APPROACHING CROP DISEASE FROM AN ECOLOGICAL PARADIGM: SUGGESTIONS FOR SUSTAINABLE AND ORGANIC MANAGEMENT OF CEREAL CROPS

Prepared by:

Jennifer Forsythe

University of British Columbia Okanagan Campus
3333 University Way
Kelowna BC

In collaboration with

Fieldstone Organics Ltd.
4851 Schubert Road
Armstrong BC

Introduction

Agricultural science has long been a topic of scientific research and is currently a critical issue in modern society. With the global population expected to reach 10 billion by the end of the 21st century (Tilman et al., 2002; De Long et al., 2013), food and water demands are expected to rise by 15-22% by 2025 (Plusquellec 2002). As such, understanding agricultural dynamics has developed into a pressing issue and has been accompanied by the push to explore alternative options to agricultural management and practices in order to preserve and restore habitats and arable lands that are currently being degraded and lost. Due to population growth, changes to global ecosystems have the ability to drastically alter the functioning of terrestrial ecosystems (Loreau et al. 2011). Since agriculture is a manipulation of natural landscapes, approaching agriculture from a sustainable paradigm requires in depth understanding of ecological perspectives that apply to both natural and managed systems.

Throughout history, ecologists and agronomists alike have been continually interested in what drives productivity of ecosystems, along with the stability of these ecosystems. Stability and productivity of ecosystems have been directly tied to increases in biodiversity (Schulze and Mooney 1993; Hector et al., 1999; Tilman et al., 2001; Nestmann et al., 2011) through a variety of mechanisms, though the major two have been deemed niche complementarity and sampling effect (Lehmann and Tilman 2000). Each of these mechanisms aims to explain how biodiversity affects natural systems in away that stimulates maximum productivity. Above ground biodiversity has also been shown to have a large impact on various aspects of ecosystem functioning including carbon and nitrogen cycling (Vitousek and Hooper 1993), productivity (McNaughton 1977), trophic

interactions, increased resilience to long term environmental stresses, and resistance to processes such as invasion and herbivory (Tilman et al., 1997; Kitzing et al., 2001). While increasing plant diversity has strong beneficial effects on ecosystems above ground, increasing biodiversity in ecosystems also has been shown to have an effect on soil microbial communities.

Soil microbial communities are an integral part of ecosystem functioning and maintaining the health of soil microbial communities is a key component of sustainable management practices. Of trophic interactions that occur in ecosystems, healthy soil microbial communities have been shown to have invaluable effects on the productivity of terrestrial ecosystems, including management of agricultural systems (Dybzinski et al., 2008; Wagg et al., 2011). It is already well documented in agricultural and ecological literature that microbial pathogens, symbionts, and root herbivores have the ability to drastically alter plant communities above ground (Bever et al., 1997; Wardle et al., 2004). It is also known that pathogens and soil predators can significantly reduce plant productivity and biomass above ground (Bever et al., 1997), while mutualisms, such as rhizobium bacteria or arbuscular mycorrhizal associations can serve to increase fitness in plant communities by increasing access to limiting nutrients in soil (Smith and Read 2008). The role of soil microbial communities in affecting plant community structure and stages of succession have also been empirically shown in literature (Brown & Gange 1992; van der Putten et al., 1993; Packer & Clay 2000; De Deyn et al., 2003). Maintaining strong biodiversity in the soil can lead to lasting benefits for plant communities. Feedback mechanisms are imperative for global scale nutrient cycling of nitrogen, carbon, phosphorus, and water, exist because of interactions between plants and

soil microbes (Ehrenfeld et al., 2005). As well, plant soil feedbacks have the potential to substantially alter the soil environment affecting existing plant species present in the community, and also new species that may enter the system (Bever 2002; Ehrenfeld et al., 2005). It has been shown that native plants create plant-soil feedbacks that alter the soil in a way that promotes growth for their own species, but also for the benefit of species occurring around them, creating an environment that promotes biodiversity (Perkins and Nowak 2013). Through understanding how plants and soil interact and through maintaining and promoting biodiversity in soil, as well as plant communities, terrestrial ecosystems cannot only be managed more effectively and sustainably, but may require less input, resulting in a reduced need for conventional management practices. This approach to agriculture not only benefits the management of systems in for longer periods of time, but it can also dramatically improve the condition of the managed systems, prevent disease, and improve soil fertility over extended periods of time. Since almost all plant diseases can be effectively managed and eventually eliminated through the proper use of crop rotation (van Bruggen 1995; Clapperton et al., 2007), this suggests that biodiversity and proper management of diversity in agroecosystems may function to prevent invasive diseases and help reduce inputs, further promoting sustainability.

Understanding how plant/soil diversity dynamics work and the potential benefits that can be harvested from this system is of great use to those practicing organic farming. Organic farming is based off of the philosophy that with minimal inputs, crops are more nutritious and contain less harmful chemicals that may have adverse effects on the environment and on organisms/humans that are consuming these crops. Although, organic farming has been shown to produce less yields than conventional farming

systems (Gabriel et al., 2010