semi-natural ecosystem that heavily relies on the ecosystem services and biodiversity embedded in the given landscape (Freibauer et al., 2004; Robertson et al., 2014; Bender et al., 2015). Organic agriculture generally provides a greater performance of ecosystem services and a higher biodiversity (Seufert & Ramankutty, 2017). However, the organic system is not a universal solution to all ecological issues, landscape heterogeneity also matters (Tscharntke et al., 2005). It has been shown that landscape heterogeneity is positively related to the performance of ecosystem services and the level of biodiversity (Walz & Syrbe, 2013). A landscape with higher landscape heterogeneity of habitats is more likely to have beneficial ecosystem services and a higher level of biodiversity (Kremen & Miles, 2012; Balzan et al., 2014; Deguines et al., 2014; Chiron et al., 2017). Unlike many other practices that are prohibited in the organic system, management of non-production perennial vegetation, like wetlands, is not listed on the organic regulations when this study began (Canadian General Standards Board, 2015). To achieve higher profit and efficiency, landscape simplification has taken places in many countries, causing serious decline in biodiversity (Tscharntke et al., 2005; Carlisle et al., 2019). Therefore, it is ecologically meaningful to investigate if farming systems affect landscape heterogeneity.

Landscape metrics are useful tools to quantify the landscape pattern and landscape diversity. Despite the convenience, landscape metrics also had inherent defects such as metrics redundancy and the potential to misunderstand the landscape by the lack of framework for interpretation (McGarigal, 2015). In addition, interpreting landscape metrics in different context is also critical. As discussed above in the landscape heterogeneity, farmer has limited abilities to choose where a perennial vegetation could exist, because perennial landscape structures are the results of natural revolution of specific geography (Tscharntke et al., 2005). Therefore, a hummocky landscape is likely to naturally provide a more diversified initial landforms as it is more topographically complex than undulating landscape and thus is likely to have higher landscape heterogeneity. The same statistic would lead to different ecological value on hummocky than it on undulating landscape. Creating a background for better understanding and interpreting landscape metrics in the Prairie landscape and following landscape ecology studies is beneficial in the long term.

Ecological compensation program has been adopted in many European countries. In Switzerland, maintaining 7% of cropland as Ecological Compensation Area (ECA) is mandatory for achieving official subsidy since last century and it successfully restored ecosystem services and biodiversity (Herzog et al., 2005; Aschwanden et al., 2007; Albrecht et al., 2010). It would provide local administration and Canadian organic standard policy makers an interesting standpoint to look into how different farming systems differ in maintaining perennial vegetation.

Most previous landscape conservation studies set study areas in European countries (Duelli & Obrist, 2003; Sjödin et al., 2010; Walz & Syrbe, 2013; Hiron et al., 2015). Meanwhile Saskatchewan has attracted less studies on its landscape, despite a vast area for agricultural production and the most organic operations in Canada. Given the underlying landscape simplification in Saskatchewan, for example, the shrinking number of order of shelterbelts trees (Amichev et al., 2015), a study investigating landscape ecology in the context of Saskatchewan is urgently needed.

2.6 Objectives and Hypotheses

Four objectives were set up to address the study gaps. Objective 1 aims at answering the main question that was found as a research gap: “will organic agriculture maintain higher landscape heterogeneity than conventional agriculture in general?” The maintenance status of Mixed Perennial Vegetation and Cultivated Lowland is addressed by Objective 2 and Objective 3, respectively. Objective 4 aims at capturing the impact of surface expression and ecoregions on agricultural landscape in Saskatchewan, Canada.

Objective 1: To investigate landscape heterogeneity in organic versus conventional farming systems.

Hypothesis: Organic agriculture will maintain a higher level of landscape heterogeneity than conventional agriculture. Because organic agriculture has been proved to include higher biodiversity in fields compared to conventional agriculture. As agricultural organisms need habitats to breed and shelter, higher biodiversity could reflect higher landscape heterogeneity.

Objective 2: To determine if organic fields contain more Mixed Perennial Vegetation than conventional fields.

Hypothesis: Mixed Perennial Vegetation is a complex of different perennial vegetation, which provides habitats to agricultural organism. Therefore, it is hypothesized that organic fields will have more Mixed Perennial Vegetation than conventional fields.

Objective 3: To determine if a higher proportion of lowland areas is cultivated on conventional farms as opposed to organic farms.

Hypothesis: Conventional farmers tend to farm more intensively than organic farmers. They are more likely to expand their production area by occupying lowland. Therefore, conventional fields would have more lowland area cultivated than organic fields.

Objective 4: To assess the influence of ecoregions and surface expression on landscape heterogeneity, providing a more solid framework for interpretation of landscape metrics.

Hypothesis: Landscape heterogeneity would be higher in the ecoregions with higher precipitation or moist climate. Landscape heterogeneity is higher in the hummocky surface expression than in the undulating surface expression.

Chapter 3: Methodology

This study consisted of 71 valid pairs of conventional vs. organic cropland located in 17 rural municipalities located in Saskatchewan, Canada. Each cropland is a quarter section represented as 800 m x 800 m. Comparisons between organic and conventional fields were made across two different surface expressions (hummocky and undulating landscape) and four different ecoregions (Boreal Transition, Aspen Parkland, Moist Mixed Grassland and Mixed Grassland) using 15 landscape metrics. Aerial images from FlySask2.ca were loaded into ArcGIS for manual mapping of landscape features. Four landscape structures - Cultivated Upland, Cultivated Lowland, Mixed Perennial Vegetation, and Shelterbelts, were digitized and rasterized for metrics calculation. Fragstats was then used to calculate landscape metrics for two main landscape structures: Cultivated Lowland and Mixed Perennial Vegetation. Principal Component Analysis (PCA) was first applied to explore metrics performance in different context and further reduce metrics redundancy. Pairwise comparison was used to investigate the overall differences in metrics between organic and conventional fields. Then boxplots were used to explore differences among ecoregions and surface expressions. A detailed description of site selection, landscape analysis, and statistical analysis follows.

3.1Study Area

Saskatchewan was selected as the background of our study areas because of the following reasons: i) it is one of the most important agricultural production areas in Canada and has the highest number of organic operations and the largest organic production acreage (Canada Organic Trade Association, 2020); ii) there were few studies investigating agricultural intensification in the Prairie Canada and it is inappropriate to apply study results from other areas due to different socio-economic context and climate; and iii) there was readily available information on farming systems and aerial photos in Saskatchewan, for example, maps of rural municipalities with organic information are accessible on some municipality websites.

3.2 Site Selection and Data Processing

Saskatchewan uses the Legal Land Location as their land registry system. In the Legal Land Location system, the largest unit of land is ‘township’, which is divided into 36, one square mile (approximately 2.6 km^2) squares known as a ‘section’. Each section can be further divided into four quarter sections, each being 0.25 mi^2 (0.64 km^2) of land, which can be divided into smaller legal subdivisions. As quarter sections generally represent the smallest management unit of agricultural land in Saskatchewan, they were used as the areal unit for this study. To represent a quarter section, a square areal unit (800 x 800 m) was used to keep the unit consistent in GIS and Fragstats 4.2.

The influence of farm management system (conventional vs. organic) on landscape heterogeneity was the primary factor of interest. Thus, neighbouring pairs of conventional vs. organic land needed to be identified. Conventional quarter sections predominate agricultural landscapes, thus confirming the location of organically managed quarter sections is the priority. Municipal maps are thematic maps provided by local administration; they display units of land ownership including owner name (and Crown land), roads, railways, pipelines, oil wells, waterways/bodies, and some municipalities indicate organically managed land). An inventory of municipal maps for the rural municipalities was first developed and assessed to determine if organically managed land was present on the map.

A secondary validation of organic status was conducted by evaluating the frequency of canola crops based on the Annual Crop Inventory from Agriculture and Agri-food Canada since 2009

(Statistic Canada, 2009). The designation of organic lands within a municipality is understood to be producer-driven, and therefore could be subject to error if the municipality was not notified if the land changed ownership or management practices. In 2009, most canola (99%) was grown in the Prairie Canada (Statistic Canada, 2009). After years of development of organic agriculture, certified organic canola production only occupied 20 acres of total canola production area in all of Saskatchewan (Guerra, 2017). Canola was thus specified as an indicator of conventional farming in Saskatchewan in this study, because canola is almost exclusively under conventional management and is widely cultivated across Saskatchewan. Quarter sections were disqualified from the selection if canola was found before the timing when aerial photos were taken. In this process, 20 pairs of sites were eliminated from the list because of the first reason covered above.

For each organic quarter section identified, an immediately adjacent conventional quarter section was identified for direct comparison. In this process, a total of 118 pairs of organic and conventional quarter sections were selected; 14 pairs were then removed from the list to avoid spatial autocorrelation. The removed quarter sections were either found in the same farm or located within two quarter sections away (1600 metres). Land use information and landscape features, such as homesteads, roads, railways, and larger water bodies were then identified in the targeted organic and conventional quarter sections based on the aerial photos from FlySaska2.ca. Croplands with landscape features mentioned above were then eliminated, as the area they occupied could confound the assessment of landscape features. In this process, nine pairs were removed because of non-crop field; three pairs were removed because of the existence of rivers and lakes; one pair was removed because road splits one quarter sections. According to the canola rotation information, 20 pairs were further excluded from the selection. The detailed process of selecting quarter sections and associated reasons is summarized in Table 2.

Created by Saskatchewan Geospatial Imagery Collaborative (SGIC), FlySask2.ca is a web browser-based interface that provides layers of political boundaries, including quarter section boundaries, and orthophotos from different times, making it possible to monitor temporal changes, as well as seasonal landscape features. In this study, FlySaska2.ca was used for searching, viewing, and downloading aerial photos in this study. Aerial photos of targeted quarter sections from year of 2008, 2012 and 2017 were downloaded at a 0.4 m spatial resolution. In the end, 71 pairs of quarter sections from 17 rural municipalities were validated based on these processes (Fig. 3 & 4).

3.3 Classification of Landscape Structures

The agriculturally managed landscape was divided into four thematic categories. Cultivated Upland, Perennial Mixed Vegetation, Cultivated Lowland and Shelterbelts (Table 3). Cultivated Uplands consist of land that are in annual crop production (or planted frequently in rotation cycle). To represent lands that were not being farmed, all non-production perennial vegetations were compounded to one studied landscape structure, Mixed Perennial Vegetation. Cultivated Lowlands referred to the cropland that were seasonally or constantly flooded, or converted from any non-production perennial vegetation. According to our assumption, there is a trade-off between Mixed Perennial Vegetation and Cultivated Lowland. For example, after removing the vegetation in a lowland area, the previous Mixed Perennial Vegetation becomes a Cultivated Lowland. Shelterbelts, unlike other landscape structures that were defined specifically for this study, represented a row of trees or shrubs that grow alongside the field boundaries, adjacent to roads and waterways, and inside fields (Agriculture and Agri-Food Canada, 2015).

As opposed to Mixed Perennial Vegetation and Shelterbelts, which had distinct boundaries separating them from other landscape structures, the boundaries of Cultivated Lowland were more difficult to identify on the aerial photos. Multiple years of aerial photos showing machinery tracks, vegetation type, presence of temporal water bodies, and soil color (grayscale) were used to identify patches of Cultivated Lowland. The exact shape of each Cultivated Lowland was highly irregular and kept changing over years or under different climate conditions (some years flooded, some years seeded, and to varying degrees). A detailed description and rationale regarding each landscape structure can be found in Table 3.

In addition, field edges, fence lines, Shelterbelts and other landscape structures that located in between organic and conventional quarter sections or along side the other edges of quarter sections were not counted in this study, because their ownership could not be identified. They could be managed by either side or both, thus it is unfair to categorize them into any side of farming systems.

3.4Landscape Structures Detection

ArcGIS Desktop 10.5 was used in the process of landscape structures digitization. Aerial imagery for each quarter section were loaded into ArcGIS where the landscape structures were manually digitized and classified. The farming equipment creates smooth and clear boundaries between interested landscape structures, making manual identification of landscape structures a feasible approach in this study. Although semi-automated approaches using supervised and unsupervised classification have been tested and were considered for this study (Rozenstein & Karnieli, 2011), the results could be noisy.

Avoiding bias was critical in landscape structures detection process. Each site-pair was assigned a unique identifier without indication of management system, allowing for a "blind" classification and analysis. In addition to the dataset itself, the processing steps were held consistent, not only to make sure there was no bias across farming systems, but also to guarantee the quality of digitized landscape structures remained the same. To ensure landscape structures were consistently delineated, the digitization process was carried out at a 1:300 map scale. This operating map scale was selected because farmers usually drive farming equipment around those landscape structures, creating smooth and clear boundaries between Mixed Perennial Land, and cropland, which made it intuitive to identify the patch of Mixed Perennial Land from the background of cropland. Moreover, the 1:300 map scale adequate to show the details on or around the boundaries, allowing us to draw outlines efficiently and accurately.

Unlike Mixed Perennial Vegetation and Shelterbelts, the shape of Cultivated Lowland was highly irregular and the patches of Cultivated Lowlands did not have clear boundaries defined by equipment operations. To assist with delineating Cultivated Lowlands, the following approaches were used: i) multiple years of aerial imagery were used to identify if the low lying areas was cropped, vacant, or flooded and the extent of those areas; ii) the Cultivated Lowlands were characterized by having a darker soil colour, since lowlands typically had a darker colour due to higher soil organic matter content and moisture, and iii) the track patterns of equipment were used. The outer edge of the Cultivated Lowland was subjectively identified based on the indicators above.

Except for the Cultivated Uplands, all other landscape structures were manually digitalized by polygons. Once Mixed Perennial Vegetation, Shelterbelts and Cultivated Lowland were identified and mapped in a quarter section, Cultivated Upland was created by erasing the layer of other three landscape features from the layer of quarter section. Following this, the layer of Cultivated Upland was merged with the layer that contained Mixed Perennial Land, Shelterbelts and Cultivated Lowland, creating a new layer with all the landscape structures digitized within the quarter sections.

All polygon of the landscape features, in the vector format, were then converted into a raster format needed for Fragstats 4.2. Considering the spatial resolution of the orthophotos was 0.4 m, and the mapping scale to digitalize the landscape structures was 1:300, the spatial resolution of output raster was set as 1 m, as it provided enough detail to calculate the various landscape metrics in Fragstats 4.2. Great care was taken during the rasterization process and the output raster was scrutinized for accurate representation of the original landscape structures.

3.5Metrics Selection and Calculation

As indicated in the literature review, there are challenges in using these metrics. First, some metrics measure both compositional and configurational heterogeneity at the same time. In addition, many landscape metrics are statistically or empirically correlated with each other, causing inherent redundancy (McGarigal, 2015). Using the smallest number of landscape metrics to quantify the landscape structures accurately and sufficiently is necessary for landscape studies. A set of metrics was chosen to calculate landscape heterogeneity (Table 4) based on the study area and research objectives.

The main objective of the research was to identify the difference in landscape heterogeneity between organic agriculture and conventional agriculture by assessing the landscape metric of landscape structures; hence, landscape metrics should reflect, assess, or explain the differences in landscape patterns between the management system. Thus, landscape metrics were chosen mainly because (1) they quantify the physical characteristics or spatial pattern of landscape structures, and (2) they are associated with ecosystem services and/or biodiversity.

Two levels of landscape metrics were applied in this study - class level and landscape level. Patch level metrics were not selected because the variation in between individual patches could not explain the influence of farming operation and thus, they were not included in this study. Each patch type (class) was studied because groups of landscape structures can reflect farmer's operation towards them as well as average values could be generated from the class level of landscape metrics. Meanwhile, some metrics, like diversity metrics, are only available in the landscape level.

The class level of metrics applied to Mixed Perennial Vegetation included (Table 4): Number of Patches (NP), Percentage of Landscape (PLAND), Mean Patch Size (AREA), Radius of Gyration (GYRATE), Fractal Dimension Index (FRAC), Euclidean Nearest Neighbor Distance (ENN), and Clumpiness Index (CLUMPY). Furthermore, the Number of Patches (NP), Percentage of Landscape (PLAND), and Mean Patch Size (AREA) were calculated for Cultivated Lowland (Table 4).

Shape metrics and aggregation metrics were not included in the metrics selection for both Shelterbelts and Cultivated Lowland, because their shape, spatial occurrence, and distribution were not controlled by farming management but by initial landform. Shelterbelts are anthropogenic landscape structure, their appearance in fields was decided neither by farming systems nor climate. To protect crop fields from wind erosion, Shelterbelts are built in multiple straight lines. Shelterbelts are a rare landscape structure created by farmers unlike Mixed Perennial Vegetation and Cultivated Lowland that can be found in most or even every landscape. Their spatial location was also ecologically and geographically meaningless as Shelterbelts were all planted in the similar or same spatial arrangement regardless of both abiotic and biotic factors. Therefore, only occurrence of Shelterbelts in different farming systems was recorded.

Cultivated Lowlands are a semi-natural landscape structure, whose boundaries are arbitrary as they change in different seasons or climate. Moreover, the spatial pattern of Cultivated Lowland is decided by the geography of landscape, which is not determined by farming systems. Therefore, describing the shape complexity and spatial pattern of both Shelterbelts and Cultivated Lowland in this study was not logical.

Contagion (CONTAG), Landscape Division Index (DIVISION), and Interspersion and Juxtaposition Index (IJI) were selected as the landscape level metrics (Table 4). In addition to the landscape metrics generated by Fragstats 4.2, one additional landscape metric was designed in this study to investigate how Cultivated Lowland differ in between organic and conventional systems in Prairie Saskatchewan. Unlike how Mixed Perennial Vegetation supports biodiversity and ecosystem services, Cultivated Lowland is frequently cropped by farmers but are likely to flood during the wet season. In other words, Cultivated Lowland mainly occur due to the combination of depressional topography and profit-motivated practices of farmers. Therefore, the ecological value of Cultivated Lowland is close to zero compared with Mixed Perennial Vegetation. However, comparing Cultivated Lowland directly between adjacent organic and conventional fields cannot reflect the true status of landscape simplification. Because neighboring fields share drastically different topology in some cases, comparing the absolute value of Cultivated Lowland could affect results in unknow directions. In this study, Cultivated Lowland was seen as the indicator of landscape simplification, the results of degradation from Mixed Perennial Vegetation. Therefore, assessing the trade-off between Mixed Perennial Vegetation and Cultivated Lowland could offer more rational results on the differences of impacts of farming systems on the management of Cultivated Lowland. This metric was calculated based on Percentage of Landscape (PLAND) of

Mixed Perennial Vegetation and Cultivated Lowland. A detailed algorithm and rationale are included in the Table 5.

3.6Statistical Analysis

As discussed in the literature review, one major limitation in using landscape metrics is the lack of background and context to appropriately interpret metrics. Therefore, understanding the impact of ecoregions and surface expression on the behaviour of these metrics is the first step. To explore the multicollinearity across the metrics and to explore which landscape metrics changed the most by looking at the variance contributed by the metrics in different ecoregions and surface expression, Principal Component Analysis (PCA) was applied as a form of exploratory data analysis.

Frequency table describing the dataset is presented in Table 6. Overall, there were 68 valid pairs of Mixed Perennial Vegetation comparisons, 13 valid pairs of Shelterbelts comparisons and 71 valid pairs of Cultivated Lowland comparisons in this study. A detailed distribution of the dataset with respect to the in four ecoregions and two surface expression is also shown in Table 6. Because of the random selection of candidate quarter sections, there was an unbalanced number of cases amongst ecoregions and surface expression (Table 6). Taking organic hummocky landscape as an example, there were 22 cases found in Moist Mixed Grassland, while only one case was found in Boreal Transition. The unbalanced design and lack makes the use of Analysis of Variance not applicable in analyzing the interactive effects of both surface expression and ecoregions on landscape metrics. Instead, boxplots were used to explore the differences in metrics between organic and conventional as well as the difference in the context of ecoregions and surface expression to investigate their impacts on the differences in landscape metrics between different farming systems. Pairwise comparisons between organic and conventional fields were used to identify any potentially significant differences. In this process, all cases were grouped into their surface expression and ecoregions classes.

Due to the restrictions caused by the lack of data and imbalanced classification of ecoregions and surface expression, only the direct comparisons between organic and conventional were conducted using statistical pairwise analysis. Quarter sections in one pair that shared different surface expressions and ecoregions were both removed from this process. The performance of landscape metrics could be highly irregular (McGarigal, 2015). Therefore, Shapiro-Wilks's normality test (α =0.05) was applied to all calculated metrics to test for normality in the difference of each metrics between organic and conventional system due to the pairwise experimental design (Table 7). Normal data were then evaluated using the Student Paired T tests with a 95% confidence level to detect the statistical differences in metrics between organic and conventional systems. Non-normal data were analyzed using a pairwise Wilcoxon Signed-Rank Test with 95% confidence level (Table 8).

Chapter 4: Results

In this chapter, the correlations among the landscape metrics for the Mixed Perennial Vegetation were first explored using principal components analysis. Following this, the differences in metric values between organic and conventional system were evaluated. Boxplots were first used to explore the difference of metrics in between organic and conventional system, followed by statistical pairwise analysis assessing the significance of difference. The influence of ecoregions and surface expression are observed using boxplots to further explore the differences in metrics between farming systems under different ecoregions and surface expression.

4.1 Shelterbelts

Shelterbelts were found in 13 of the 71 pairs of comparison. In those 13 pairs, only two conventional fields had Shelterbelts, the other 11 pairs had Shelterbelts on organic fields but no Shelterbelts on conventional fields. Thus, shelterbelts were found on 15.5% of organic fields and <3% of conventional fields. There was no further analysis of shelterbelts due to the limited and unbalanced sample size.

4.2 Principal Component Analysis

In this study, principal component analysis was used to explore the correlation among metrics of Mixed Perennial Vegetation prior to the pairwise comparisons, with the intention to identify the landscape metrics that contributed the most to the variance among farming systems, ecoregions, and surface expression.

In the PCA analysis of the pooled dataset for Mixed Perennial Vegetation, the confidence ellipse for the conventional and organic farming systems largely overlapped, however, the organic confidence ellipse was slightly more aligned with the Mean Patch Size, Radius of

Gyration, and Percentage of Landscape (Fig. 5a). The confidence ellipse for the conventional fields was aligned more with Number of Patches and Euclidean Nearest Neighbor Distance and to a lesser extent, Clumpiness Index (Fig. 5a).

The PCA for the Mixed Perennial Vegetation, when separated by ecoregion, resulted in a variety of confidence ellipses (Fig. 5b). The confidence ellipse for Mixed Grassland was smallest, suggesting lower variability. Boreal transition had the largest confidence ellipse suggesting greater variation but was especially aligned with Mean Patch Size or Radius of Gyration. Aspen Parkland also had greater variation but was more aligned with Number of Patches and Clumpiness Index (Fig. 5b). Mixed Grassland had the second smallest confidence ellipse, which was highly aligned with Euclidean Nearest Neighbor Distance (Fig. 5b).

When separated by surface expression, the PCA results for the Mixed Perennial Vegetation indicated that the confidence ellipse for hummocky was largely overlapped by confidence ellipse for undulating landscape, however, the confidence ellipse for hummocky landscape was more aligned with Percentage of Landscape and Radius of Gyration (Fig. 5c). The confidence ellipse for undulating landscape was more aligned with Number of Patches and Clumpiness Index (Fig. 5c).

In the context of surface expression under organic management, the Mean Patch Size and Percentage of Landscape contributed the most to the variance on undulating landscape while Number of Patches and Fractal Dimension Index contributed the most to variance on hummocky landscape (Fig. 6a). Under conventional management, however, all metrics contributed similarly to the variance of both surface expressions (Fig. 6b).

In the context of ecoregions under organic management, the Mean Patch Size and Percentage of Landscape contributed the most to the variance in Boreal Transition, Number of Patches and Fractal Dimension Index contributed the most to the variance in Aspen Parkland and Mixed Grassland, Number of Patches and Euclidean Nearest Neighbor Distance contributed the most to the variance in Moist Mixed Grassland (Fig. 7a). When separated by ecoregions under conventional management, the Mean Patch Size and Radius of Gyration contributed the most variance in Aspen Parkland and Mixed Grassland. Number of Patches and Euclidean Nearest Neighbor Distance contributed the most to the variance in the Moist Mixed Grassland ecoregion, Radius of Gyration and Percentage of Landscape contributed the most to the variance in Boreal Transition (Fig. 7b).

In general, the ellipses for both different surface expression and ecoregions had more areas overlapped in conventional fields than in organic fields. For example, the shape of ellipses for both undulating and hummocky fields was more elongated in organic fields than in conventional fields (Fig. 6); only a part of ellipsis for each surface expression overlapped in organic fields (Fig. 6a) while most area of ellipsis for hummocky and undulating landscape was overlapping in conventional fields (Fig. 6b). For ecoregions, the overlapping pattern was distinct between organic fields and conventional fields (Fig. 7).

4.3 Percentage of Landscape (PLAND)

4.3.1 Conventional Versus Organic Quarter Sections

4.3.1.1 Boxplots for Percentage of Landscape

Overall, the Percentage of Landscape of Mixed Perennial Vegetation was much higher on organic land than on conventional land with median values being 11.5% and 8% for organic and conventional, respectively (Figure 8a). Organic land had only a slightly wider distribution (range) of data for Percentage of Landscape of Mixed Perennial Vegetation than conventional Land (range). For the Cultivated Lowland, the Percentage of Landscape was significantly higher on conventional fields than organic fields, as more than 75% of conventional fields were greater than the median value of organic fields. Conventional fields also had a higher variation than organic fields (Figure 8b). For both the Mixed Perennial Vegetation and Cultivated Lowland, organic quarter sections had more outliers (Figure 8).

4.3.1.2 Pairwise Comparisons of Percentage of Landscape of Mixed Perennial Vegetation and Cultivated Lowland

According to the Shapiro-Wilk test ($\alpha = 0.05$), the difference in the Percentage of Landscape for both Mixed Perennial Vegetation and Cultivated Lowland and when comparing between organic and conventional system were normally distributed (Table 7). Significant differences in Percentage of Landscape were detected for both Mixed Perennial Vegetation and Cultivated Lowland between organic and conventional quarter sections (Table 8). The Percentage of Landscape of Mixed Perennial Vegetation was significantly higher in organic than in conventional quarter sections; in comparison, the Percentage of Landscape of Cultivated Lowland was significantly lower in organic than in conventional quarter sections (Table 8).

Approximately 48% of conventional cases had $\leqslant$7% of Mixed Perennial Vegetation on the land whereas 26% of organic cases had $\leqslant$7% of total landscape (Fig. 9). In other words, more organic fields had Mixed Perennial Vegetation exceeding 7% of total landscape than conventional fields. Moreover, there were always more organic fields that had larger Percentage of Landscape of Mixed Perennial Vegetation than conventional fields (Fig. 9).

4.3.2 Organic Versus Conventional Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 10a. The median value of Percentage of Landscape (PLAND) of Mixed Perennial Vegetation was higher on organic land than conventional land in all ecoregions except for Mixed Grassland where there was no difference (Fig. 10a). In both Aspen Parkland and Moist Mixed Grassland, more than 75% of organic cases were larger than the median value of conventional cases. In Mixed Grassland, the median and interquartile range were both smaller for organic fields than conventional fields. In Boreal Transition, the range between two whiskers was significantly longer for organic fields than for conventional fields (Fig. 10a). Overall, the Percentage of Landscape of Mixed Perennial Vegetation tended to be higher on Aspen Parkland, Boreal Transition than on Moist Mixed Grassland and Mixed Grassland.

The ecoregions are also presented from wetter and cooler to drier and warmer in Figure 10b. In all ecoregions, the median value of Percentage of Landscape (PLAND) of Cultivated Lowland was larger for conventional than organic fields; the interquartile range was significantly larger for conventional than organic fields, indicating a larger variation in conventional fields (Fig. 10b). The interquartile range for conventional fields was higher than the median for organic fields in all ecoregions except the Mixed Grassland, indicating that more than 75% of conventional cases were larger than the median value for organic fields. All outliers were found on organic fields, including two extreme outliers (Fig. 10b). Overall, the Percentage of Landscape of Cultivated Lowland was higher on Aspen Parkland and Moist Mixed Grassland than on Boreal Transition and Mixed Grassland.

4.3.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared by surface expression, the Percentage of Landscape for Mixed Perennial Vegetation and Cultivated Lowland both had a larger median value on hummocky landscape than on undulating landscape despite limited differences. On both hummocky and undulating landscapes, organic quarter sections tended to have a higher Percentage of Landscape of Mixed Perennial Vegetation and a lower Percentage of Landscape of Cultivated Lowland than conventional fields based on median values and interquartile ranges (Fig. 11).

4.4Number of Patches (NP)

4.4.1 Conventional Versus Organic Quarter Sections

4.4.1.1 Boxplots for Number of Patches

The median the Number of Patches of Mixed Perennial Vegetation was slightly larger for organic than conventional fields with the median value being 5 and 4 for organic and conventional fields, respectively (Fig. 12a). The median of the Number of Patches of Cultivated Lowland was similar between two farming systems (Fig. 12b). The interquartile range of Number of Patches of both Mixed Perennial Vegetation and Cultivated Lowland was larger for conventional fields than organic fields, indicating larger variation on conventional sites. For both Mixed Perennial Vegetation and Cultivated Lowland, the Number of Patches had more extreme values in organic fields (Fig. 12). Overall, the Number of Patches of Mixed Perennial Vegetation was larger and had less variation in organic than in conventional fields; the Number of Patches of Cultivated Lowland was similar between organic and conventional fields; however, there was larger variation on the conventional fields.

4.4.1.2 Pairwise Comparison of Number of Patches of Mixed Perennial Vegetation and Cultivated Lowland

According to the Shapiro-Wilk test ($\alpha = 0.05$), the difference in the Number of Patches (NP) for Mixed Perennial Vegetation and when comparing between organic and conventional system was normally distributed; but the difference of Number of Patches of Cultivated Lowland was not normally distributed (Table 7). The Number of Patches of Mixed Perennial Vegetation was further compared between farming systems using a paired T test; the Number of Patches of Cultivated Lowland was further compared for farming systems by Wilcoxon Signed Ranks Test. No significant difference in the mean Number of Patches of Mixed Perennial Vegetation by pairwise comparison was measured between organic and conventional quarter sections but there were significantly more patches of cultivated lowland on conventional land (Table 8).

4.4.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 13. When compared by ecoregions, the Number of Patches of both Mixed Perennial Vegetation and Cultivated Lowland shared similar pattern, they were larger on the ecoregions that were wetter and cooler based on the median value and interquartile range except in the Boreal Transition. In the Boreal Transition zone, both the Number of Patches of Mixed Perennial Vegetation and Cultivated Lowland had extremely low median value and small variation. The Moist Mixed Grassland zone had the most extreme values in all cases combined (Fig. 13). For the Mixed Perennial Vegetation, the Number of Patches was larger in organic than conventional quarter sections in Boreal Transition and Moist Mixed Grassland, but smaller in organic than in conventional quarter sections in Aspen Parkland and Mixed Grassland (Fig. 13a). For the Cultivated Lowland, the Number of Patches was larger in conventional than in organic quarter sections from Boreal Transition, Aspen Parkland, and Moist Mixed Grassland, but slightly smaller on conventional fields in the Mixed Grassland zone (Fig. 13b).

4.4.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared between surface expression, the Number of Patches of Mixed Perennial Vegetation and Cultivated Lowland both had a larger median value and variation on hummocky landscape than on undulating landscape. On both hummocky and undulating landscapes, organic quarter sections tended to have higher Number of Patches of Mixed Perennial Vegetation and lower Number of Patches of Cultivated Lowland than conventional fields based on median values and interquartile ranges (Fig. 14).

4.5Mean Patch Size (AREA_MN)

4.5.1 Conventional Versus Organic Quarter Sections

4.5.1.1 Boxplots for Mean Patch Size

The median value of Mean Patch Size of Mixed Perennial Vegetation was slightly higher for organic than conventional field with median values being 1.5 hectares and 0.8 hectares for organic and conventional, respectively (Fig. 15a). The interquartile range was similar between two farming systems. More than 75% of organic cases were larger than median value for conventional fields (Fig. 15a). Overall, the Mean Patch Size of Mixed Perennial Vegetation was higher on organic than on conventional fields based on the median and maximum values.

The median value of the Mean Patch Size of Cultivated Lowland was slightly lower for organic than conventional fields with a median value of 1 hectare and 0.7 hectares for conventional and organic, respectively (Fig. 15b). The interquartile range and the range between two whiskers were both larger on conventional than organic fields, indicating a larger variation on conventional fields. Overall, the Mean Patch Size of Cultivated Lowland was lower for organic than conventional fields based on their median and maximum values.

4.5.1.2 Pairwise Comparison of Mean Patch Size of Mixed Perennial Vegetation and Cultivated Lowland

According to the Shapiro-Wilk test ($\alpha = 0.05$), the difference in the Mean Patch Size for Mixed Perennial Vegetation and Cultivated Lowland and when comparing between organic and conventional system were both non-normally distributed (Table 7). The Mean Patch Size of the Mixed Perennial Vegetation and Cultivated Lowland were further compared between organic and conventional quarter sections by Wilcoxon Signed Ranks Test. Significant difference were detected in Mean Patch Size of both Mixed Perennial Vegetation and Cultivated Lowland between organic and conventional quarter sections. Combined with the results of the mean values, the Mean Patch Size of Mixed Perennial Vegetation was significantly larger in organic quarter sections than in conventional quarter sections; the Mean Patch Size of Cultivated Lowland was significantly larger in conventional quarter sections than in organic quarter sections (Table 8).

4.5.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 16. When compared between ecoregions, the Mean Patch Size of both Mixed Perennial Vegetation and Cultivated Lowland shared similar pattern, they were larger on ecoregions that were wetter and cooler based on the median value and interquartile range. Both Mean Patch Size of Mixed Perennial Vegetation and Cultivated Lowland had extremely large variation in Boreal Transition. Both Aspen Parkland and Moist Mixed Grassland had more extreme values (Fig. 16). For Mixed Perennial Vegetation, the Mean Patch Size was larger in organic than conventional quarter sections in most ecoregions except Boreal Transition (Fig. 16a). For Cultivated Lowland, the Mean Patch Size was larger in conventional than in organic quarter sections from Boreal Transition, Aspen Parkland, and Moist Mixed Grassland ecoregions, but slightly smaller on conventional quarter sections in the Mixed Grassland ecoregion (Fig. 16b).

4.5.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared between surface expression, the Mean Patch Size of Mixed Perennial Vegetation and Cultivated Lowland both had larger median value and variation on undulating landscape than on hummocky landscape. On both hummocky and undulating landscapes, organic quarter sections tended to have higher Mean Patch Size of Mixed Perennial Vegetation and lower Mean Patch Size of Cultivated Lowland than conventional fields based on median values (Fig. 17).

4.6Cultivated Lowland/Total Lowland (CL/TL)

4.6.1 Conventional Versus Organic Quarter Sections

4.6.1.1 Boxplot for Cultivated Lowland/Total Lowland

The median value of Cultivated Lowland/Total Lowland was larger for conventional than organic fields with median value being 0.55 and 0.30 for conventional and organic, respectively. The interquartile range was also larger for conventional than organic fields, indicating a larger variation on conventional fields; nearly 75% of conventional cases were larger than organic median value. Overall, Cultivated Lowland/Total Lowland was larger for conventional than organic fields.

4.6.1.2 Pairwise Comparison of Cultivated Lowland/Total Lowland

According to the Shapiro-Wilk test ($\alpha = 0.05$), the difference in the Cultivated Lowland/Total Lowland comparing between organic and conventional system was non-normal data (Table 7). The Cultivated Lowland/Total Lowland was pairwise compared by Paired T test. Based on the mean, Cultivated Lowland/Total Lowland was significantly larger on organic than on conventional fields (Table 8).

4.6.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 40. The Cultivated Lowland/Total Lowland was higher on Moist Mixed Grassland and Mixed Grassland, but lower on Aspen Parkland and Boreal Transition. In other words, the Cultivated Lowland/Total Lowland was larger on drier and warmer ecoregions. The median value was larger for conventional than organic fields in all ecoregions. The interquartile range was larger for organic than conventional in Moist Mixed Grassland and Mixed Grassland, but larger for conventional than organic in Boreal Transition and Aspen Parkland. There was one extreme outlier found on organic fields in Boreal Transition, and another extreme outlier found on organic fields in Aspen Parkland (Fig. 40).

4.6.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared between surface expression, both organic and conventional fields had their median value larger on undulating landscape then on hummocky landscape, despite limited differences. The median value was larger for conventional than organic in both surface expression. The interquartile range was similar between organic and conventional on hummocky landscape, indicating a similar variation on hummocky landscape between two farming systems. The interquartile range was larger for organic than conventional in undulating landscape, indicating larger variation on organic undulating landscape. There were two outliers found on organic hummocky landscape (Fig. 41). Overall, Cultivated Lowland/Total Lowland was slightly higher on undulating landscape based on interquartile range and median values.

4.7 Shape Metrics of Mixed Perennial Vegetation

4.7.1 Conventional Versus Organic Quarter Sections

4.7.1.1 Boxplots

In general, both Shape Metrics were similar comparing between organic and conventional system. The Radius of Gyration of Mixed Perennial Vegetation was slightly larger on organic fields than on conventional fields based on the median values (Fig. 18). The difference in the Fractal Dimension Index of Mixed Perennial Vegetation was even less obvious comparing between organic and conventional systems (Fig. 21).

4.7.1.2 Pairwise Comparisons

According to the Shapiro-Wilk test ($\alpha = 0.05$), the difference of both Radius of Gyration and Fractal Dimension Index of Mixed Perennial Vegetation comparing between organic and conventional system was not normally distributed (Table 7). Thus, they were further compared between organic and conventional quarter sections by Wilcoxon Signed Ranks Test. There were no statistically significant differences detected in both Radius of Gyration and Fractal Dimension Index of Mixed Perennial Vegetation (Table 8).

4.7.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 19 and Figure 22. Both Radius of Gyration and Fractal Dimension Index of Mixed Perennial Vegetation displayed similar patterns among Prairie ecoregions. Boreal Transition either had the highest value of median and/or had the maximum value. Organic fields generally had higher median values than conventional fields except for Fractal Dimension Index of Mixed Perennial Vegetation in Aspen Parkland (Fig. 19 & Fig. 22).

4.7.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared between surface expression, the Radius of Gyration of Mixed Perennial Vegetation was larger on undulating than hummocky landscape based on median value (Fig, 20) while the Fractal Dimension Index of Mixed Perennial Vegetation was similar between hummocky and undulating landscape (Fig. 23). The interquartile ranges were both larger for undulating than hummocky landscape. Overall, organic fields had slightly higher values in both Shape Metrics (Fig. 20 & Fig. 23).

4.8Aggregation Metrics of Mixed Perennial Vegetation

4.8.1 Conventional Versus Organic Quarter Sections

4.8.1.1 Boxplots

Both Euclidean Nearest-Neighbor Distance and Clumpiness Index of Mixed Perennial Vegetation were similar comparing between organic and conventional. Interquartile ranges were both larger for conventional fields than organic fields. (Fig. 24 & Fig. 27).

4.8.1.2 Pairwise Comparisons

According to the Shapiro-Wilk test ($\alpha = 0.05$), the differences in the Euclidean Nearest-Neighbor Distance and Clumpiness Index of Mixed Perennial Vegetation comparing between organic and conventional system were not normal distribution (Table 7). Thus, they were further compared between organic and conventional quarter sections by Wilcoxon Signed Ranks Test. There was no statistically significant difference in both metrics comparing between organic and conventional system (Table 8).

4.8.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 25 and Figure 28. Both two Aggregation Metrics showed no difference among ecoregions except a specifically high median value of Euclidean Nearest-Neighbor Distance of Mixed Perennial Vegetation from organic fields in Mixed Grassland (Fig. 25 & Fig. 28). Organic fields did not always have a higher aggregation index than conventional fields. For the Euclidean Nearest-Neighbor Distance of Mixed Perennial Vegetation, the median value was smaller for organic fields than conventional fields in Boreal Transition and Aspen Parkland (Fig. 25). For the Clumpiness Index of Mixed Perennial Vegetation, the median value was slightly larger for organic than conventional fields in all ecoregions except for Boreal Transition (Fig. 28).

4.8.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared by surface expression, undulating landscape had slightly greater aggregation index than hummocky landscape in general. Except for the Euclidean Nearest-Neighbor Distance of Mixed Perennial Vegetation on undulating landscape, Mixed Perennial Vegetation were more likely to clump to each other in organic fields for the both two Aggregation Metrics. Interquartile ranges of both Aggregation Metrics were larger for undulating landscape than hummocky landscape (Fig. 27 & Fig. 29).

4.9 Aggregation Metrics in the Landscape Level

4.9.1 Conventional Versus Organic Quarter Sections

4.9.1.1 Boxplots

Based on the median value in boxplots, there was no difference between organic and conventional fields for Contagion, Interspersion and Juxtaposition Index, and Landscape Division Index (Fig. 30, Fig. 33 & Fig. 37).

4.9.1.2 Pairwise Comparisons

According to the Shapiro-Wilk test ($\alpha = 0.05$), the differences in the Contagion and Interspersion and Juxtaposition Index comparing between organic and conventional system were normal data; while the difference in the Landscape Division Index comparing between organic and conventional system was non-normal data (Table 7). Therefore, Contagion and Interspersion and Juxtaposition Index were pairwise compared between organic and conventional system by paired T Test; Landscape Division Index was pairwise compared between organic and conventional system by Wilcoxon Signed Ranks Test. All three Aggregation Metrics in landscape level found no statistically significant differences comparing between organic and conventional fields (Table 8).

4.9.2 Conventional Versus Organic Quarter Sections in Different Ecoregions

The ecoregions are presented from wetter and cooler to drier and warmer in Figure 31, Figure 34 and Figure 37. In general, the median value of Contagion was larger in drier and warmer area than in wetter and cooler area. The median value was larger for conventional than organic fields in Boreal Transition but larger for organic than conventional fields in Moist Mixed Grassland and Mixed Grassland; there was no difference between two farming systems in Aspen Parkland (Fig. 31). Interspersion and Juxtaposition Index was similar among different ecoregions. The median value was larger for organic than conventional fields in Boreal Transition and Moist Mixed Grassland, but larger for conventional than organic fields in Aspen Parkland and Mixed Grassland (Fig. 34). Landscape Division Index was greater in Boreal Transition and Aspen Parkland than in Moist Mixed Grassland and Mixed Grassland. The median value of Landscape Division Index was smaller for organic than conventional fields in Mixed Grassland (Fig. 37).

4.9.3 Conventional Versus Organic Quarter Sections in Different Surface Expression

When compared by surface expression, the Contagion was similar on between undulating and hummocky landscape except organic fields from undulating landscape had a particularly large median value and maximum value (Fig. 32). Both Interspersion and Juxtaposition Index and Landscape Division Index were similar on between hummocky and undulating landscape (Fig. 35 & Fig. 38). On hummocky landscape, the median value of both Contagion and Interspersion and Juxtaposition Index were larger for organic, but was larger for conventional on undulating landscape (Fig. 32 & Fig. 35). On the contrary, Landscape Division Index was greater for organic fields on hummocky landscape and for conventional fields on undulating landscape (Fig. 38).

Chapter 5: Discussion

5.1 Higher Landscape heterogeneity on organic fields

In this study, four landscape structures and 14 metrics from the class and landscape levels of landscape metrics were included to assess the landscape heterogeneity at a quarter section scale in both organic and conventional farms. Significant differences were found between organic and conventional fields for five metrics: Percentage of Landscape of both Mixed Perennial Vegetation and Cultivated Lowland, Mean Patch Size of both Mixed Perennial Vegetation and Cultivated Lowland, and Number of Patches of Cultivated Lowland. As indicated in previous landscape studies (Riitters et al., 1995; Cushman et al., 2008) and the description of the metrics (McGarigal, 2015), many metrics are inherently correlated with each other, and that interpreting them separately cannot represent the actual status of landscape heterogeneity. Therefore, the metrics were grouped in a way that could better support the interpretation of the differences of landscape heterogeneity in real world.

5.1.1 The Impacts of Ecoregions and Surface Expression on Landscape Heterogeneity.

In organic fields, the Number of Patches was a key defining feature on hummocky landscapes, but the size of patches was more important on undulating landscapes, as shown in Fig. 6a. This resulted in a different distribution according to surface expression. In conventional fields (Fig. 6b), the confidence ellipses were not as distinct. Overall, it suggests that the patches of Mixed Perennial Vegetation were influenced more by surface expression on organic land than on conventional land. On organic undulating landscape, variance in the metrics were best explained by Mean Patch Size and Percentage of Landscape (compositional metrics) of Mixed Perennial Vegetation, indicating the overall area of Mixed Perennial Vegetation was extremely important in this case. On organic hummocky landscapes, the variance was explained by the Number of Patches and Fractal Dimension Index (configurational metrics), indicating the shape and number of Mixed Perennial Vegetation patches mattered in this case. In general, our results implied that differences in surface expression might affect landscape heterogeneity differently among organic farms. The confidence ellipses for ecoregions were distinct from each other in both organic (Fig 7a) and conventional (Fig 7b) fields, suggesting that landscape metrics had different responses in different ecoregions. This observation implied that the same metric could perform quite differently among ecoregions.

Landscape structures also differed among ecoregions and surface expression. Mixed Perennial Vegetation is more likely to exist in a more complex landscape or a wetter and cooler area (Fig. 11a & Fig. 14a). A hummocky landscape is expected to have more topographic variability and/or deeper depressions where water may accumulate than undulating landscapes. In drier ecoregions, depressional or lowland areas are more likely to be dry in time for spring planting. Thus, hummocky landscapes with a higher frequency of wet conditions are less likely to have depressional areas cleared of vegetation, and if cleared, they are less likely to be cultivated due to wet spring conditions.

Organic farmers rely on mechanical cultivation to remove herbaceous vegetation considered to be weeds and tillage is still part of seedbed preparation (Teasdale et al., 2012; Canadian General Standards Board, 2020). Wet soil conditions do not allow these operations to occur, thus there is less benefit for an organic producer to clear depressional areas. Conventional farmers do require the use of equipment that opens the soil and places the seed even if in a no-till system. However, seedbed preparation may be limited to pre-plant herbicide application. Modern high-clearance sprayers allow farmers to drive through wet soils or reach into depressional areas with wide booms to apply herbicide to control herbaceous vegetation. Thus, there is greater likelihood of a conventional farmer benefitting from clearing a depression, and controlling lowland vegetation despite wet conditions, and even in wet years when they cannot be planted to control weeds for future years. This is illustrated in the Aspen Parkland, where there is an overall lower area of and smaller average size of patches of Mixed Perennial Vegetation among conventional fields compared with organic fields (Fig. 10a & Fig. 16a). However, in the dry conditions of the Mixed Grassland, organic producers appeared to be just as likely to cultivate depressional areas as their conventional counterparts (Fig. 10b, Fig. 13b & Fig. 16b), likely because lowlands dry out soon enough to allow field operations. This might suggest farmers' perception to the ecological value of Mixed Perennial Vegetation can be overridden by the ecological benefits, regardless of the type of farming system.

Landscape metrics varied among different ecoregions and surface expression, implying that natural factors influenced land management which in turn influenced landscape heterogeneity. In general, larger areas of and larger Number of Patches of Mixed Perennial Vegetation is associated with wetter and cooler climate with hummocky landscape in Prairie. In contrary, drier and warmer area with undulating landscape tended to have lower landscape heterogeneity. This finding is in line with the expectation that landscape heterogeneity is somewhat associated with abiotic factors (Fahrig et al., 2011; McGarigal, 2014). Therefore, it is important that landscape studies consider natural factors like ecoregions and surface expression to avoid misinterpretation of landscape metrics. It would be important to set up context-specific plans and goals for those regions that shares different environmental factors.

5.1.2 Higher Proportion of Mixed Perennial Vegetation in Organic Lowland Area Led to Higher Landscape Heterogeneity in Organic Fields.

The pairwise comparison result indicated that organically managed land is more likely to contain a larger percentage area of Mixed Perennial Vegetation than conventional fields. This difference mainly caused by significantly larger patch sizes of Mixed Perennial Vegetation on organic sites. These findings are consistent with our hypotheses that organic agriculture would maintain both an average larger size of patches and an overall larger area of Mixed Perennial Vegetation than conventional agriculture. Combined with the findings of landscape ecology studies that larger perennial vegetation is associated with higher biodiversity and ecosystem services (Tscharntke et al., 2005; Bianchi et al., 2006; Brown, 2009; Hiron et al., 2015), our results confirmed that organic management could bring higher biodiversity and ecosystem services into agricultural fields. This is critical as the land used for agricultural production accounts for roughly 40% of global land surface (FAO, 2020). Our results also indicated that the magnitudes of differences between the Percentage of Landscape and Mean Patch Size of Mixed Perennial Vegetation in organic and conventional fields among ecoregions and surface expression could be quite different. Both metrics in organic systems were dramatically larger than their conventional counterparts in Aspen Parkland and Moist Mixed Grassland but were in the same level with their conventional counterparts in Mixed Grassland (Fig. 10a & Fig. 16a). The same metric also differed between hummocky and undulating landscapes (Fig. 11a & Fig. 17a). As indicated in the discussion above, Mixed Perennial Vegetation is less likely to be cultivated in organic fields in wetter and cooler area and hummocky landscape. In drier area and flat landscapes, there was negligible difference between organic and conventional management.

Using pairwise comparison, the mean value of the Number of Patches of Mixed Perennial Vegetation was numerically higher on organic fields than conventional fields, however the difference was not significantly different. This overall mean does not account for the variation among ecoregions. The Number of Patches of Mixed Perennial Vegetation was overall much smaller in the Mixed Grassland, and there was no difference between organic and conventional there. In Aspen Parkland, however, organic fields tended to have more Mixed Perennial Vegetation than conventional fields. These differences are a reflection of climate, where depressional areas are more likely to remain wet through spring planting in the Aspen Parkland and thus are less likely to be cleared, drained and cultivated. Our findings are in line with the conclusion that the occurrence or spatial arrangement of non-production perennial vegetation is largely decided by initial landforms, less affected by farming operations (Fahrig et al, 2011).

Cultivated Lowland exist as the trade-off with Mixed Perennial Vegetation. However, the lack of consistent perennial vegetation would suggest lower ability to support biodiversity and ecosystem services. Our pairwise comparison found the patches of Cultivated Lowland were significantly larger in conventional fields than in organic fields. At the same time, significantly more patches of Cultivated Lowland were found in conventional fields (Table. 8). As Cultivated Lowland are seen as the consequence of intensive farming practices, our results indicate that conventional management would lead to a simplification of the agricultural landscape (Lambin et al., 2001; Benton et al., 2003; Tscharntke et al., 2005), contrary to landscape heterogeneity contributed by organic management. However, the difference between organic and conventional was not consistent across ecoregions and different surface expressions. In general, the differences between organic and conventional were smaller in Mixed Grassland and undulating landscapes, suggesting that organic lowland in drier and warmer ecoregions and with a flat surface expression are similarly vulnerable to cultivation as conventional lowlands. In Aspen Parkland and Moist Mixed Grassland, organic fields had less variation and tendency to have more Cultivated Lowland than conventional fields. These findings were consistent with the maintenance of Mixed Perennial Vegetation.

To account for potential variation between lowland vegetation, the proportion of total lowland area that was cultivated was also considered by overall pairwise comparison (Table 8, Fig. 39), and then by ecoregions (Fig. 40) and surface expression (Fig. 41). Overall, the proportion of total lowland area that was cultivated was significantly higher in conventional fields (Table 8). When assessed by ecoregion, there was no clear difference in the proportion of lowland cultivated in the organic and conventional fields in the two Grassland ecoregions where up to 100% of lowland area was cultivated in both farming systems, however, in Aspen Parkland and Boreal Transition ecoregions it was clear that there was a lower tendency for lowlands to be cultivated in organic fields. Our results indicated the conversion rate of Mixed Perennial Vegetation to Cultivated Lowland is significantly higher in conventional fields, and thus a more serious status of landscape simplification in conventional agriculture compared with organic fields in agricultural landscape in Saskatchewan. Given the equal exposure to Mixed Perennial Vegetation in crop fields, conventional farmers are more likely to move the features and cultivate the lowland area, indicating habitats are more vulnerable under conventional management. Intensified agricultural operations under conventional agriculture were more likely to modify the landscape by removing perennial landscape structures, thereby enhance farming efficiency and extending the farming area (Benton et al., 2003). For example, farmers would remove hedgerows to allow the use of larger farming equipment (Westmacott and Worthington, 1984). These operations that cause landscape simplification (Tilman et al., 2002; Tscharntke et al., 2005) and subsequent declines in biodiversity in, for example, birds (Donald et al. 2001).

Differences in Cultivated Lowland/Total Lowland (CL/TL) between organic and conventional quarter sections were also found in different surface expression. In both hummocky and undulating landscapes, more than 75% of conventional quarter sections had larger value than organic median values, however, there was tremendous variation among organic farms in the undulating landscape making it difficult to state there was a clear difference from the conventional fields. In hummocky fields, however, the difference was clearer with a tendency for organic farms to cultivate a smaller proportion of the lowland area than conventional farms. The effect of surface expression was not as strong however as seen in the ecoregions suggesting that ecoregion may be more important than surface expression in this regard. The lack of statistically significant difference may be caused by the unbalanced data distribution as Moist Mixed Grassland accounted for the largest number of valid cases in this study (Table 6).

5.1.3 Similar Configurational Heterogeneity in between Organic and Conventional Fields.

No statistically significant differences were found in Radius of Gyration and Fractal Dimension Index of Mixed Perennial Vegetation between organic and conventional fields although mean values were larger for organic fields than conventional fields. This result implies that the shape characteristics of Mixed Perennial Vegetation were not affected by farming systems. This might be because (1) the shape of lowland areas was generally similar between organic and conventional fields; or (2) the similar farming practices or habits applied by both organic and conventional farmers lead to the similar modification on the shape of Mixed Perennial Vegetation.

Both Euclidean Nearest Neighbor Distance and Clumpiness Index were metrics used to measure the spatial pattern of Mixed Perennial Vegetation. Statistically, the spatial distribution of Mixed Perennial Vegetation was similar in between organic and conventional fields, and further indicated that farming systems do not have a significant impact on the spatial pattern/distribution of Mixed Perennial Vegetation in this study. From an ecological perspective, our results indicated a shorter average travel distance in organic agriculture which benefits biodiversity by providing a potentially better resource accessibility (Fahrig et al., 2011).

Contagion, Interspersion and Juxtaposition, and Landscape Subdivision Index were landscape level of Aggregation Metrics used in this study to quantify the spatial pattern of whole landscape. Despite no statistically significant differences between the organic and conventional system, these three configurational metrics both displayed higher mean values on organic fields. Combined with the results of Euclidean Nearest Neighbor Distance and Clumpiness Index of Mixed Perennial Vegetation, our results agreed with the previous findings that the spatial occurrence and/or spatial distribution of landscape structures are mainly decided by initial landforms (Fahrig et al, 2011). Therefore, there is less opportunity for farmers and farming practices to modify the configurational heterogeneity.

5.1.4 Higher Frequency of Shelterbelts in Organic Fields.

Shelterbelts were a less common landscape features found in only 13 valid pairs out of total 71 pairs of comparison. Of those 13 pairs, Shelterbelts were found in only two conventional fields with no Shelterbelts found on organic side; the other 11 pairs found Shelterbelts on organic fields but no Shelterbelts on conventional side. Both conventional Shelterbelts were found in Moist Mixed Grassland from undulating landscape. No organic Shelterbelts were found in the Boreal Transition ecoregion; one organic Shelterbelts was found in the Aspen Parkland ecoregion; five organic Shelterbelts were from the Moist Mixed Grassland ecoregion; six organic Shelterbelts were from the Mixed Grassland ecoregion. Eight out of 11 organic Shelterbelts were in hummocky landscape. The randomly selected dataset had most Shelterbelts located in the Mixed Grasslands and Moist Mixed Grasslands, this finding was consistent with previous studies that Dark Brown soil had the longest Shelterbelt, followed by Brown soil and Black soil (Piwowar et al., 2016)

Shelterbelts have been used to control the impact of wind on farmland, for example, soil erosion, snow blowing over roads and providing ecological corridors and wildlife habitats (Wiseman et al., 2009). Meanwhile, Shelterbelts played a significant role in carbon reserve in the agricultural landscape in Prairie Canada. Amichev et al. (2016) assessed that more than 130,000 tonnes of carbon has been sequestrated in tree biomass in Saskatchewan alone, and trees are the preferred species in the composition of Shelterbelts, accounting for 81% of Shelterbelts total length in Saskatchewan (Piwowar et al., 2015). Despite many good effects provided by Shelterbelts, those benefits were perceived as non-economic from farmers' standpoint (Rempel et al., 2017). Our results were in line with this previous assumption as most Shelterbelts were found in organic fields, this might be because conventional farmers are more likely to be profit-driven and intensive farming practices featured by conventional agriculture led to landscape simplification (Tscharntke et al., 2005). With drier conditions, the Mixed Grassland and Moist Mixed Grassland ecoregions are more vulnerable to wind erosion and transpiration losses, so shelterbelts are likely to provide more benefits to farmers in that region. However, these services of shelterbelts are reduced or redundant in no-till or conservation tillage systems where residue is left to protect the soil surface (Amichev et al., 2015).

5.2 More Organic Fields Meet Swiss Ecological Compensation Area (ECA) Standard

Many countries have initiated plans to counter landscape simplification caused by development and agricultural production, though most of them failed to achieve the proposed goals. As the pioneer in this work, Switzerland demonstrated that their ecological compensation area (ECA) policy could have positive effects on biodiversity (Herzog et al., 2005). Swiss farmers who maintain at least 7% of their cropland area as ecological compensation area (ECA) are qualified for government subsidy, and this target is a requirement within the Swiss organic standards (Bio Suisse, 2021). For organic agriculture, preserving high conservation value areas is mandatory. It is also required to keep 20% of the land in legume crops or green manures or forage (Bio Suisse, 2021).

Although keeping 7% of the landscape as ECA is a policy designed specifically for Switzerland, it is interesting to know if organic fields were more likely to meet this Swiss standard of (ECA) than conventional fields. In this study, 48% of conventional fields and 26% of organic fields did not meet this Swiss target of 7%. In Fig. 9, the curve for organic fields was consistently below the conventional curve, indicating that regardless of the target value, a larger proportion of organic fields would meet the target than conventional fields. This result was in line with the results of compositional metrics and indicates that organic management has a greater impact on fields have a higher likelihood of maintaining perennial vegetation. However, 26% of organic fields did not meet the 7% standard, and some organic field had little or no Mixed Perennial Vegetation.

As previously indicated, the impact of abiotic factors was important in the pairwise comparison of farming systems. Overall, Mixed Perennial Vegetation area was higher on organic land than conventional land, however, this was most prominent in wetter ecoregions and with hummocky landscapes (Fig. 10a & Fig. 11a). However, in Mixed Grassland, there was limited difference in the area of Mixed Perennial Vegetation between organic and conventional fields (Fig. 10a). Thus, habitat conservation and policy implications may vary depending on ecoregion and landform.

5.3 Policy Implications

What is the appropriate ‘target’ for landscape heterogeneity in agricultural landscape? In answering this question from an agricultural perspective, we have to realize that agriculture is not a natural ecosystem, but a semi-natural system taken advantage of by humans to feed the world and for economic prosperity, and that the market leads agriculture policies. Therefore, it has been suggested that the agricultural landscape should not be compared with the natural landscape without humans (Fahrig et al., 2011).

The compositional heterogeneity of habitats was significantly higher in organic quarter sections than in neighboring conventional quarter sections as indicated by the larger percentage area occupied by Mixed Perennial Vegetation as opposed to cropland. Combined with the findings that higher compositional heterogeneity is associated with higher biodiversity (Brown, 2009; Hiron et al., 2015), our results strengthen the point that organic agriculture is likely to support higher biodiversity. Among many aspects of landscape heterogeneity, our study indicated that the overall area and average size of Mixed Perennial Vegetation contributed the most to the landscape heterogeneity. Hence, government policies or programs which support organic agriculture are likely to support higher landscape heterogeneity through Mixed Perennial Vegetation and associated benefits of habitat provision supporting biodiversity, carbon sequestration, and reduced risk of input losses in temporarily flooded cultivated lowlands

(Gleason et al., 2005). The latest revision of the Canadian organic standards added a standard about protecting perennial landscape structures in organic fields during the period our research was conducted (Canadian General Standards Board, 2020):

" *5.2.4. Management practices shall include measures to promote and protect ecosystem health on the operation and incorporate one or more of the following features: a) pollinator habitat; b) insectary areas; c) wildlife habitat; d) maintenance or restoration of riparian areas or wetlands; or e) other measures which promote biodiversity.*".

The standard is followed by an informative note with the following recommendation: "Existing native prairie, parkland, or wetland habitats should be maintained and enhanced whenever possible." While the informative note has not become a part of the standard, it is clear that the Technical Committee of the standard is suggesting that these habitats should be conserved when possible. In the USA, assessment would be conducted towards certified organic farmers to monitor if their operations comprehensively maintain perennial vegetations like wetlands (USDA, 2016). The same guidance document also specified the examples of activities that may maintain or improve biodiversity, where it contains a variety of perennial vegetation, like shrublands, woodlands, riparian areas, should be preserved. Other than pointing out the importance of compositional heterogeneity, it also highlights configurational heterogeneity by mentioning the diverse mixtures of plants can enhance the accessibilities of agricultural organisms (USDA, 2016). Compared with the USA, Canada shall further detail the organic regulation and standards to include more information and limits on organic farmers operations towards perennial vegetation, as organic farmers were found to cultivate as intensively as conventional farmers in Mixed Grassland.

Countries like Germany (BMUB, 2010), South Africa (DEA&DP, 2007), and some states in the USA (EPA, 2008) have demonstrated that simply moving the perennial vegetation from one to another place to offset the landscape simplification failed to address the loss of biodiversity and ecosystem services. This type of landscape compensation policy has been taken advantage of by developers to get planning permission by buy-offing objections or failed to meet the initial protection goals because of the lack of comprehensive landscape plan. For example, if the benefits of removing Mixed Perennial Vegetation are larger than government fines, then farmers might choose to take the risk of breaking the rules rather than following the regulations. By contrast, the successful Swiss policy highlighted the importance of maintaining landscape heterogeneity in farmers' own fields (Herzog et al., 2005; Aschwanden et al., 2007; Albrecht et al., 2010).

To practically maintain local landscape structures, education program towards stakeholders (Landis, 2017) and context-specific subsidization (McGarigal, 2014) are both critical. To stem the loss of non-production perennial vegetation in agricultural fields requires actions at a scale that is at least larger than farm-scale (Stoate et al., 2009). For example, while some farmers are open to maintaining non-production perennial vegetation, others still pursue higher production by clearing the non-production perennial vegetation from their fields thereby simplifying the landscape.

Previous studies showed that the market and policy shape the current agricultural production models, therefore switching to ecological conservative farming or organic demands education towards farmers and other stakeholders (Landis, 2017; Rempel et al., 2017). Geertsema et al. (2016) determined that famers in Iowa, USA, needed "actionable knowledge" (i.e., knowledge that specifically supports stakeholder decision making and consequent actions) to enact change to agricultural intensification through biodiversity conservation and management of ecosystem services in landscape level. In Saskatchewan, advances in seeding technology and field equipment made some farmers believe that the ecological value of Shelterbelts can be ignored, while some farmers chose to maintain and expand Shelterbelts, because they learned that Shelterbelts can efficiently provide shade and moisture distribution in fields (Amichev et al., 2015). Education programs can not only promote the spontaneous non-production perennial vegetation maintenance, but also create a better environment to collaborate farmers. An Agri-Environment Program in EU called on groups of farms to undertake practices towards a common goal of restoring birds' populations by maintaining or creating different types of grassland to meet birds' different life stages (Whittingham, 2007; Melman et al., 2008).

Other than education, context-specific financial support is effective to promote the maintenance of non-production perennial vegetation (Herzog et al., 2005; Moreira et al., 2005). This research has identified the difference among ecoregions in the maintenance of Mixed Perennial Vegetation; stricter standards related to habitat provision will pose a greater burden on farmers in the Mixed Grassland and Moist Mixed Grassland ecoregions than those in the Parkland ecoregion. The goals for subsidization for particular agricultural landscape shall be varied according to landscape characteristics and the degree of landscape simplification (Gabriel et al., 2013). Highly simplified landscapes feature the coexistence of soil, climate, and farming technologies that support high yields (Landis, 2017). In such landscapes, the priority would be maintaining productivity and restoring the lost ecosystem services as well as mitigating negative impacts. The same rule shall be applied to our study area. Saskatchewan has the largest average farm size in Canada, 675.1 hectares (Statistics Canada, 2011), while the average size of farm in Switzerland is less than 16.2 hectares (Federal Statistical Office, 2002), which is even smaller than a quarter section area (64.7 hectares) in Saskatchewan. It would be irrational to apply Swiss landscape policy on Saskatchewan agricultural landscape. The subsidization goal for Mixed Grassland in Saskatchewan would be restoring the lost Mixed Perennial Vegetation as much as possible and maintaining the existing non-production perennial vegetation whenever possible. For the Aspen Parkland and Moist Mixed Grassland ecoregions, they shared a relatively balanced landscape heterogeneity; hence, their management goals would be to ensure stability in their current level of landscape heterogeneity. In the meantime, agencies could offer incentives to the farmers that enhance landscape heterogeneity. For the Boreal Transition ecoregion, more relative studies are needed as it is from another ecozone. Specific goals for landscape conservation require the collaboration of geographers, economists, sociologists, and farmers. Local experts are also recommended to join the localization of and implementation of landscape conservation plan, because farmers are more likely to cooperate with local effort instead of country-wide approaches (Stallman & James 2015).

Chapter 6: Conclusion

This research assessed how farming systems might affect biodiversity through provision of habitat. To quantify the status of habitats, landscape metrics were applied to calculate the landscape heterogeneity. To control the various factors, pairwise comparisons were used as the experimental design for investigating the differences in landscape heterogeneity between organic and conventional quarter sections. It was concluded that landscape heterogeneity was higher on organic fields than on conventional fields. The results indicated that the organic quarter sections had significantly larger area and mean patch size of Mixed Perennial Vegetation than their neighboring conventional quarter sections. Organic management maintained more Mixed Perennial Vegetation than conventional management, while conventional management cultivated more lowland areas. This contrast implies that landscape simplification is occurring under the conventional management in Saskatchewan. In general, the results indicated that organic management maintained a higher landscape heterogeneity than conventional management in Saskatchewan agricultural landscape.

This study also accounted for abiotic factors, where a higher landscape heterogeneity was observed in the wetter and cooler Prairie ecoregions, and hummocky landscapes. The lowest landscape heterogeneity was found in the Mixed Grassland ecoregion, where organic and conventional shared a similar level of landscape heterogeneity. The lowest level of landscape heterogeneity in the Mixed Grassland ecoregion implied the drier climate allowed more cultivation of depressional areas. It also suggested the need for applying context-specific conservation plans.

6.1 Study Limits and Future Research

This study carried out a pairwise comparison of landscape heterogeneity between organic and conventional fields using 71 pairs of quarter sections, whereby the environmental factors were carefully controlled for in in both methodology and data analysis. Despite these strengths, there were still possible sources or error, as well as opportunities to strengthen the analysis.

A potential error was related to the identification of organic fields when the data was collected. The study relied on sourcing out rural municipalities maps that identified organic quarter sections. Although the identification of organic quarter sections was accurate when the maps were produced, the current state of every single field remained unknown. Furthermore, the amount of to time that the land had been in organic production was also unknown as the land could have been recently converted after clearing. However, the presence of canola was used as an indicator of non-organic status as a means for ground-truthing the data whereby fields with canola present were removed; although, there was still a chance that the identity of the farming system could be mistaken.

This study was limited by the availability of datasets. Landscape digitization in this study was based on aerial photos downloaded from FlySaska2.ca, which provides aerial photos covering Saskatchewan for three periods: 2008-2011, 2012-2016, and 2017-2021. However, each period of aerial photos only covered parts of Saskatchewan, leaving the rest of the areas captured by aerial photos from other periods. For example, in the rural municipality of Moose Creek, most quarter sections had imagery for the 2008-2011 and 2017-2021 periods, but quarter sections in the rural municipality of Torch River were only available from 2008-2011. It was possible that quarter sections in the same rural municipalities could have datasets from different periods. For example, some part of rural municipality of Carmichael had datasets available for 2012-2016, while the rest area in Carmichael had datasets only available for 2008-2011. Although the experimental design using pairwise comparisons may have mitigated the errors in the differences between organic and conventional systems that could be generated in the datasets selection, the datasets captured for different time periods might have influenced the overall variance. Moreover, datasets captured for the different periods might have influenced our understanding of landscape heterogeneity and biodiversity conservation (Bradley et al., 2003; McGarigal, 2014). Therefore, the lack of datasets from other years might affect the accuracy for depicting the boundaries of Cultivated Lowland. Further studies are needed when more datasets become available to accurately digitize the landscape structures and to include impacts of temporal changes on landscape heterogeneity. Social studies are recommended to quantify the modification of organic management on organic farmers behavior and attitudes.

As Fahrig et al. (2011) identified that "most of landscape speculation is based on extrapolation to the landscape scale from results of local-scale studies on the effects of farmland features and patterns". Different spatial scales within a study would lead to different levels of biodiversity (Paula et al., 2018). For example, the investigation of biodiversity conservation was suggested to be based on a whole-farm scale (Schneider et al., 2014). In this study, the quarter section was used as the unit for assessing landscape heterogeneity. In addition, some landscape structures located on the boundaries of quarter sections were not accounted for in this study because the ownership of those landscape structures could not be identified, neither could they be treated as part of organic fields nor could they be attributed to conventional fields. As a result, if a larger spatial scale was applied as the study unit for the calculation of landscape heterogeneity, for example, a section, then the landscape structures not accounted for in this study would be accounted for at the larger scale. Issues related to spatial scales are inherent flaws in every landscape study that uses sample areas to infer the spatial patterns at the larger landscape scale (McGarigal, 2015).

This study also did not provide information that was detailed enough to characterize specific ecosystem services or evaluate biodiversity. The aerial imagery did not separate vegetation classes, and the resolution of the imagery and time constraints did not allow for such delineation of vegetation types. Thus, the ecological value of the Mixed Perennial Vegetation in supporting biodiversity could not be assessed and could vary within and among fields and ecoregions. Using landscape heterogeneity as an indicator to infer the status of biodiversity needs a thorough understanding on the reliance of organisms on associated land covers and a detailed classification of land covers (McGarigal, 2014). Therefore, it is not recommendable to use these results to assess the level of plant diversity within the fields or its potential to support other organisms. For further studies, this study served as a base for investigating landscape heterogeneity differences between farming systems. In the following research, information on the reliance of specific agricultural species on habitats are needed to better explain the landscape heterogeneity within ecological terms.

The exploration on the impact of ecoregions and surface expression also needed more statistical support because of the unbalanced number of cases; however, factors in landscape studies are difficult to control (Kremen et al., 2012). This study served as a pilot study in investigating impacts of environmental factors on landscape heterogeneity. Future studies should take the impact of ecoregions and surface expression into account. More studies are needed to quantify the impact of environmental factors on landscape heterogeneity, especially in designing local-scale, landscape conservation plans.

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APPENDIX

Table 1. Summary of key features of ecoregions in the south Saskatchewan (Acton et al., 1998).

Ecoregion	Annually Mean Precipitation (mm)	Annually Mean Temperature Range (Degrees Celsius)	Soil	Native Vegetation
Boreal Transition	450-550	-13.5 - 14	Grey	Trembling aspen, balsam poplar, and mixed herbs. Sedges, willow, some black spruce, and tamarack could be found in wetlands.
Aspen Parkland	400-500	-12.5 - 15	Black	Trembling aspen, oak groves, mixed tall shrubs, and intermittent fescue grasslands. Sedge and willow could be in wetlands.
Moist Mixed Grassland	350–400	-11 - 15.5	Dark brown	Spear grass and wheat grass, and a variety of deciduous shrubs. Patches of scrubby aspen, willow, cottonwood could be found in the valleys and river terraces.
Mixed Grassland	250-350	-10 - 16	Brown	Spear grass, blue grama grass, and wheat grass. Patches of scrubby aspen, willow, cottonwood could be found in the valleys and river terraces. Local saline areas support alkali grass, wild barley, and greasewood.

Table 2. Process of selection of study sites and rationale.

Steps	Selection Behavior	Rationale
1	Identification of municipalities with digital maps that designate land which was under organic management.	Searching available data.
2	Identified all organic quarter sections in all rural municipal maps.	Finding out all potentially feasible study sites.
3	Selected organic quarter sections randomly with a minimum separation of 1600 m in all directions and recorded their legal land location.	Avoiding spatial autocorrelation that is caused by similar farm ownership or farming practices.
4	Conventional quarter sections were selected adjacent to the organic quarter sections in a random direction and kept a minimum distance of 1600 m between each identified conventional quarter section.	Adjacent conventional quarter sections were selected but sufficiently separated to avoid spatial autocorrelation.
5	Located quarter sections in aerial images by referring to the recorded legal land location.	Identifying land uses and landscape features, and acquiring aerial photos in FlySask2.ca, which is the baseline dataset for digitalization.
6	Removed quarter sections which may confound analysis: 1) a farmstead or residential area; 2) pasture; 3) ravine, forest, large water body, and streams; 4) industrial infrastructure, highway, roads, or rail lines that are perceived to have a major impact on land management.	Other agricultural land uses like pastures and natural landscape as well as human facilities were excluded so that the data did not become confounded by different factors not related to field management.
7	Removed quarter sections which Canola was found before the timing when aerial photos were taken.	If Canola was found after the aerial photos were taken, the aerial photos were then hypothesized to display the landscape pattern under organic management.
8	Quarter sections were further characterized by ecoregions (Fig. 3) and surface expression (Fig. 4).	Both ecoregions and surface expression may affect the initial level of landscape heterogeneity. Their interaction on landscape heterogeneity were estimated by comparing the value of landscape metrics across these sub-classifications.
9	Two data sheets were created to collect and filter data. The data in the first form recorded the following information for each quarter section: records of sources municipal maps and digital layers of ecoregions and surface	Although selection of the quarter sections required identification of farming system status, the digitization of the land classes needed to be done in a “blind” fashion to avoid bias. As

	expression, legal land location, surface expression, ecoregion, autocorrelation and farming systems status. In the second data sheet, pair ID was assigned to each pair of comparison, followed by legal land location, land cover/land use information, and alternative quarter sections if one of the targeted quarter sections was found to be disqualified due to land cover/land use.	such the second data sheets identifies pairs and legal locations without their farming system status and this was subsequently used for metrics calculations for each quarter sections. The status was then reassigned to the quarter sections to permit statistical analysis.

Table 3. Classification of studied landscape structures.

Class	Description	Rationale
Cultivated Upland	Land used primarily for production of annual crops. On satellite image, the primary indications of cultivated land will be the absence of perennial vegetation and tracks produced by mechanized equipment.	The study area is cropland. Cultivated Upland is thus the matrix of targeted landscape features.
Cultivated Lowland	These are topographically low-lying areas in the landscape where water from spring runoff and rainfall may accumulate during wet periods, preventing seeding or flooding established crops, but can be cultivated or travelled through during dry periods. Thus, these lowlands may be planted to a crop in dry spring conditions; if too wet in some years, these patches may be flooded, weedy, or remain bear with herbicide application.	Organic farmers rely on mechanical weed control which cannot be used in wet soils; however, conventional farmers may have large equipment for herbicide application that can reach into or drive through wet lowland areas. Thus, it is hypothesized in this study that these intermittently wet lowland areas are more likely to be cultivated in conventional fields as opposed to organic fields.
Perennial Mixed Vegetation	Land occupied by natural perennial vegetation including grasses, forbs, shrubs and trees and may or may not include a wetland.	It is recognized that plant community composition can influence the biodiversity within a patch. This study focuses on characterizing the impact of organic vs. conventional farming on landscape heterogeneity based on the premise that higher heterogeneity will support higher biodiversity. Thus, instead of assessing the capacity of plant communities to support biodiversity, this study effectively divides the landscape into cropped land vs. land that is occupied by natural perennial vegetation. .
Shelterbelts	One or more rows of trees or shrubs intentionally planted to provide shelter from the wind and to protect soil from erosion.	A perennial landscape features introduced by humans, it is interesting to know if there is difference in anthropogenic perennial landscape vegetation in organic and conventional farms.

Table 4. Metrics selection based on Fragstats, and their associated rationales and hypotheses (McGarigal, 2015). Abbreviation: Mixed Perennial Vegetation = MPV, Cultivated Lowland = CL, metrics at landscape level = LL

Landscape Metrics	MPV	CL	LL	Rationale
Percentage of Landscape (PLAND)	√	√		A measure of landscape composition that equals the percentage the landscape comprised of the corresponding class. A larger value indicates a higher landscape heterogeneity. Percentage of Landscape is also used as a base metric to calculate two other metrics.
Fractal Dimension Index (FRAC)	√			It measures shape complexity across a range of spatial scales. A higher value indicates a more convoluted shape, and therefore a higher landscape heterogeneity. It also implies a larger 'edge effects'.
Mean Patch Size (AREA_MN)	√	√		It represents the average patch size in a given quarter section. A higher value indicates a larger average size of calculated landscape structures, and therefore a higher landscape heterogeneity.
Radius of Gyration (GYRATE)	√			It is a measure of shape that is affected by the extent and elongation of the patch. The greater the radius of gyration value is, the more extensive the patch is, and therefore a higher landscape heterogeneity. In other word, the patch is elongated and is less compact. Long narrow patches can be more disruptive to field operations and thus are more likely to be cultivated.
Euclidean Nearest-Neighbour Distance (ENN)	√			It calculates the average shortest distance between two patches, a measure of the isolation of habitat patches. A smaller value indicates closer distance between two patches, and therefore a higher landscape heterogeneity. For Mixed Perennial Vegetation, closer distance implies more opportunities for fields organisms to travel but also means the farmer must take more time to circle obstructions. Very close patches may interfere with operations with large equipment.
Clumpiness Index (CLUMPY)	√			It is a measure of class-specific aggregation, providing effective index of fragmentation of a class. A higher value indicates a higher aggregation condition of calculated landscape structure and less landscape heterogeneity.
Number of Patches (NP)	√	√		It equals the number of patches of a specific landscape structure. It is a simple and straightforward measure of the degree of subdivision. A larger value indicates a larger landscape heterogeneity.
Landscape Division Index			√	It is a measure of landscape configuration. A higher value indicates a higher level of breakup and higher heterogeneity. From an ecological perspective, division

(DIVISION)		can be interpreted as the probability that two organisms that are randomly located in a field are likely to occur in the same patch.
Contagion (CONTAG)	√	It is a measure of both landscape composition and landscape configuration. A measure of how clumpy patches in the landscape are. Lower values indicate that patches are more broken up, and therefore more heterogeneity in the landscape.
Interspersion and Juxtaposition Index (IJI)	√	It is a measure of both landscape composition and landscape configuration. It refers to the intermixing of units of different patch types and mix of different types being adjacent. A higher value indicates a higher variety of types, and therefore more heterogeneity.

Table 5. Additional metric for Cultivated Lowland.

Landscape metrics	Algorithm	Rationale	Hypotheses
Percentage of Lowland that is Cultivated (CL/TL)	Cultivated Lowland /Total Lowland (Cultivated Lowland + Mixed Perennial Vegetation)	This metrics calculates what percentage of lowland area is cultivated. A higher value indicates a larger likelihood of farming the lowland area.	Percentage of Lowland that is Cultivated would be larger on conventional fields, in the ecoregions further south, and on undulating landscape.

Table 6. Frequencies for of valid cases of Mixed Perennial Vegetation and Cultivated Lowland.

Frequencies of valid cases of Mixed Perennial Vegetation					
	Conventional		Organic		
	Hummocky	Undulating	Hummocky	Undulating	Total
Boreal Transition	2	8	1	9	20
Aspen Parkland	12	3	11	4	30
Moist Mixed Grassland	20	13	22	11	66
Mixed Grassland	5	5	4	6	20
Total	39	29	38	30	136
	68		68		

Frequencies of valid cases of Cultivated Lowland					
	Conventional		Organic		
	Hummocky	Undulating	Hummocky	Undulating	Total
Boreal Transition	2	8	1	9	20
Aspen Parkland	12	3	11	4	30
Moist Mixed Grassland	20	16	23	13	72
Mixed Grassland	5	5	4	6	20
Total	39	32	39	32	142
	71		71		

Table 7. Normality tests for the difference of metrics between organic and conventional system.

Metrics	Object	Shapiro-Wilk		
		Statistic	df	Significance
Percentage of Landscape (PLAND)	Mixed Perennial Vegetation	0.973	68	0.240
	Cultivated Lowland	0.982	71	0.394
Number of Patches (NP)	Mixed Perennial Vegetation	0.961	68	0.062
	Cultivated Lowland	0.959	71	0.021
Mean Patch Size (AREA_MN)	Mixed Perennial Vegetation	0.816	68	0.001
	Cultivated Lowland	0.843	71	0.001
Radius of Gyration (GYRATE)	Mixed Perennial Vegetation	0.816	68	0.002
Fractal Dimension Index (FRAC)	Mixed Perennial Vegetation	0.816	136	0.001
Euclidean Nearest-Neighbor Distance (ENN)	Mixed Perennial Vegetation	0.816	136	0.001
Clumpiness Index (CLUMPY)	Mixed Perennial Vegetation	0.816	136	0.001
Contagion (CONTAG)	Landscape Level	0.972	71	0.208
Interspersion and Juxtaposition Index (IJI)	Landscape Level	0.981	71	0.510
Division Index (DIVISION)	Landscape Level	0.981	71	0.001
Cultivated Lowland/Total Lowland (CL/TL)	Landscape Level	0.979	71	0.267

Table **8**. Mean value and paired tests for metrics.

Metric	Object	Mean Organic	Mean Conventional	df	Significance
Percentage of Landscape (PLAND) (Percent)	Mixed Perennial Vegetation	9.31	6.06	67	**0.001**[a]
	Cultivated Lowland	4.61	9.04	70	**0.001**[a]
Number of Patches (NP)	Mixed Perennial Vegetation	6.41	5.43	67	0.134[a]
	Cultivated Lowland	9.13	11.86	70	**0.014**[b]
Mean Patch Size (AREA_MN) (Hectares)	Mixed Perennial Vegetation	1.82	1.50	67	**0.014**[a]
	Cultivated Lowland	0.44	0.74	70	**0.001**[a]
Radius of Gyration (GYRATE) (Meters)	Mixed Perennial Vegetation	53.20	46.88	67	0.086[b]
Fractal Dimension Index (FRAC)	Mixed Perennial Vegetation	1.82	1.50	67	0.296[b]
Euclidean Nearest-Neighbor Distance (ENN) (Meters)	Mixed Perennial Vegetation	117.87	143.92	67	0.852[b]
Clumpiness Index (CLUMPY) (Percent)	Mixed Perennial Vegetation	94.59	84.36	67	0.050[b]

Metric	Object	Mean		df	Significance
		Organic	**Conventional**		
Contagion (CONTAG) (Percent)	Landscape Level	72.14	71.93	70	0.129[b]
Interspersion and Juxtaposition Index (IJI) (Percent)	Landscape Level	63.51	61.41	70	0.478[b]
Division Index (DIVISION) (Proportion)	Landscape Level	0.39	0.37	70	0.559[b]
Cultivated Lowland/Total Lowland (CL/TL) (Percent)	Landscape Level	40.24	55.57	70	**0.001**[a]

a. Analyzed by Student Paired T Test.
b. Analyzed by Wilcoxon Signed Ranks Test.

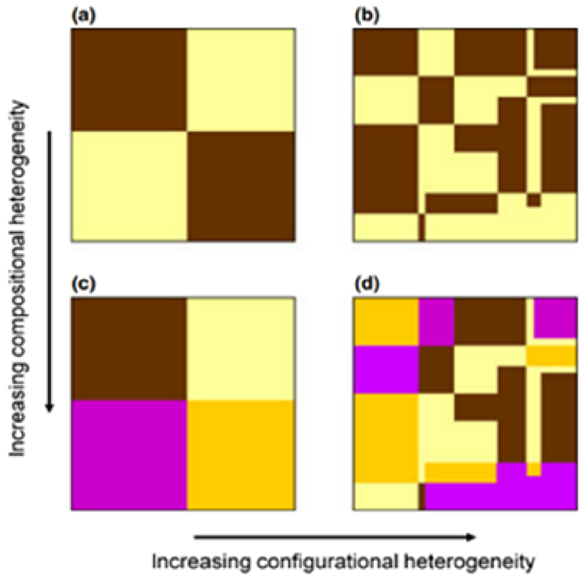
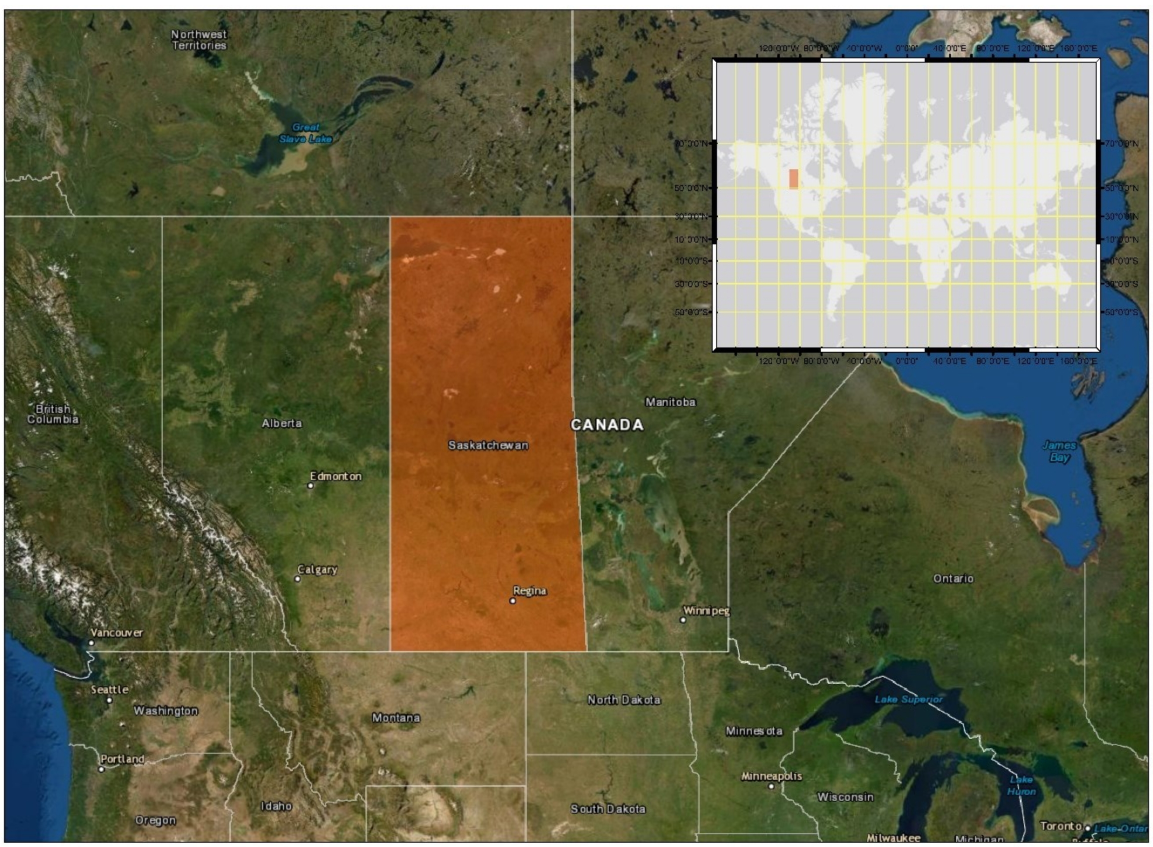


Fig. 25. The change flow of both compositional and configurational heterogeneity (Fahrig et al., 2011). On the X axis, configurational heterogeneity is increasing with more complex and random spatial distribution; on the Y axis,



compositional heterogeneity is increasing with more types of land covers.

Fig. 26. The spatial location of Saskatchewan in North America. Saskatchewan is bordered on the west by Alberta, on the north by the Northwest Territories, on the east by Manitoba, and on the south by the United States. Basemap source: ESRI Canada. Projection: WGS_1984_Web_Mercator_Auxiliary_Sphere.

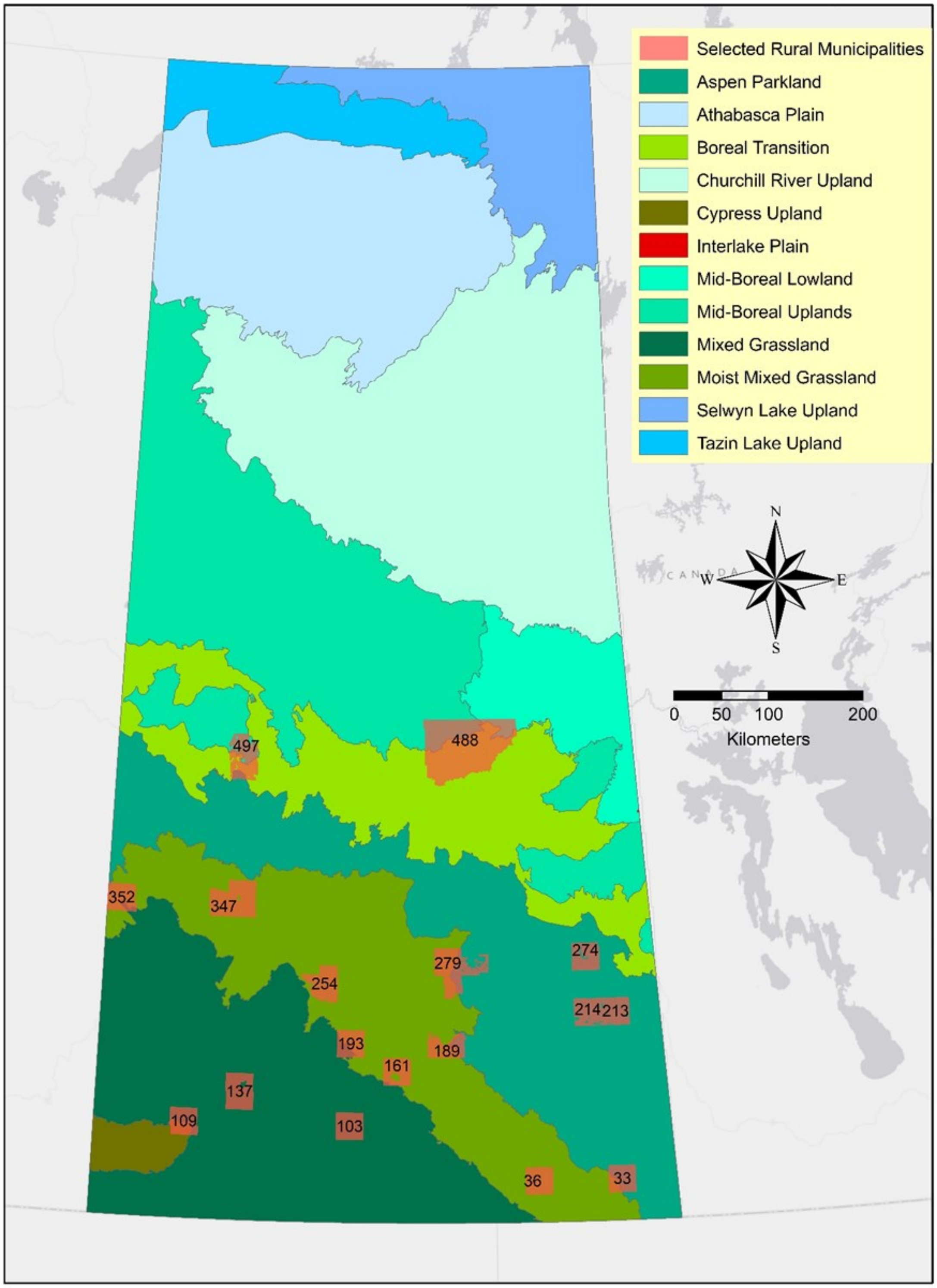


Fig. 27. Spatial location of selected rural municipalities (identified by municipal number) and ecoregions. Basemap source: ESRI Canada. Projection: WGS_1984_Web_Mercator_Auxiliary_Sphere.

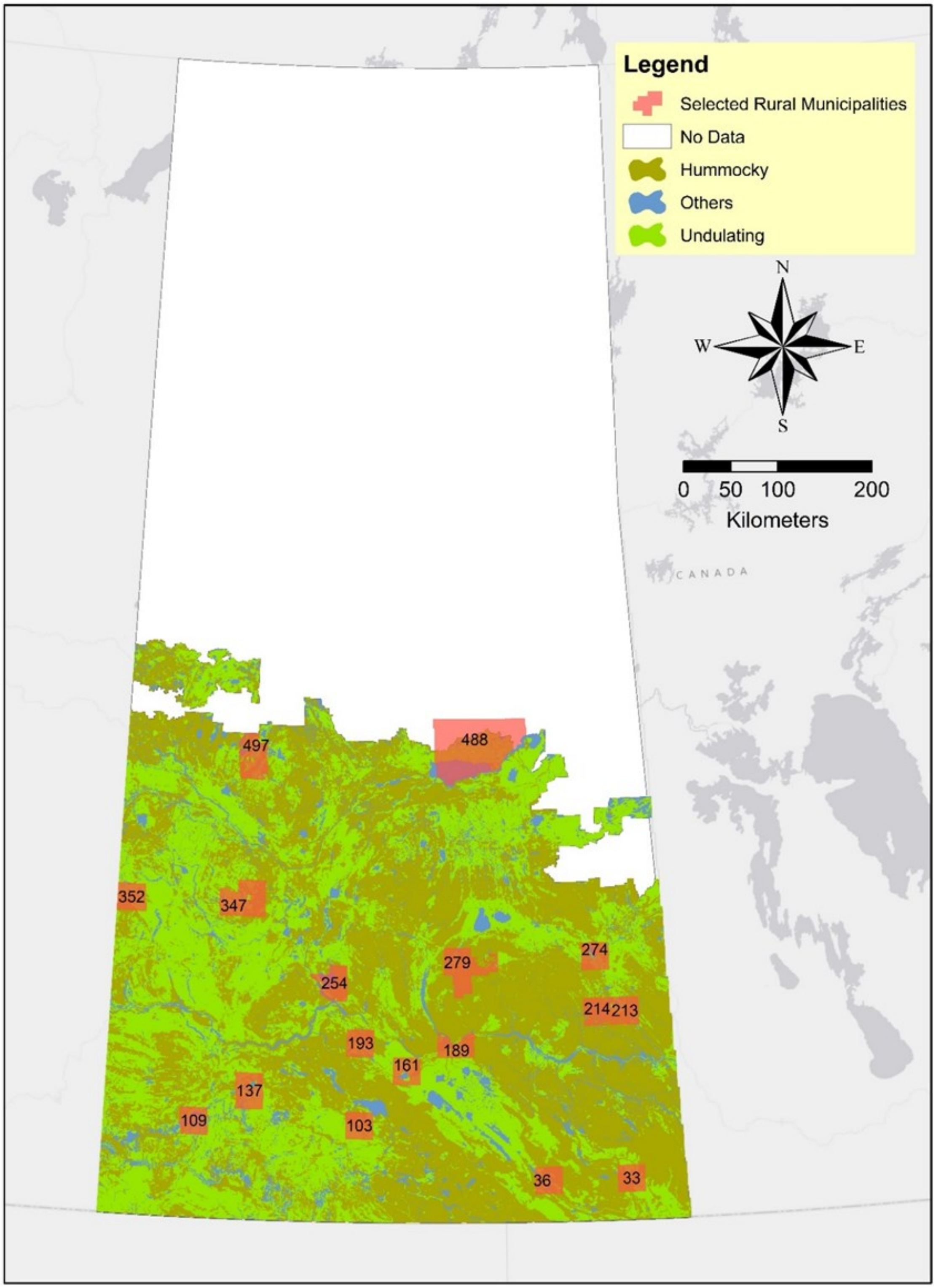
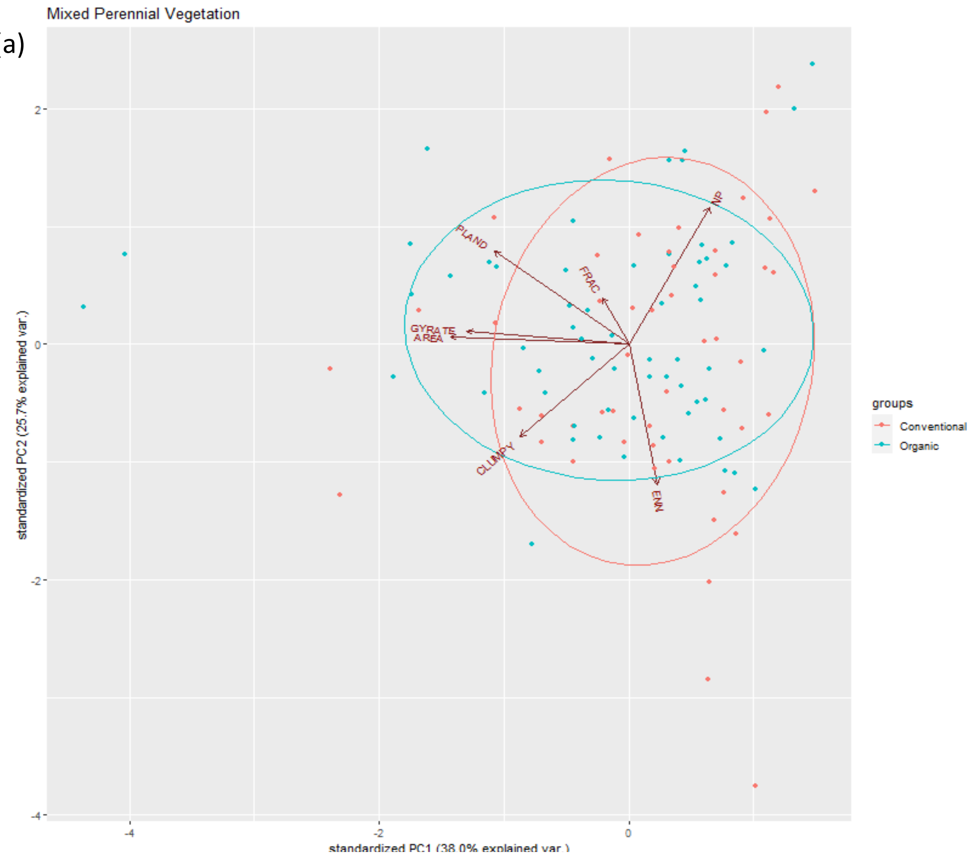
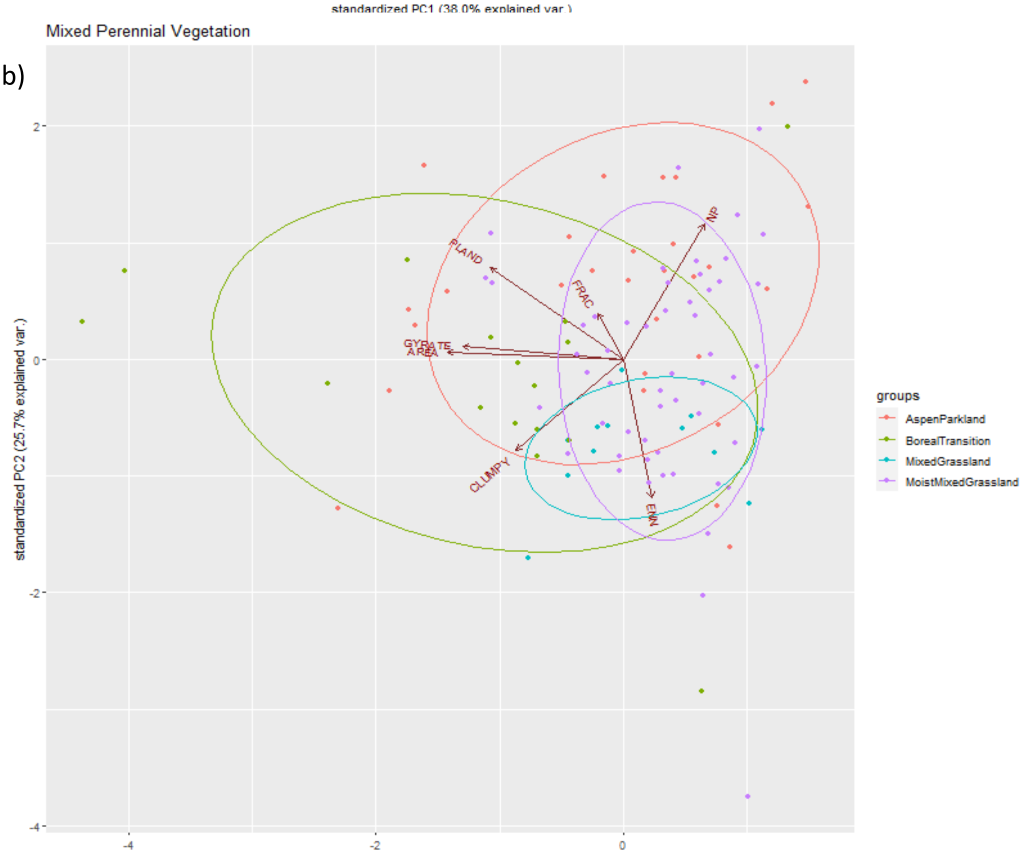


Fig. 28. Spatial location of selected rural municipalities (identified by municipal number) and surface expression. Basemap source: ESRI Canada. Projection: WGS_1984_Web_Mercator_Auxiliary_Sphere.

(a)


Mixed Perennial Vegetation
NP
PLAND
FRAC
GYRATE
AREA
CLUMPY
ENN
standardized PC2 (25.7% explained var.)
standardized PC1 (38.0% explained var.)
groups
Conventional
Organic

(b)


Mixed Perennial Vegetation
NP
PLAND
FRAC
GYRATE
AREA
CLUMPY
ENN
standardized PC2 (25.7% explained var.)
standardized PC1 (38.0% explained var.)
groups
AspenParkland
BorealTransition
MixedGrassland
MoistMixedGrassland

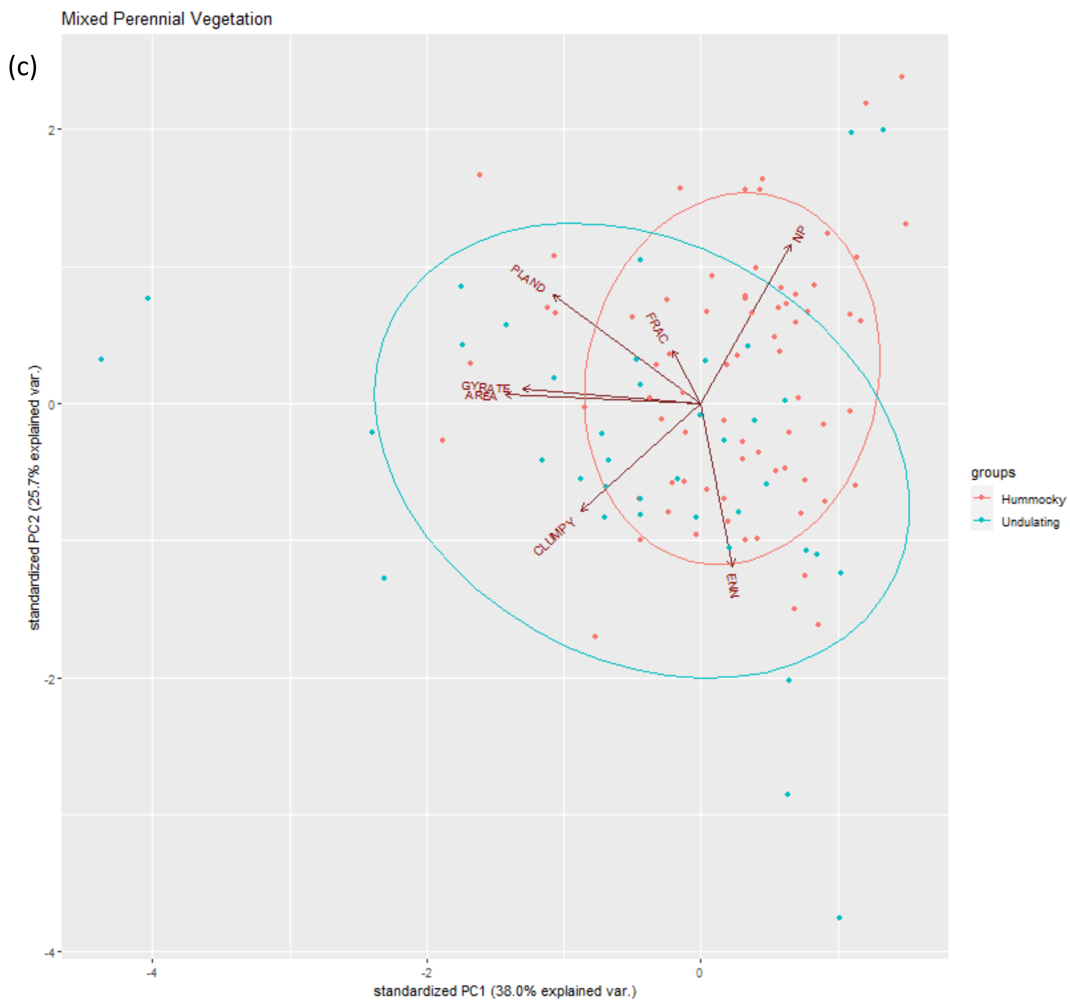


Fig. 29. Biplots for landscape metrics of Mixed Perennial Vegetation in a) farming system, in b) ecoregions and c) surface expression with 95% confidence ellipses.

(a)

(b)

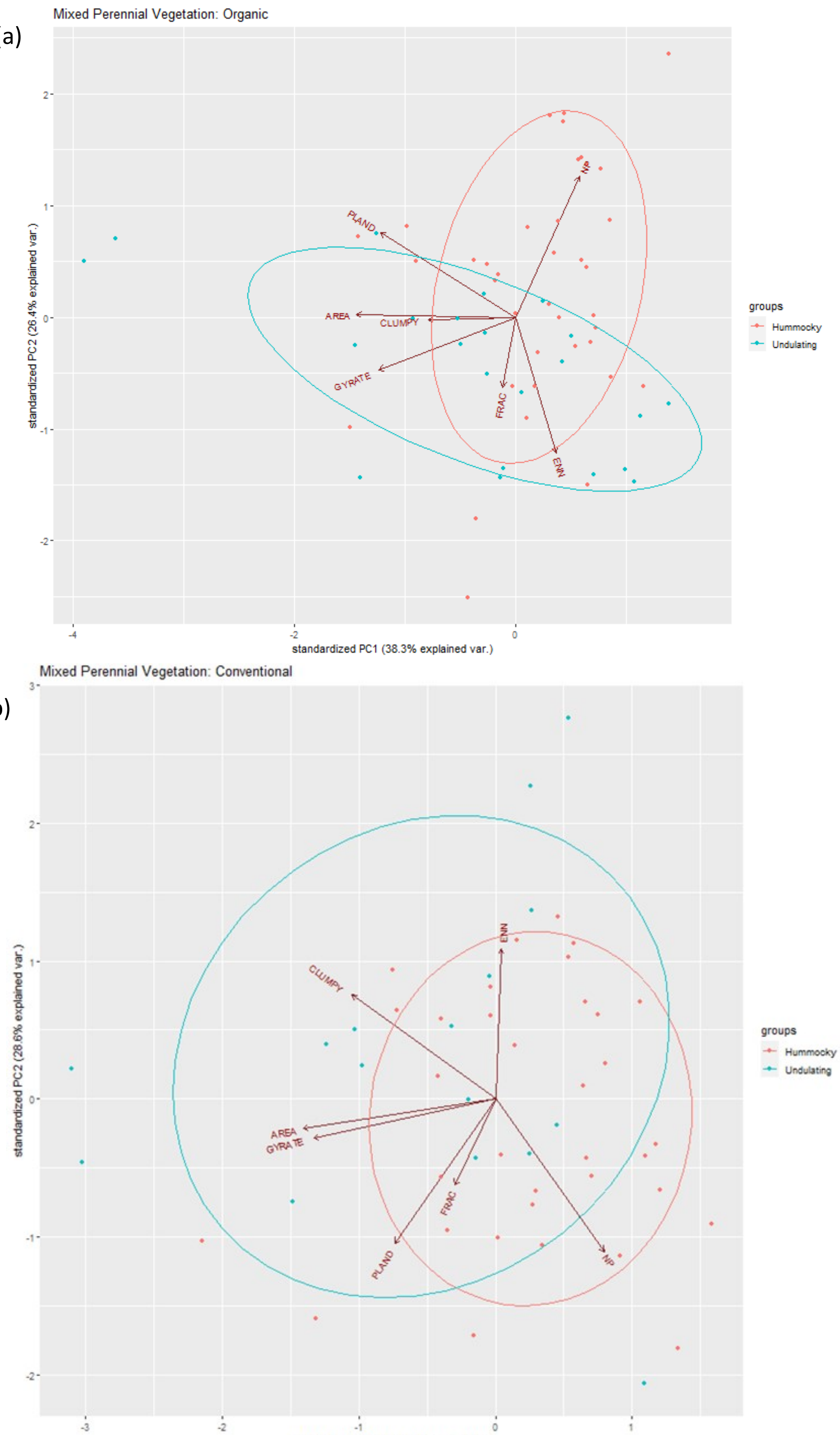
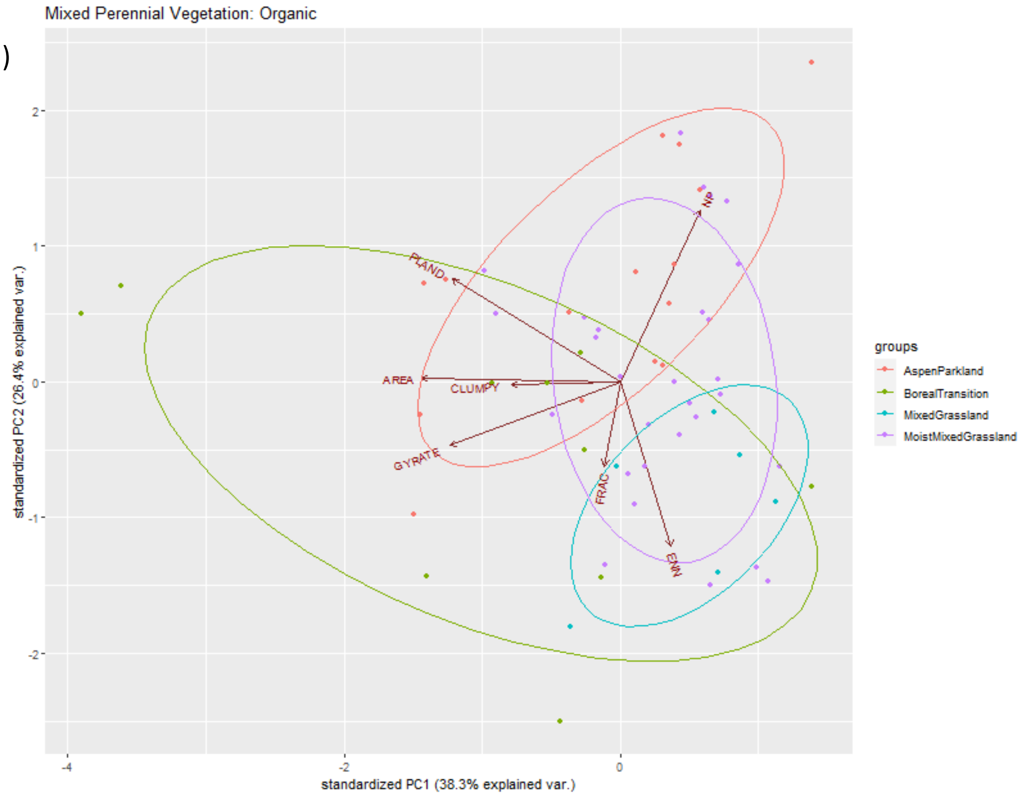


Fig. 30. Biplots for landscape metrics of Mixed Perennial Vegetation in the context of surface expression separated by a) organic and b) conventional system with 95% confidence ellipses.

(a)



(b)

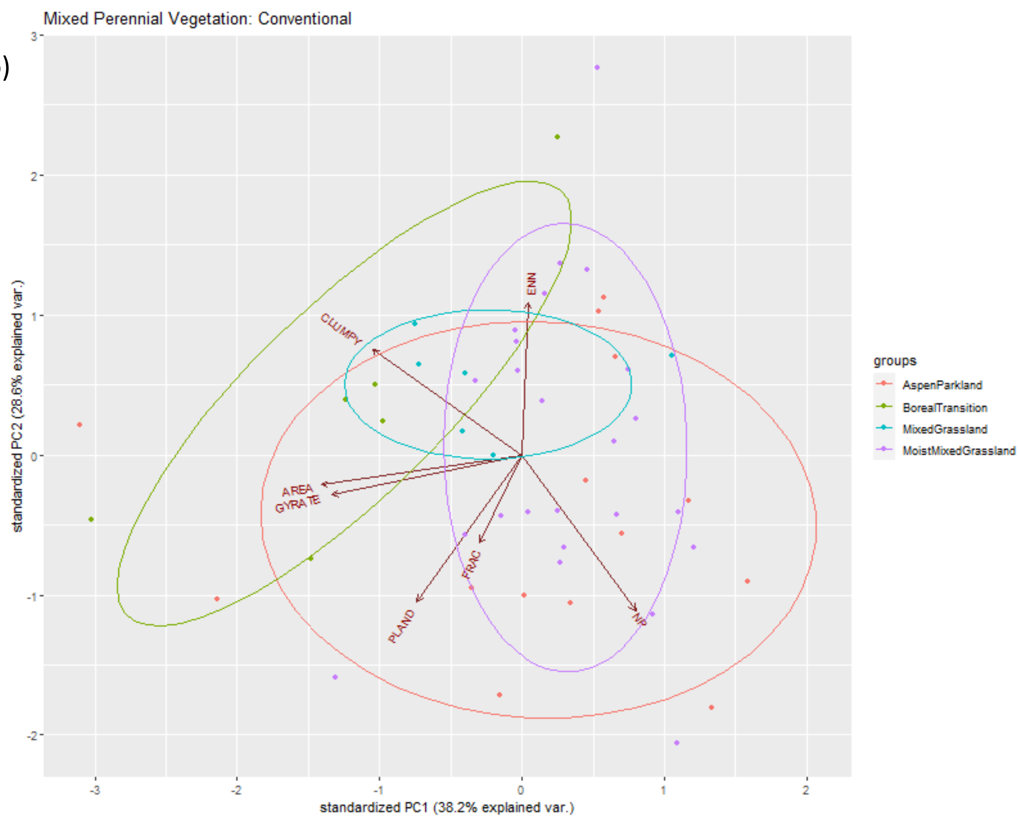


Fig. 31. Biplots for landscape metrics of Mixed Perennial Vegetation in the context of ecoregions separated by a) organic and b) conventional system with 95% confidence ellipses.

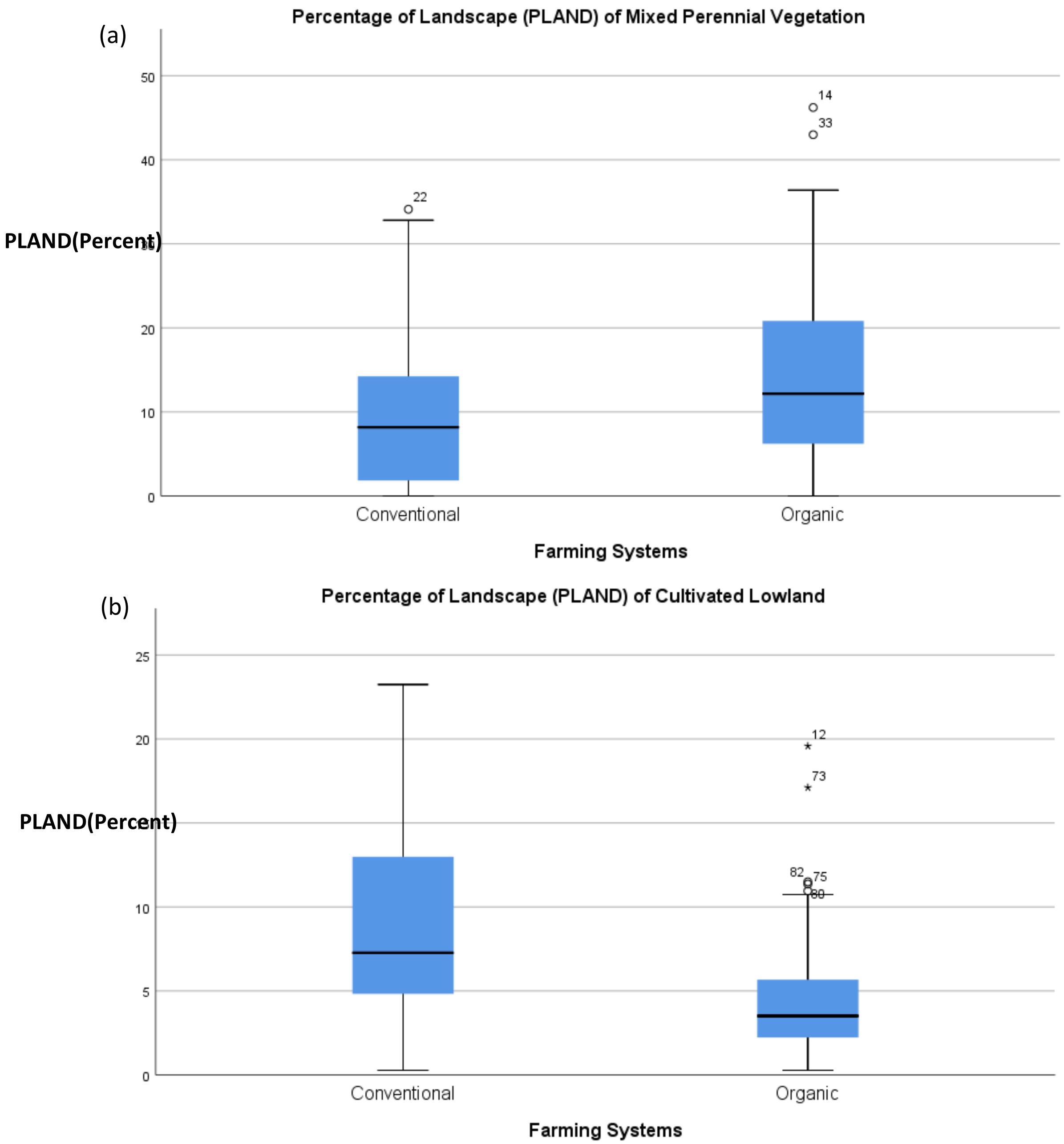


Fig. 32. Boxplots of Percentage of Landscape (PLAND) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems.

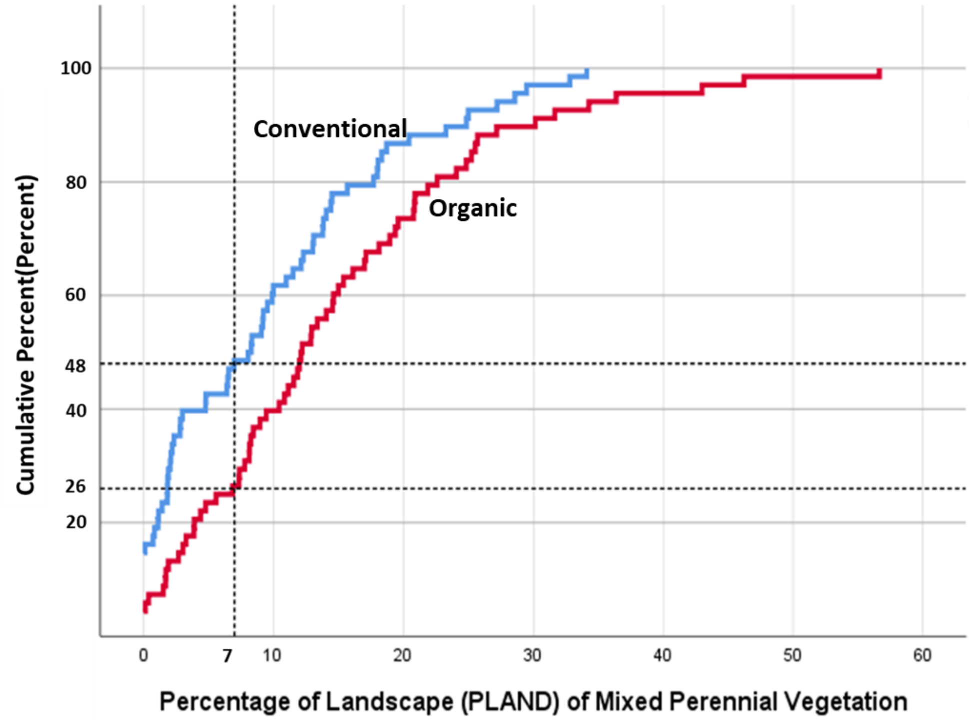


Fig. 33. Multiple lines chart showing cumulative percentage of farms against the Percentage of Landscape (PLAND) of Mixed Perennial Vegetation classified by farming systems. The figure illustrates that organic fields ranged from 0% to >40% area of Mixed Perennial Vegetation with 26% of fields not reaching a hypothetical target of 7% Mixed Perennial Vegetation as compared with conventional fields where 48% did not meet the 7% hypothetical target.

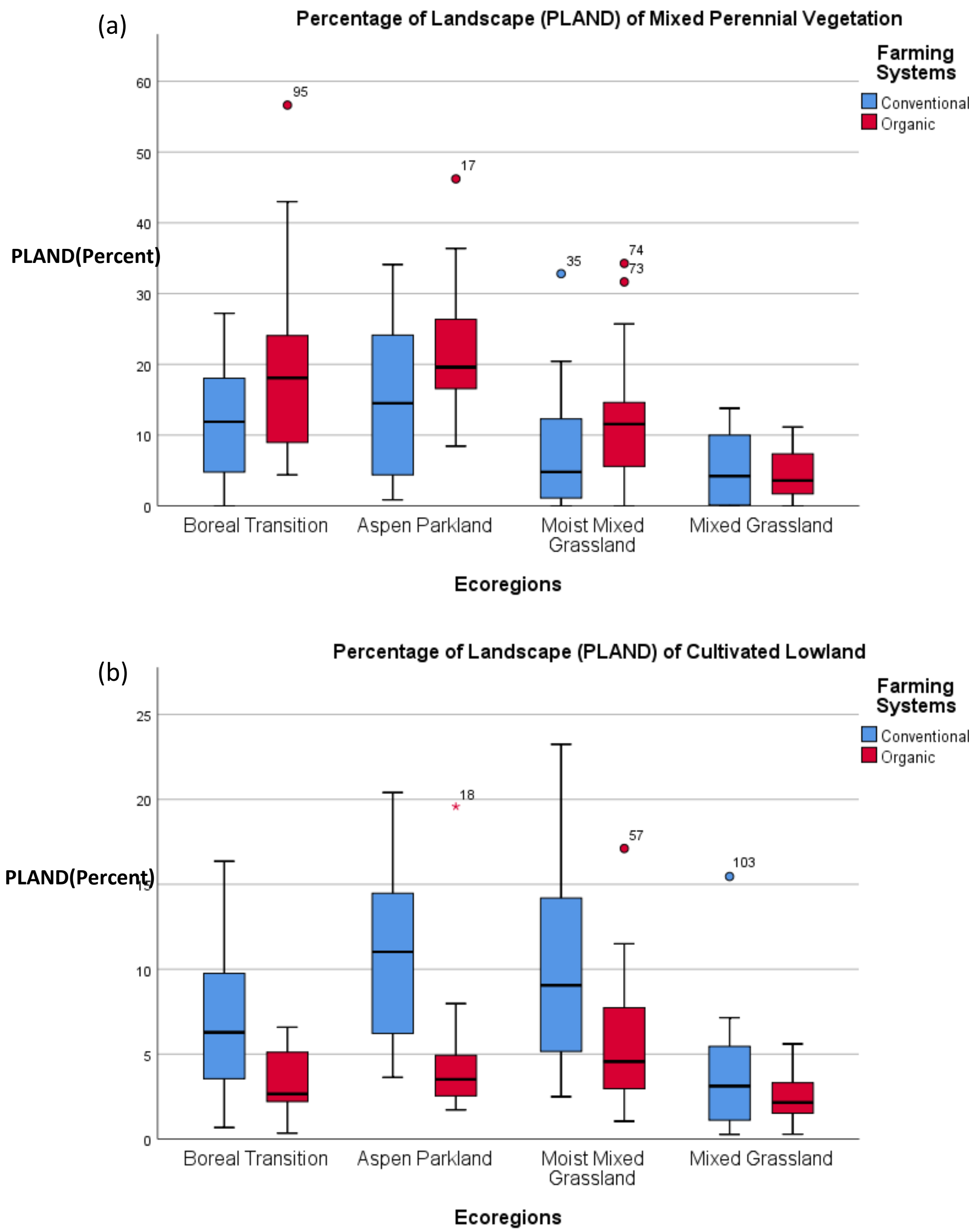


Fig. 34. Boxplots of Percentage of Landscape (PLAND) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems and ecoregions.

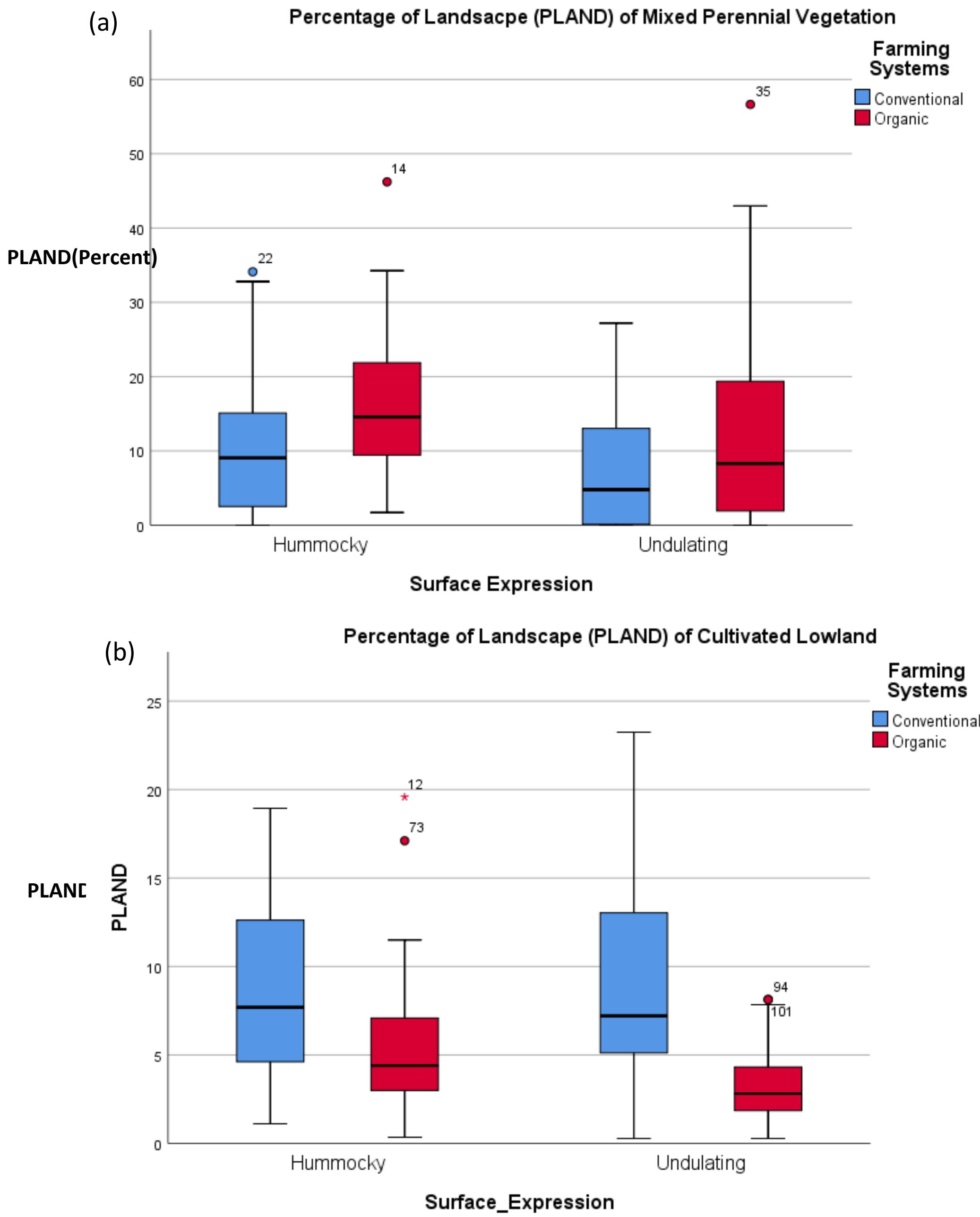


Fig. 35. Boxplots of Percentage of Landscape (PLAND) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems and surface expression.

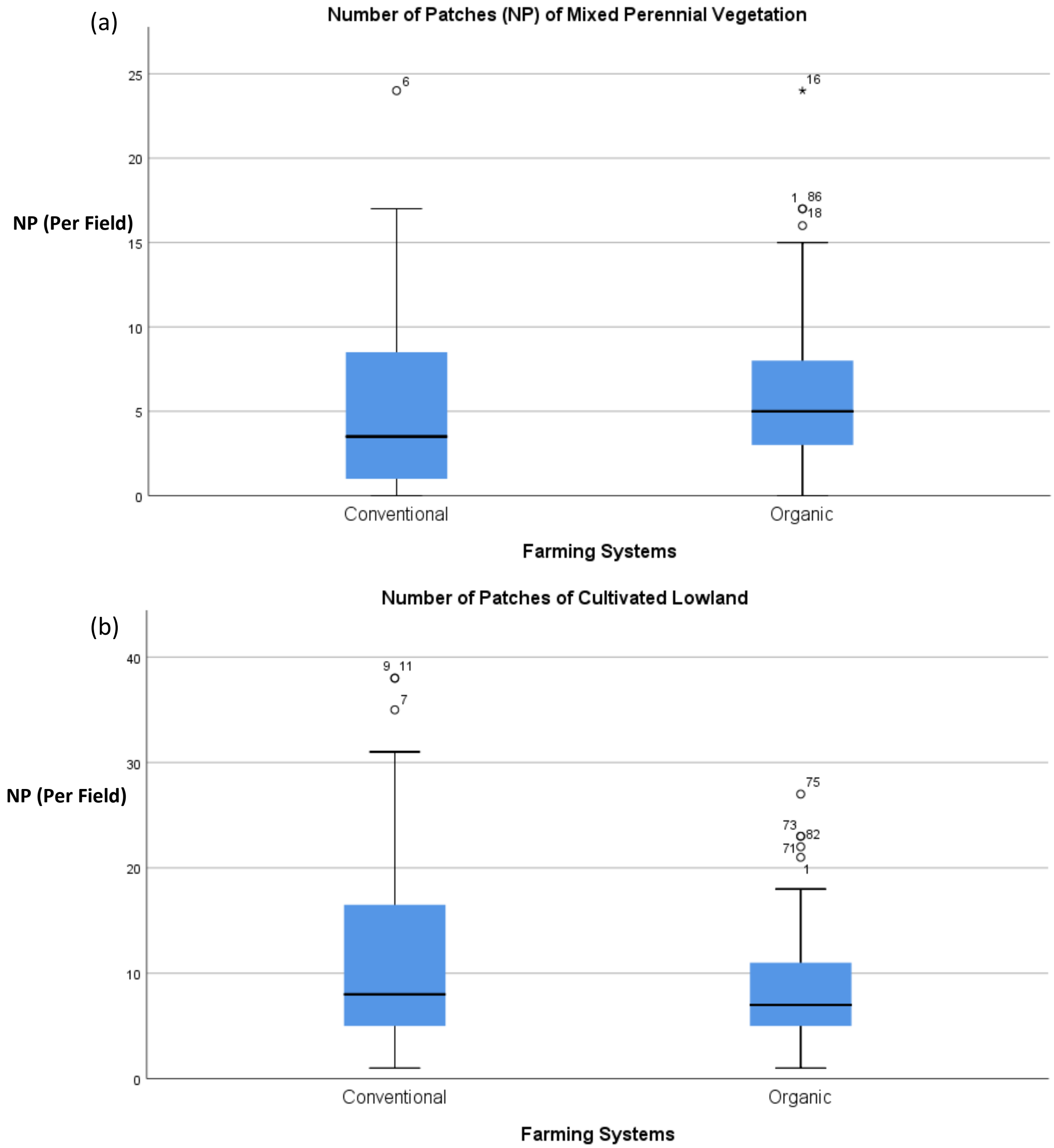


Fig. 36. Boxplots of Number of Patches (NP) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems.

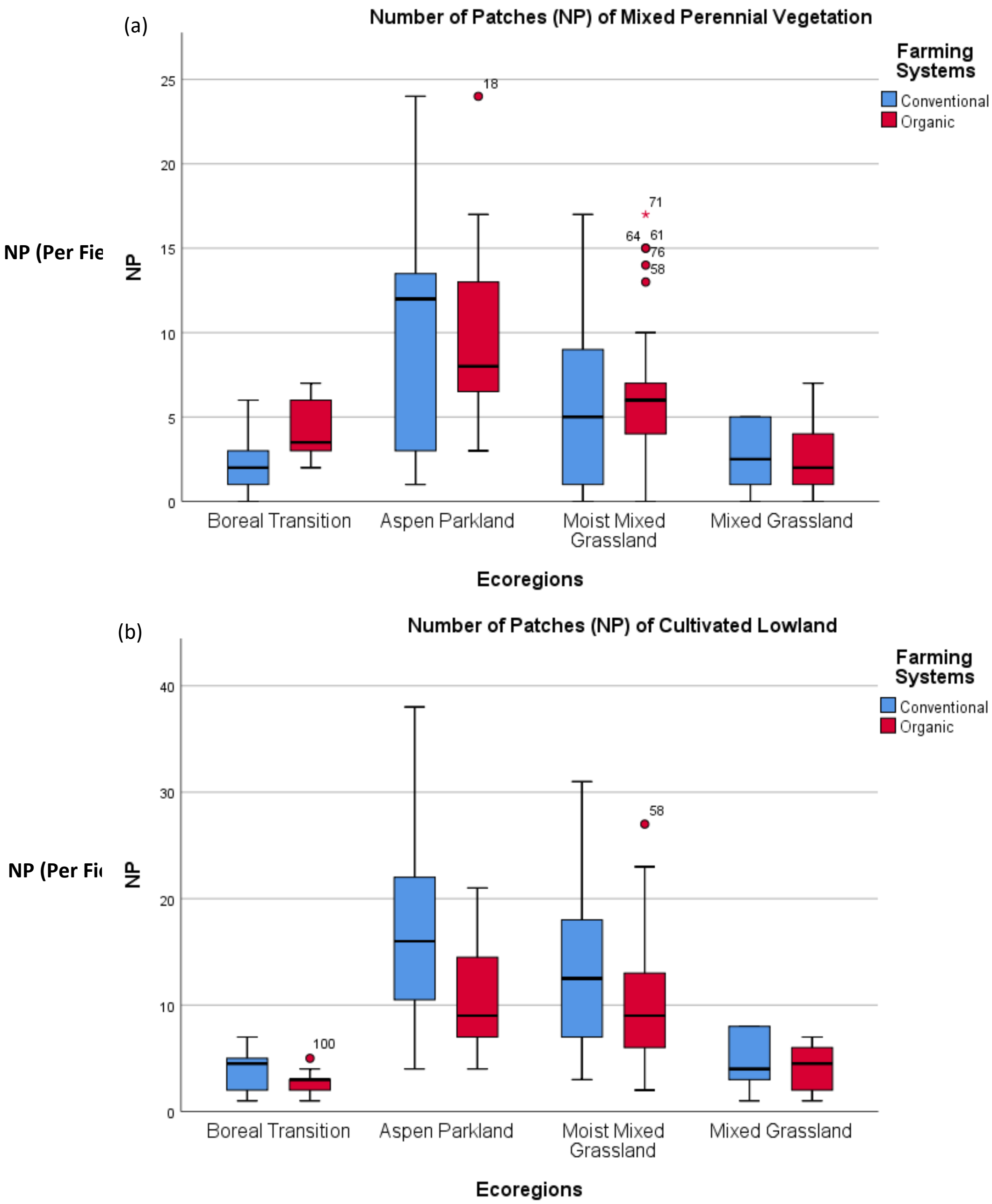


Fig. 37. Boxplots of Number of Patches (NP) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems and ecoregions.

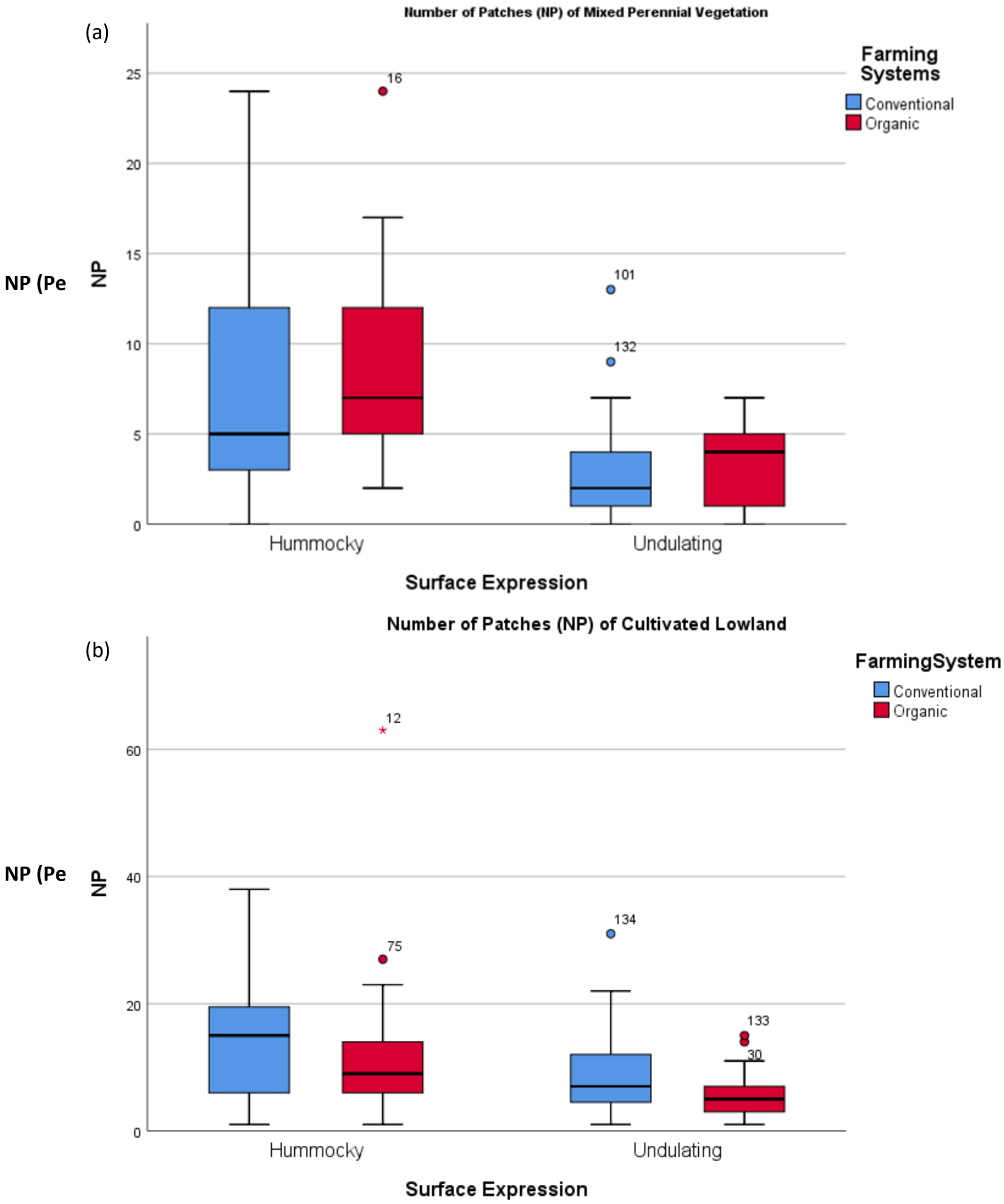


Fig. 38. Boxplot of Number of Patches (NP) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems and surface expression.

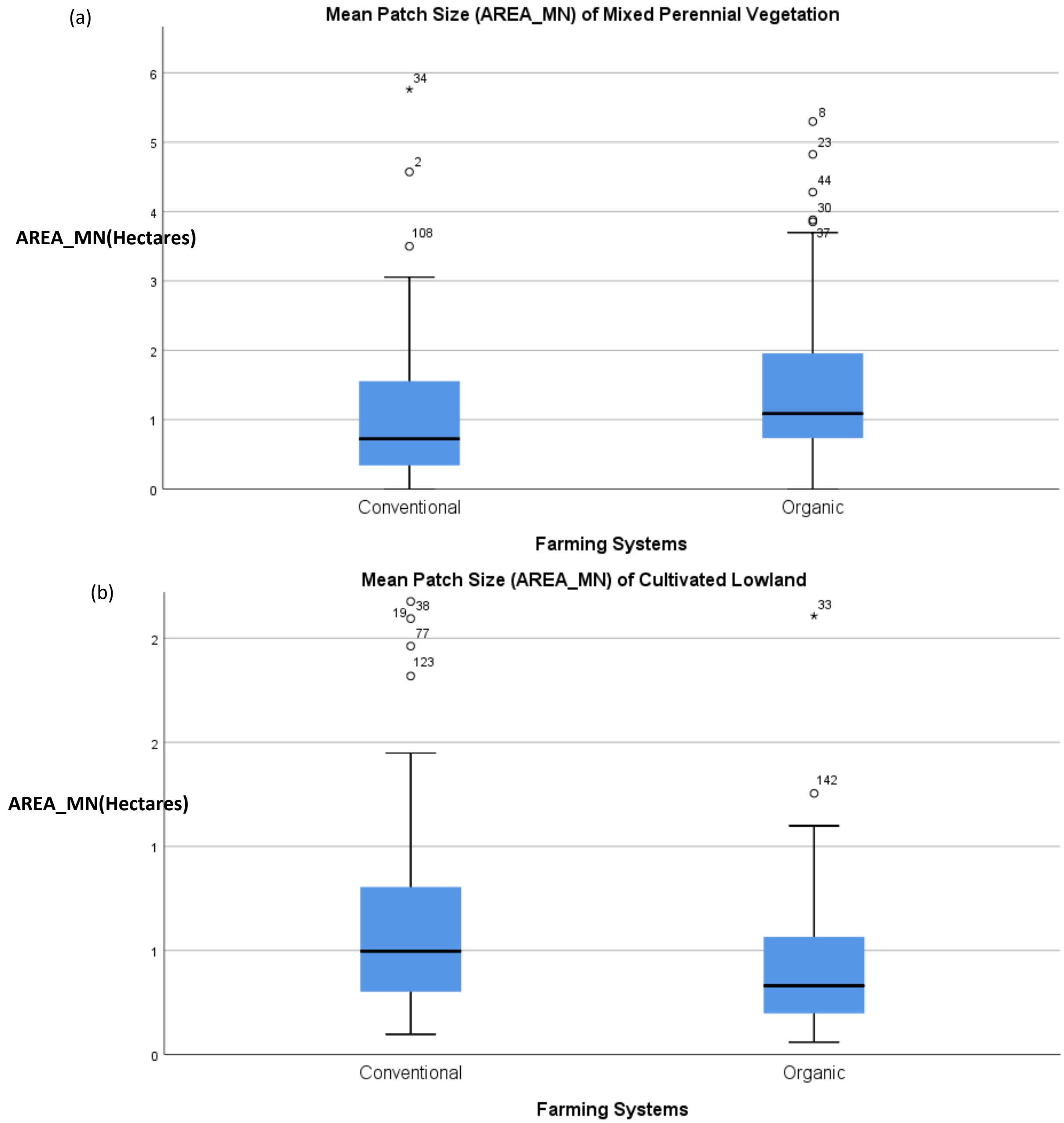


Fig. 39. Boxplots of Mean Patch Size (AREA_MN) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems.

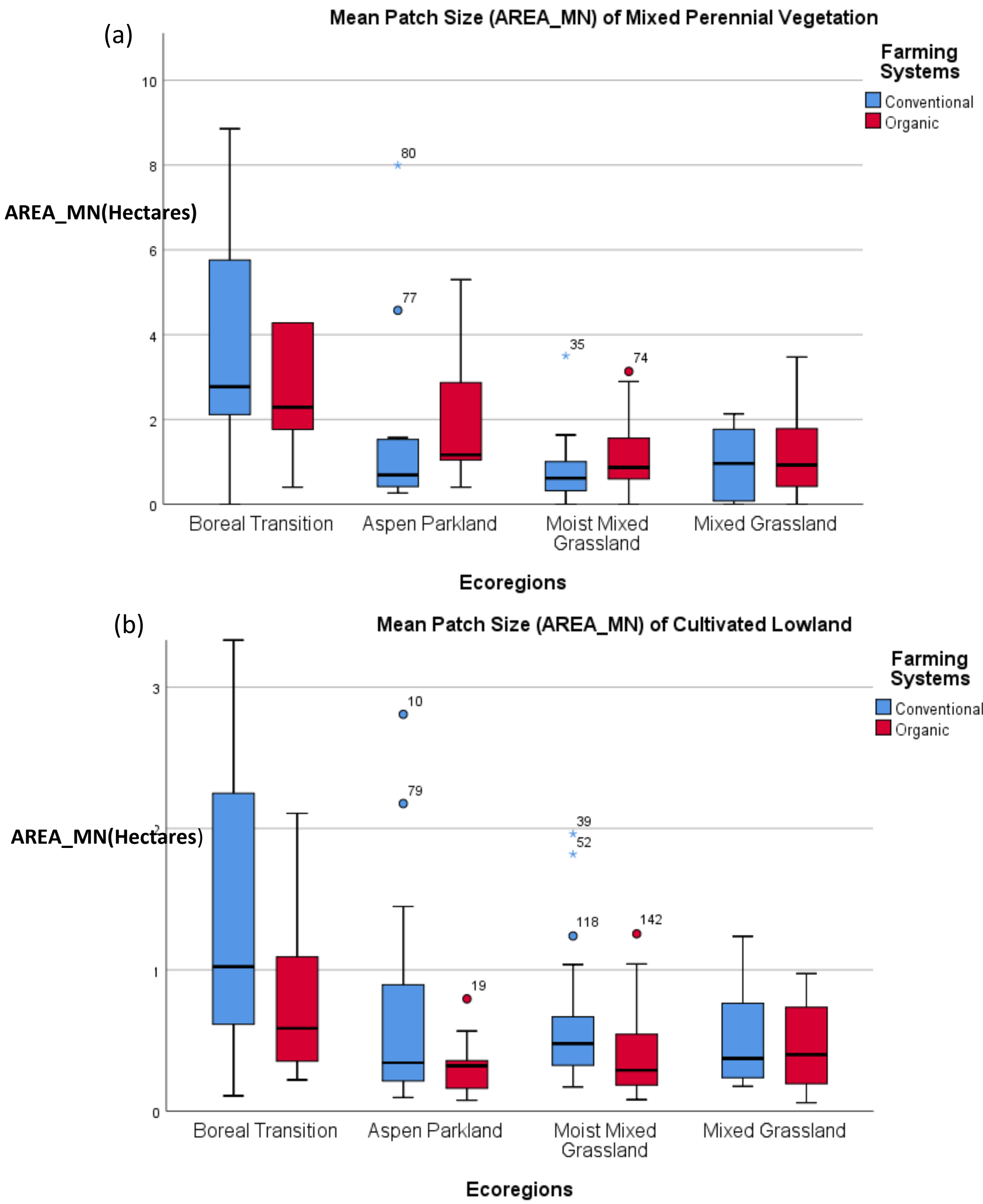
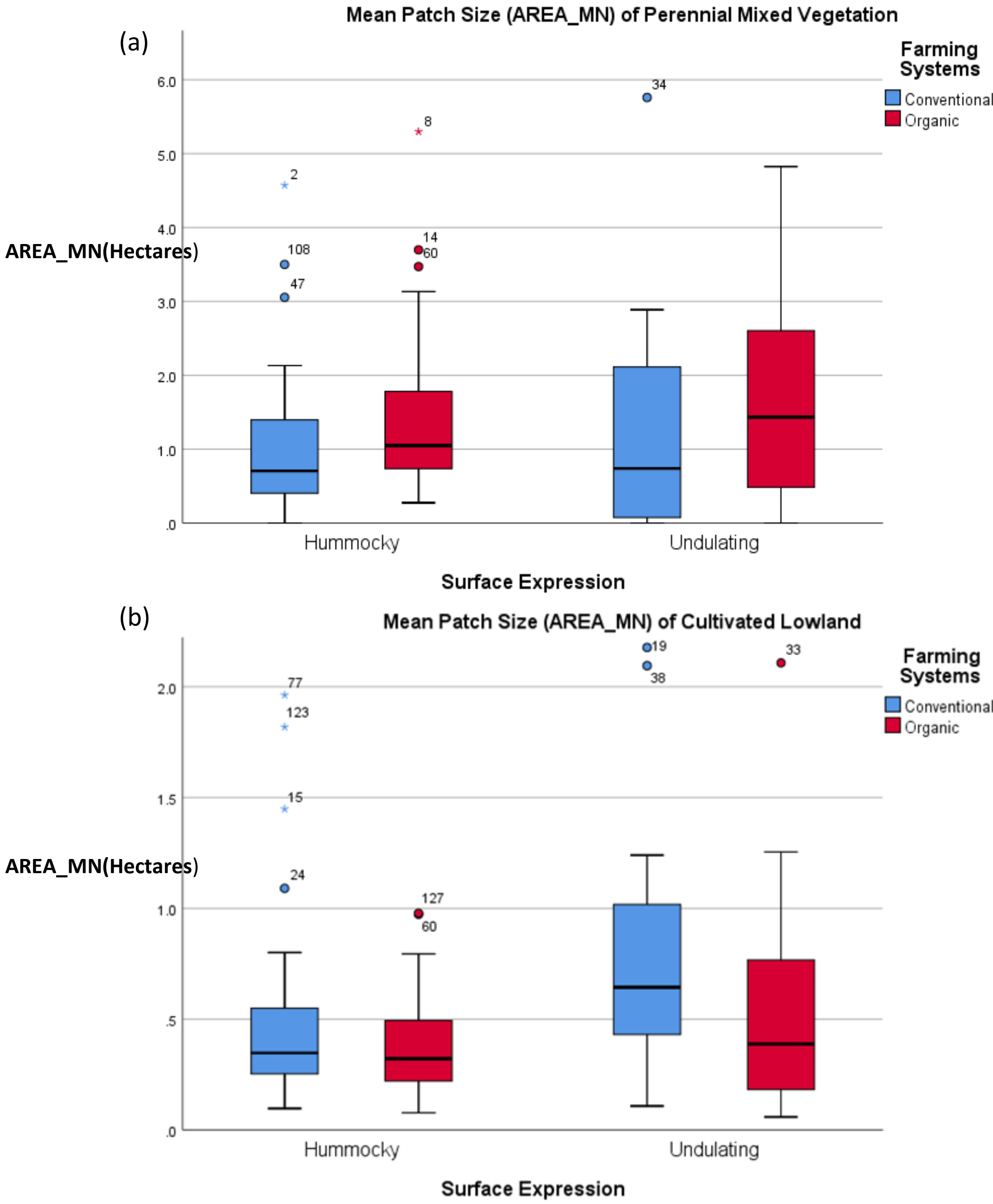


Fig. 40. Boxplots of Mean Patch Size (AREA_MN) of a) Mixed Perennial Vegetation and b) Cultivated Lowland classified by farming systems and ecoregions.

Fig. 17. Boxplots of Mean Patch Size (AREA_MN) of a) Mixed Perennial Vegetation and b) Cultivated Lowland



classified by farming systems and surface expression.

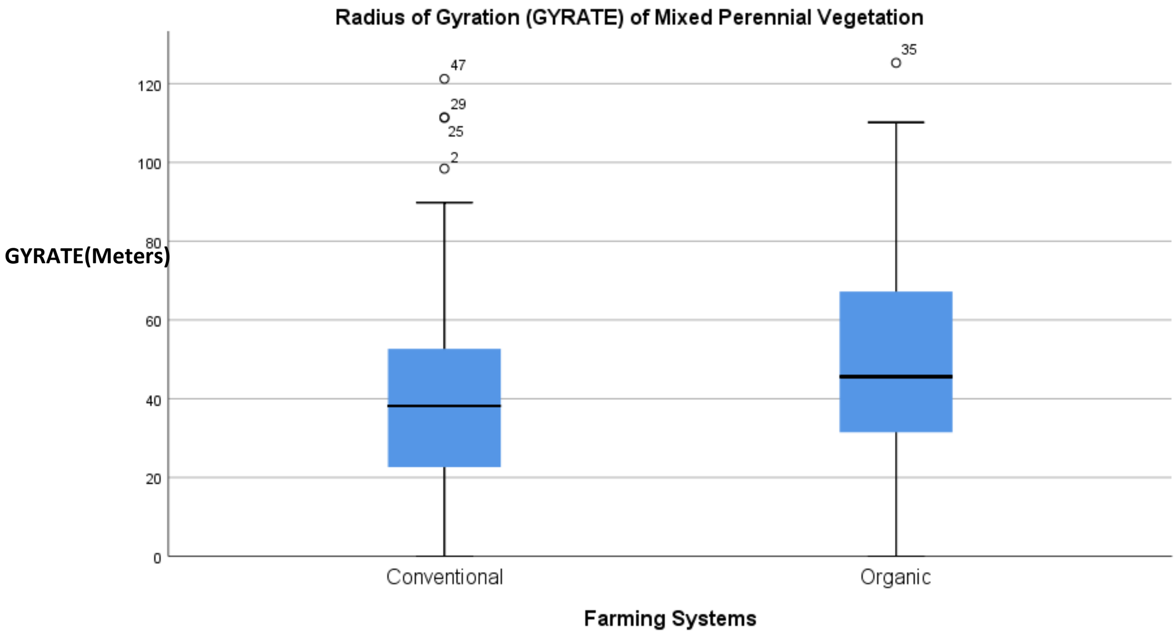


Fig. 41. Boxplot of Radius of Gyration (GYRATE) of Mixed Perennial Vegetation classified by farming systems.

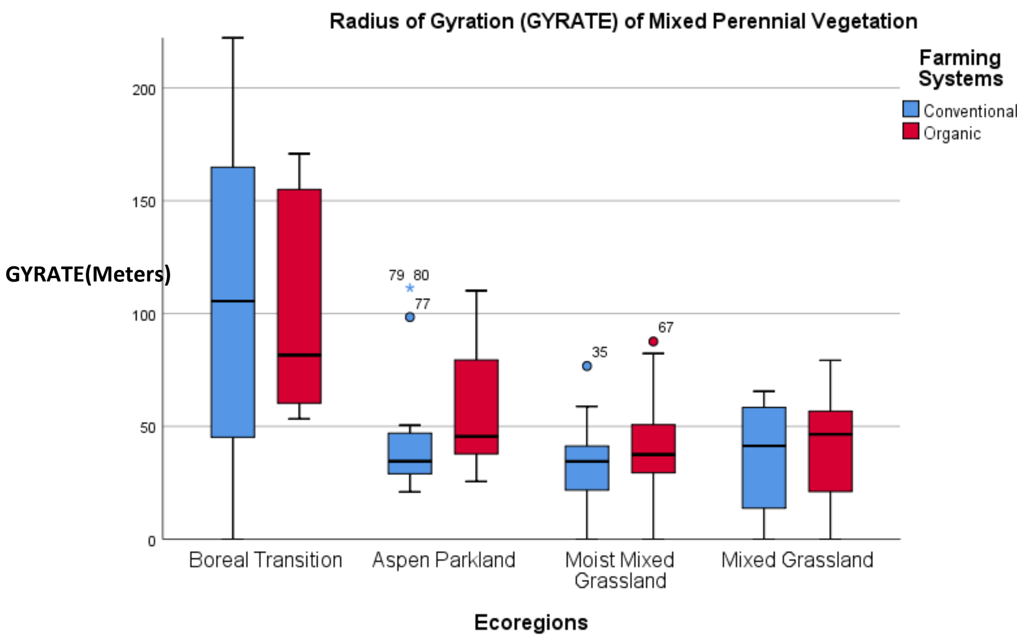


Fig. 42. Boxplot of Radius of Gyration (GYRATE) of Mixed Perennial Vegetation classified by farming systems and ecoregions.

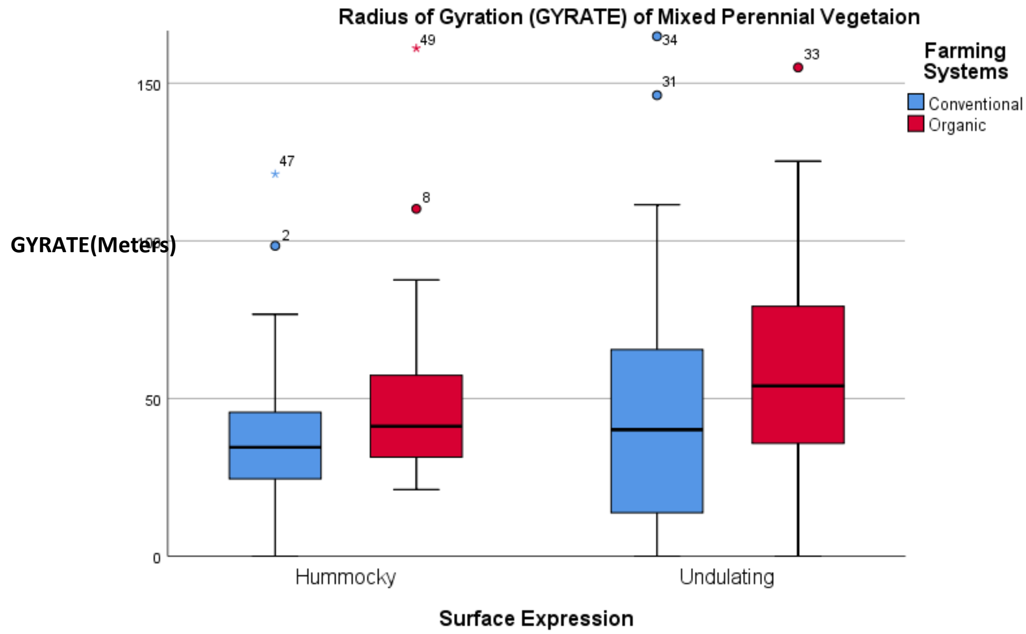


Fig. 43. Boxplot of Radius of Gyration (GYRATE) of Mixed Perennial Vegetation classified by farming systems and surface expression.

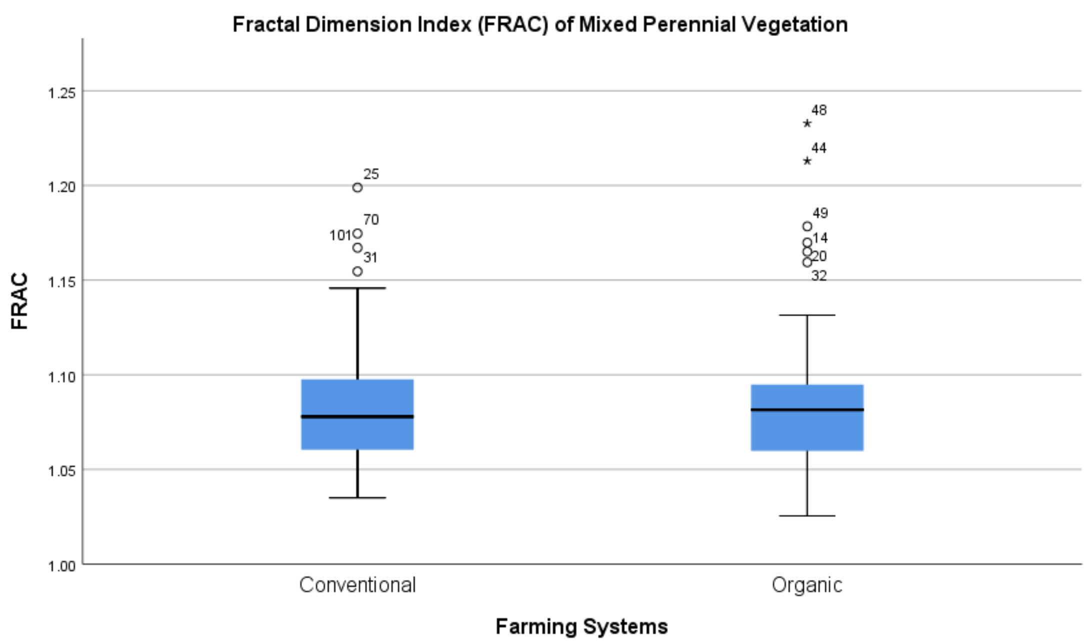


Fig. 44. Boxplot of Fractal Dimension Index (FRAC) of Mixed Perennial Vegetation classified by farming systems.

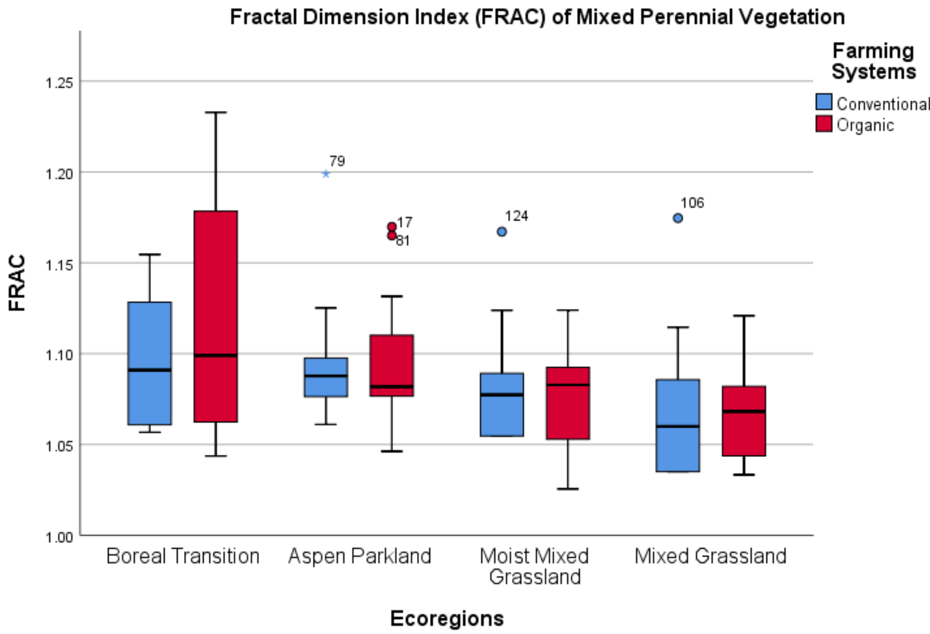


Fig. 45. Boxplot of Fractal Dimension Index (FRAC) of Mixed Perennial Vegetation classified by farming systems and ecoregions.

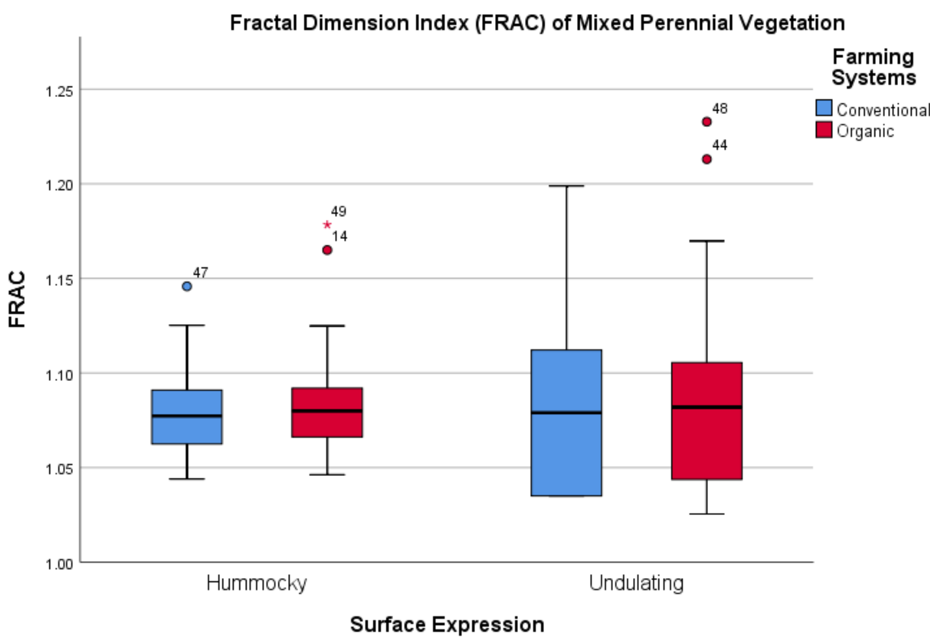


Fig. 46. Boxplot of Fractal Dimension Index (FRAC) of Mixed Perennial Vegetation classified by farming systems and surface expression.

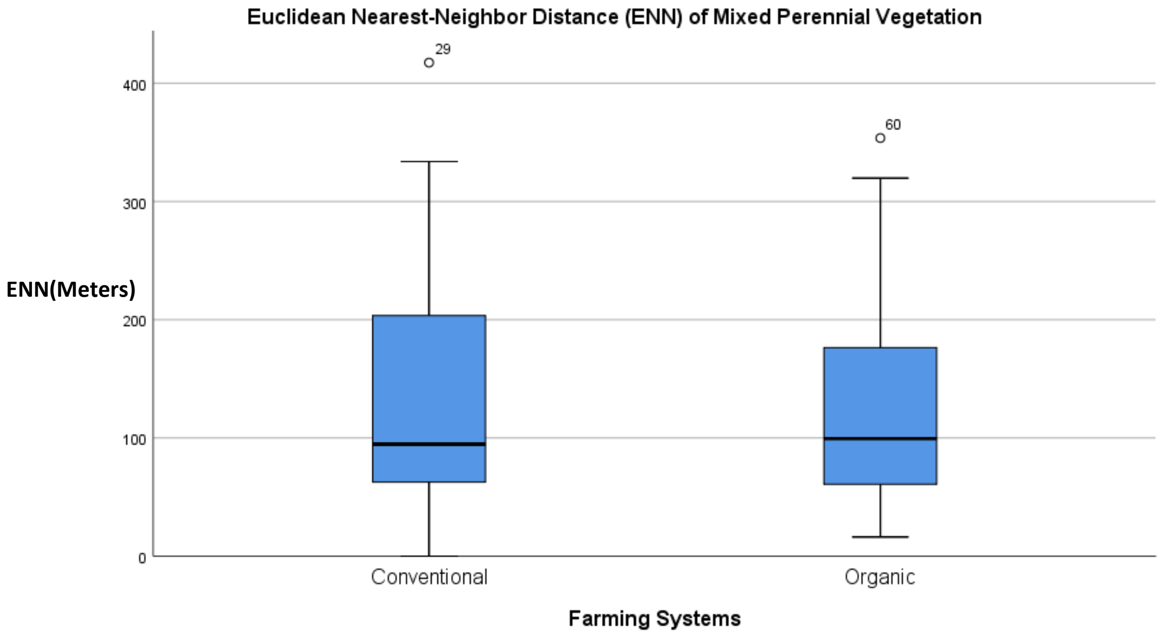


Fig. 47. Boxplot of Euclidean Nearest-Neighbor Distance (ENN) of Mixed Perennial Vegetation classified by farming systems.

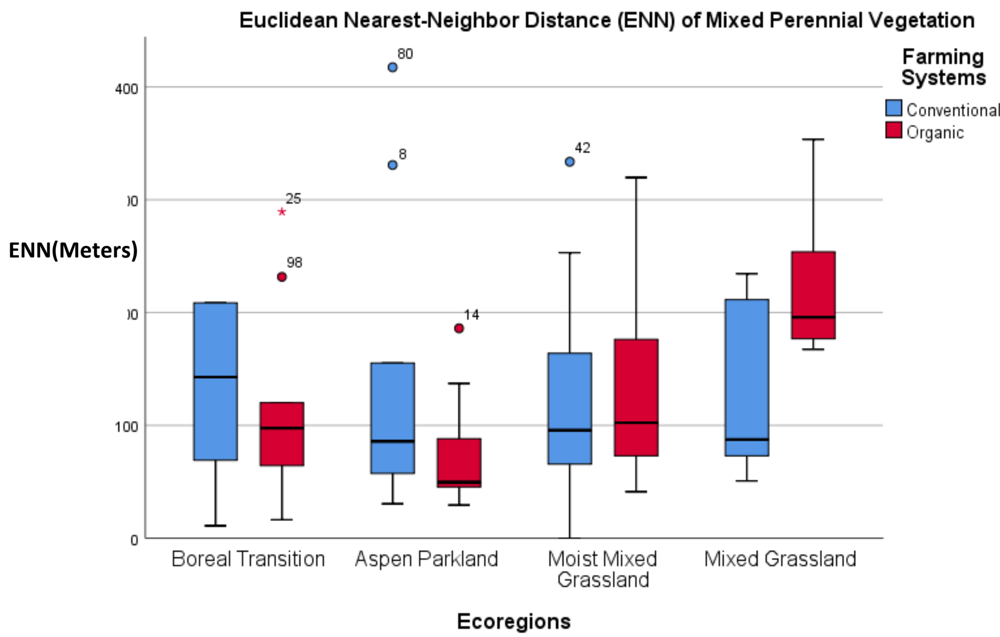


Fig. 48. Boxplot of Euclidean Nearest-Neighbor Distance (ENN) of Mixed Perennial Vegetation classified by farming systems and ecoregions.

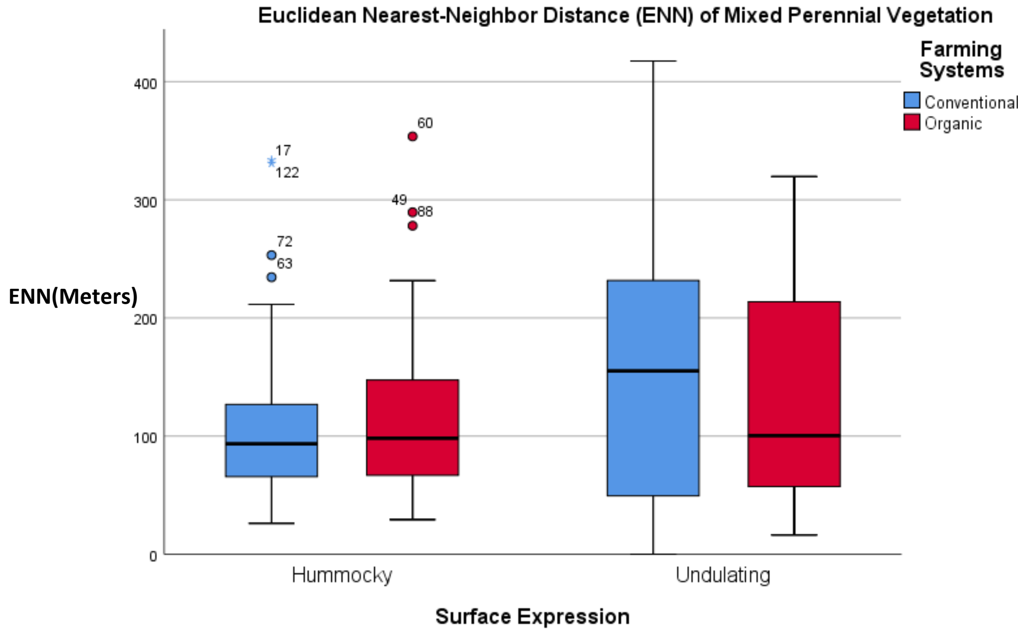


Fig. 49. Boxplot of Euclidean Nearest-Neighbor Distance (ENN) of Mixed Perennial Vegetation classified by farming systems and surface expression.

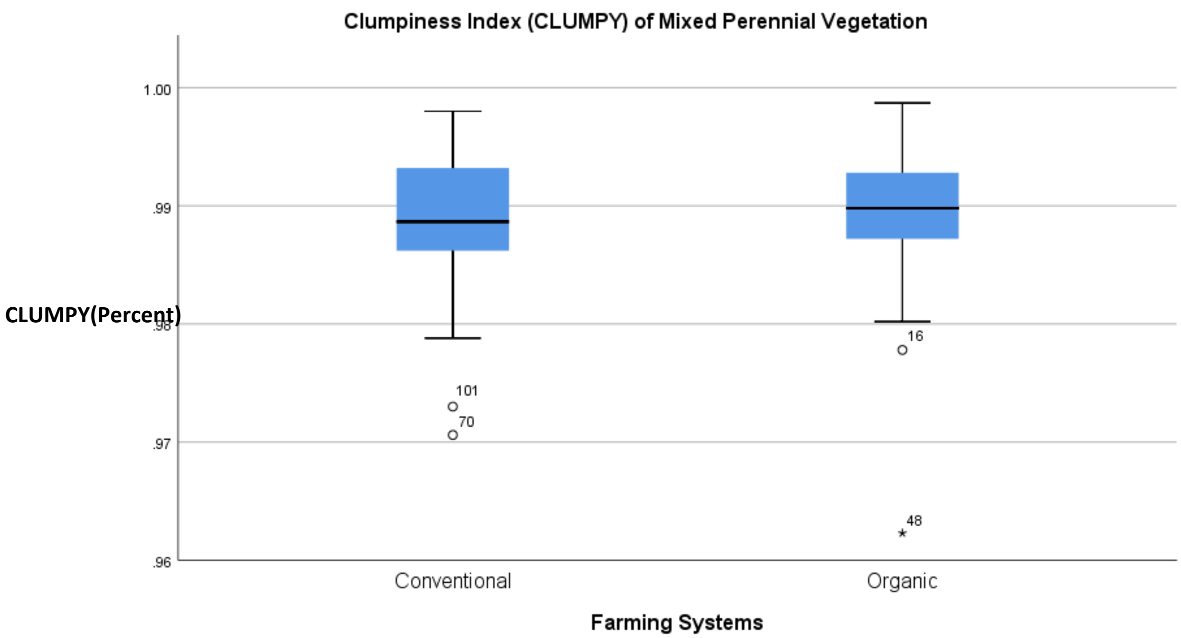


Fig. 50. Boxplot of Clumpiness Index (CLUMPY) of Mixed Perennial Vegetation classified by farming systems.

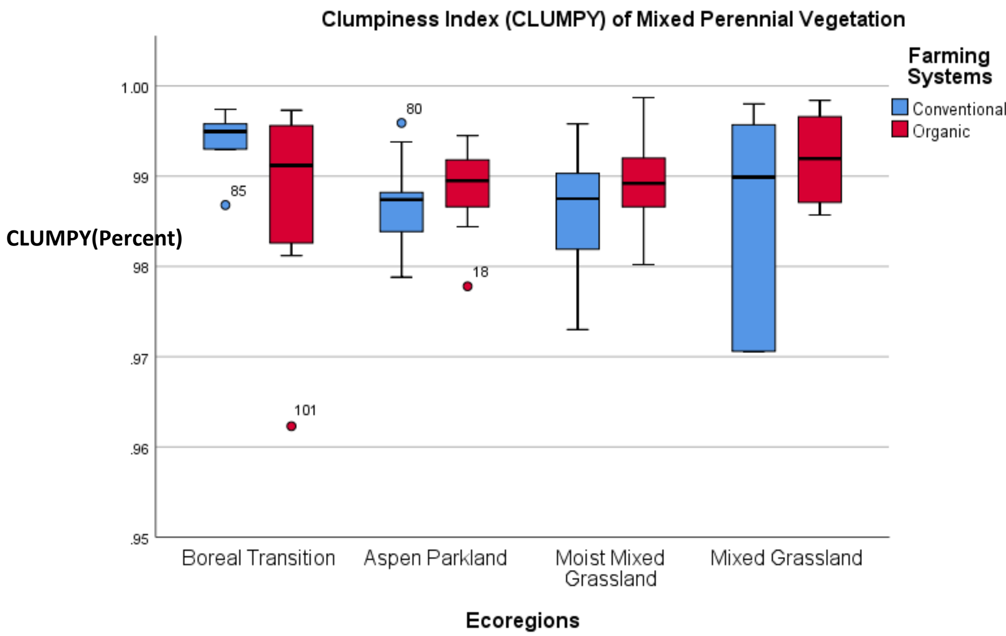


Fig. 51. Boxplot of Clumpiness Index (CLUMPY) of Mixed Perennial Vegetation classified by farming systems and ecoregions.

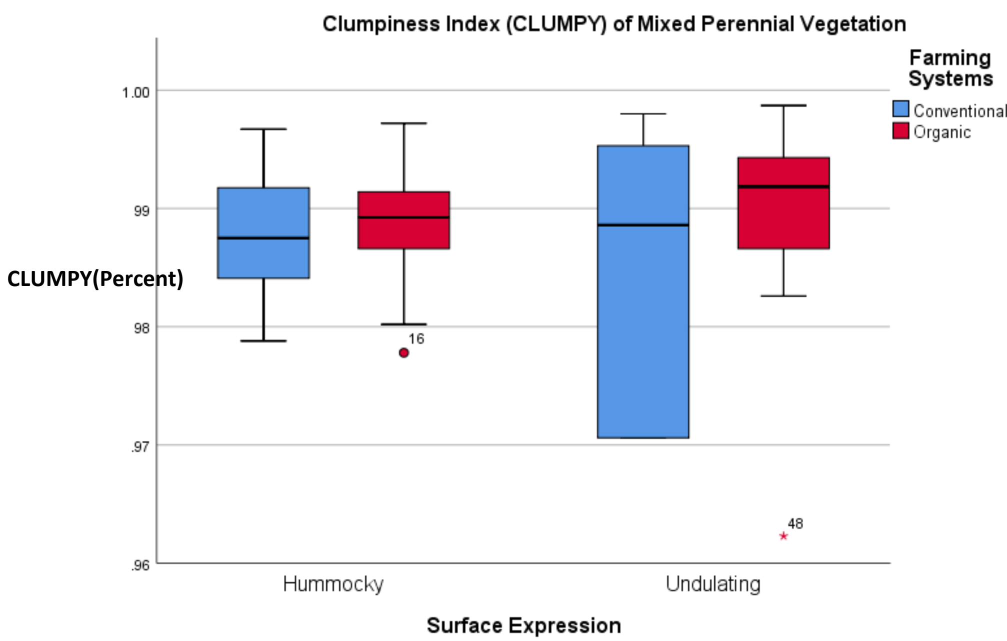


Fig. 52. Boxplot of Clumpiness Index (CLUMPY) of Mixed Perennial Vegetation classified by farming systems and surface expression.

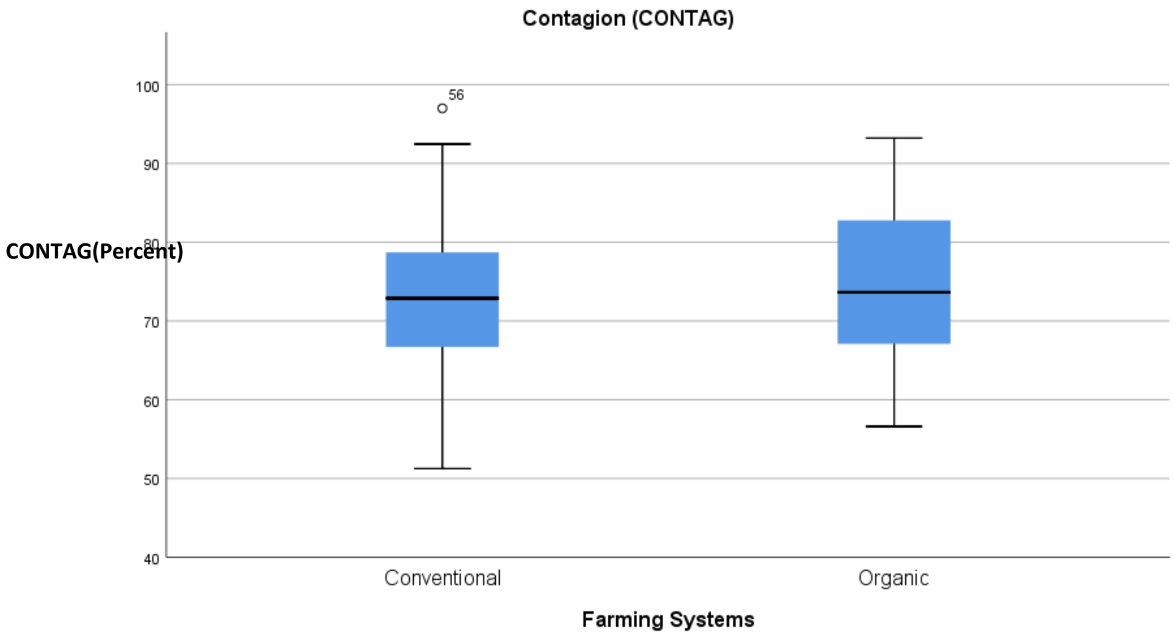


Fig. 53. Boxplot of Contagion (CONTAG) classified by farming systems.

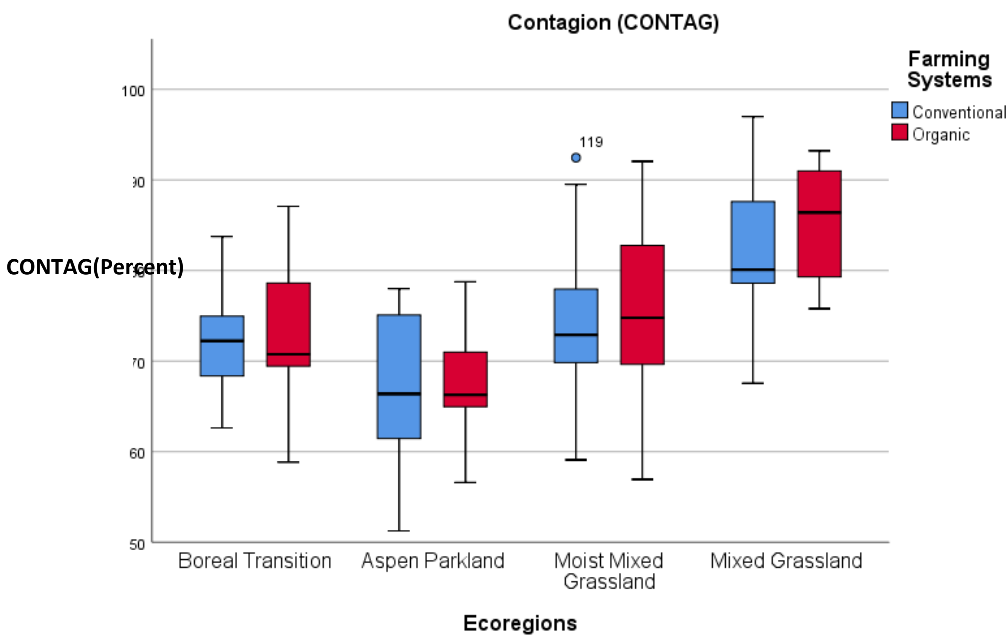


Fig. 54. Boxplot of Contagion (CONTAG) classified by farming systems and ecoregions.

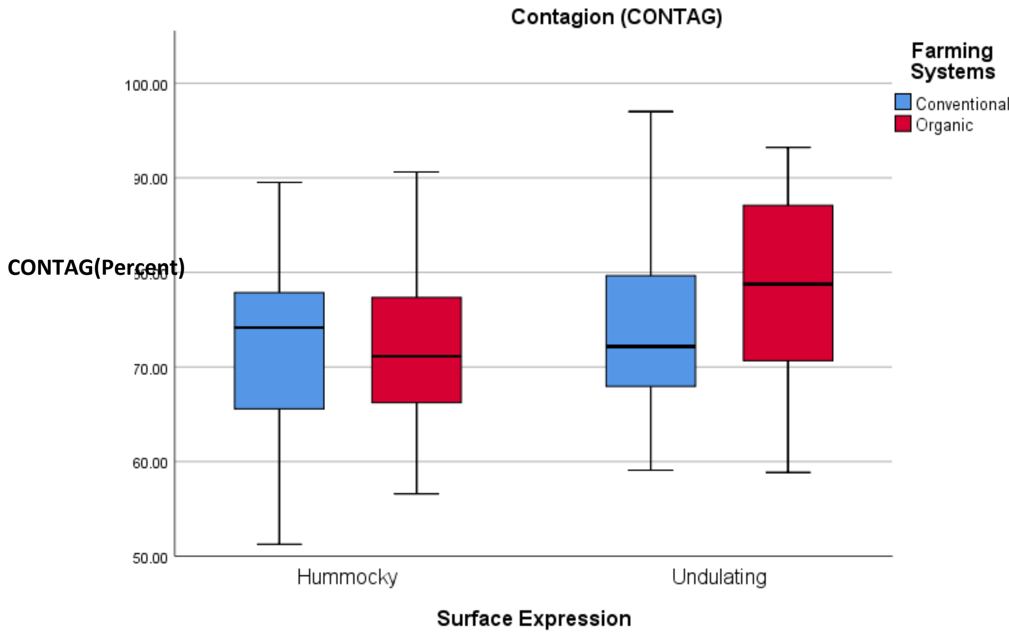


Fig. 55. Boxplot of Contagion (CONTAG) classified by farming systems and surface expression.

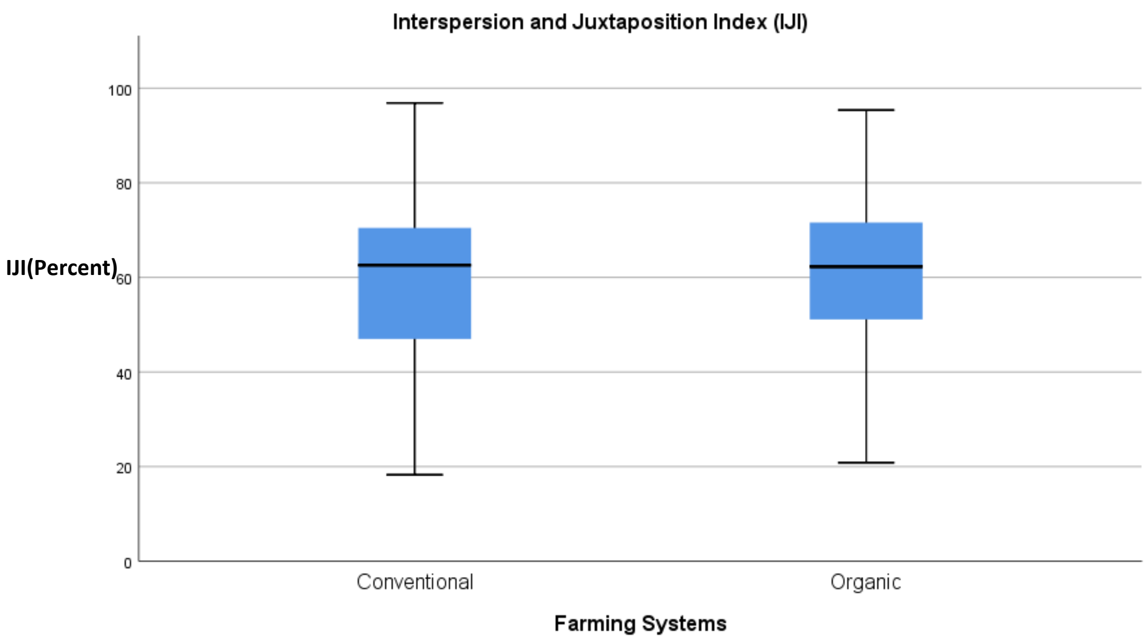


Fig. 56. Boxplot of Interspersion and Juxtaposition Index (IJI) classified by farming systems.

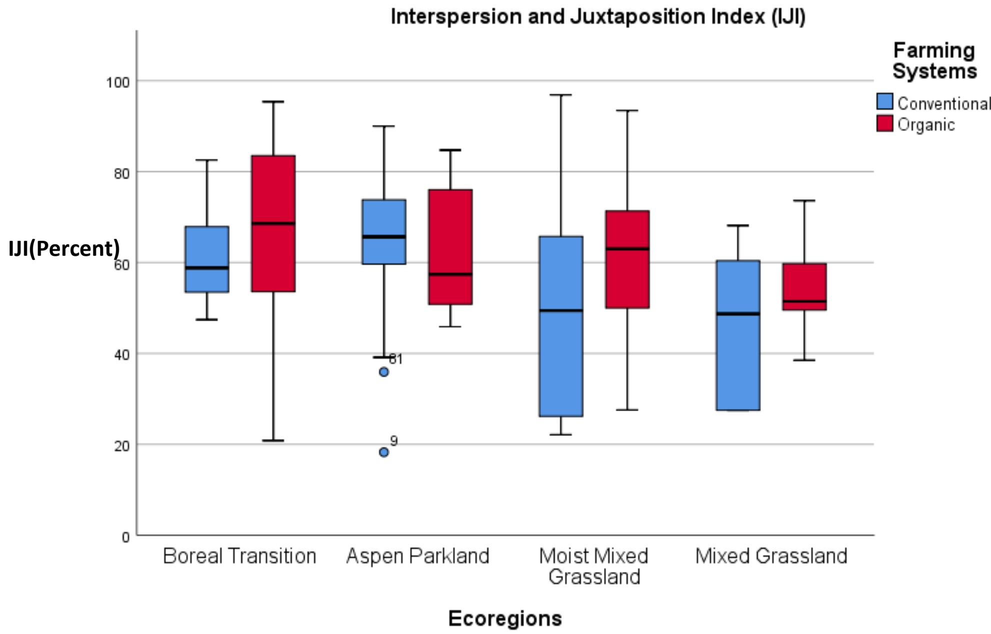


Fig. 57. Boxplot of Interspersion and Juxtaposition Index (IJI) classified by farming systems and ecoregions.

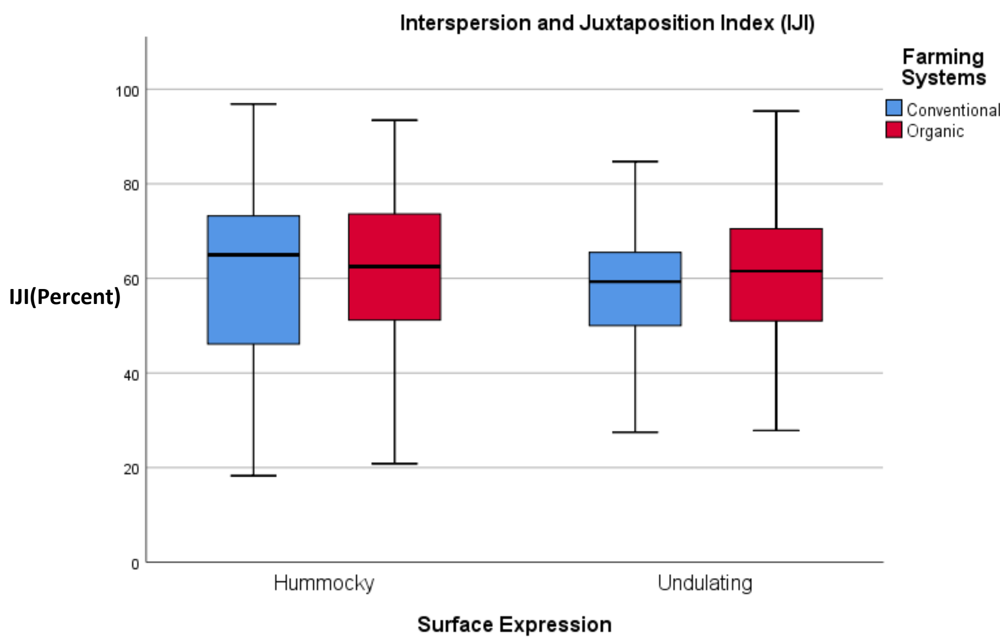


Fig. 58. Boxplot of Interspersion and Juxtaposition Index (IJI) classified by farming systems and surface expression.

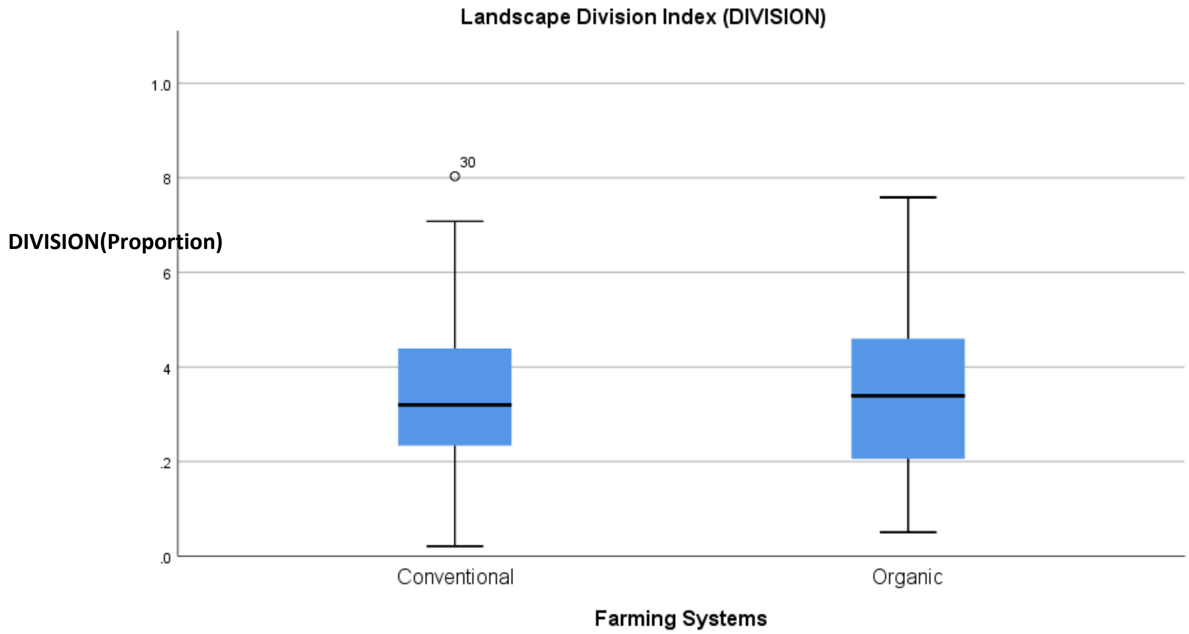


Fig. 59. Boxplot of Landscape Division Index (DIVISION) classified by farming systems.

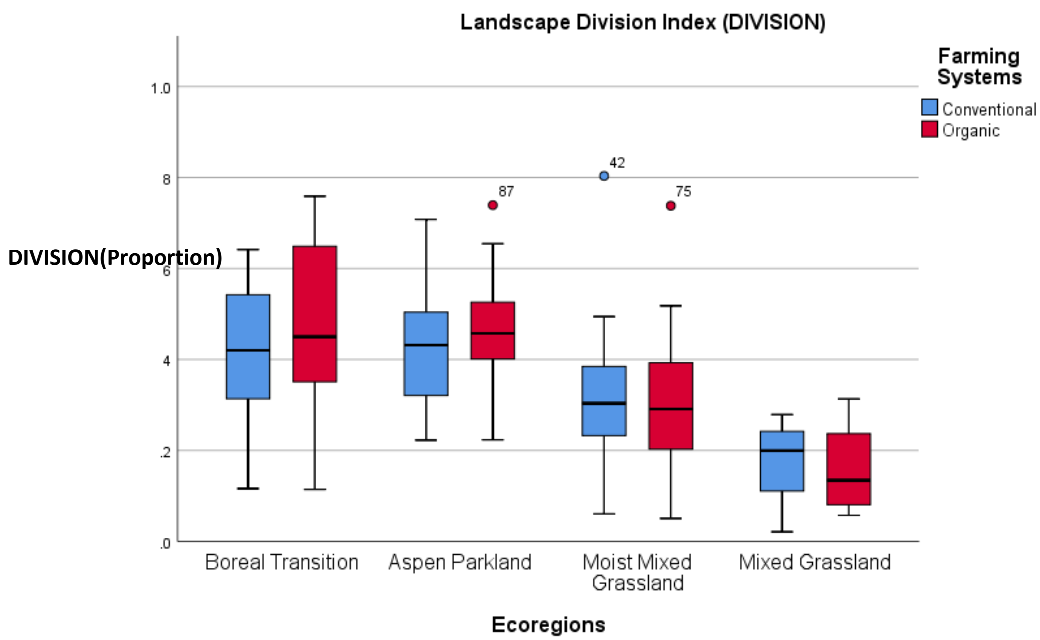


Fig. 60. Boxplot of Landscape Division Index (DIVISION) classified by farming systems and ecoregions.

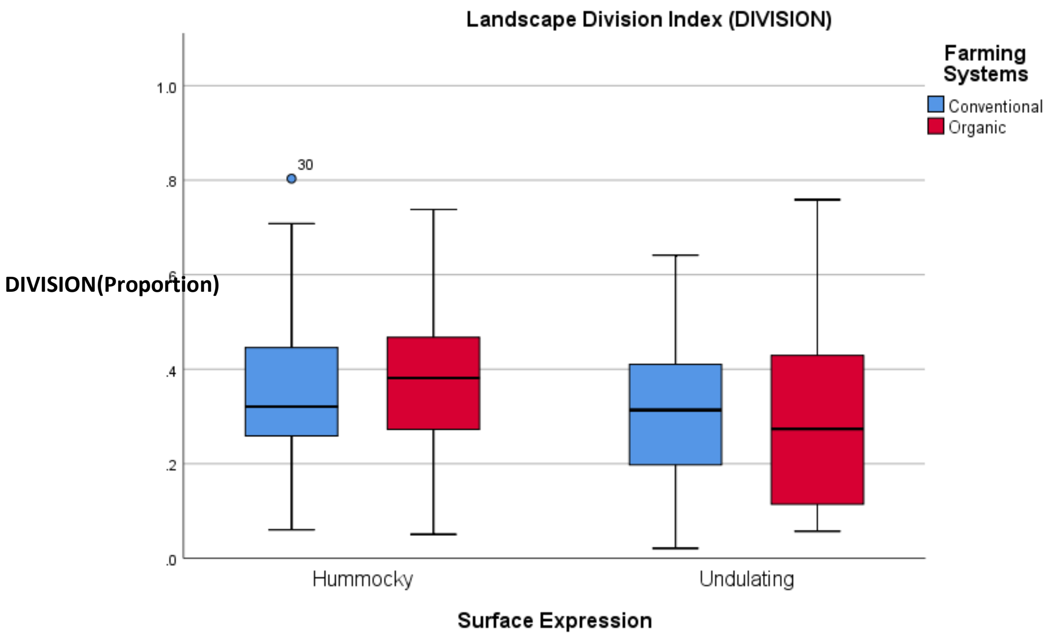


Fig. 61. Boxplot of Landscape Division Index (DIVISION) classified by farming systems and surface expression.

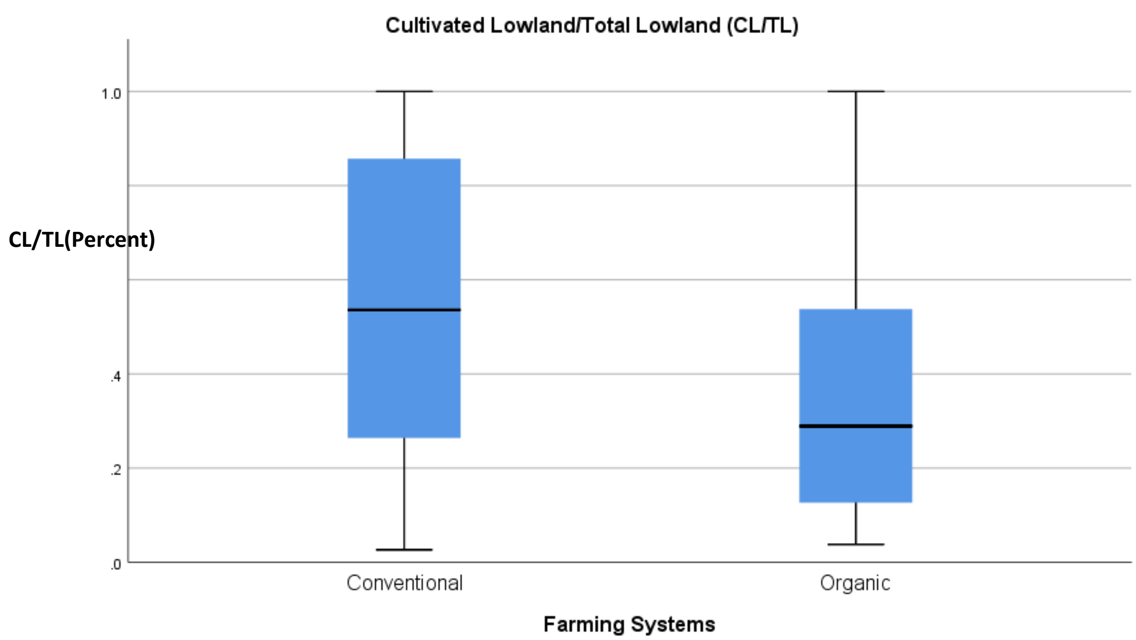


Fig. 62. Boxplot of Cultivated Lowland/Total Lowland (CL/TL) classified by farming systems.

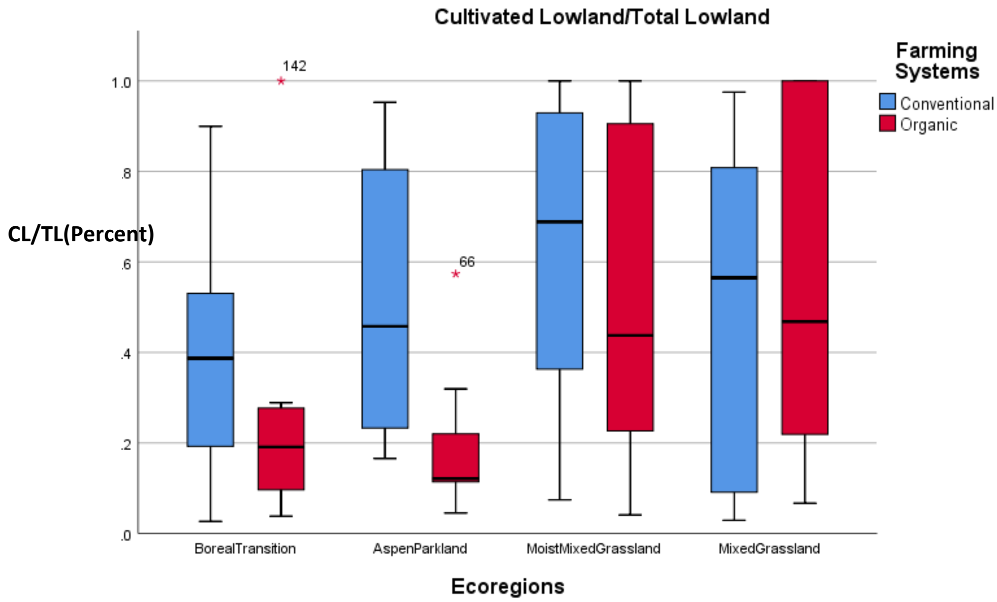


Fig. 63. Boxplot of Cultivated Lowland/Total Lowland (CL/TL) classified by farming systems and ecoregions.

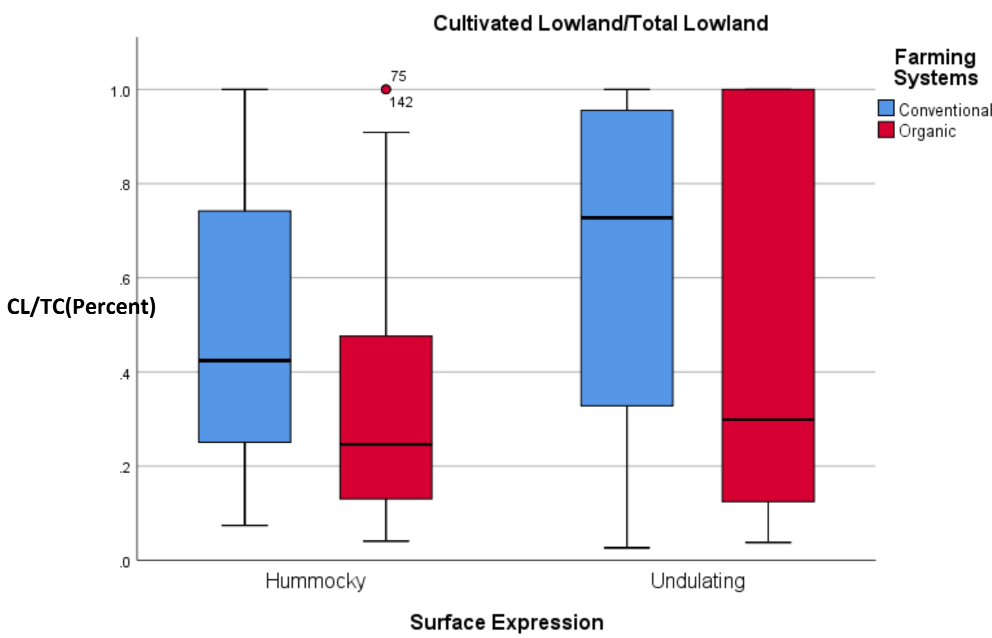


Fig. 64. Boxplot of Cultivated Lowland/Total Lowland (CL/TL) classified by farming systems and surface expression.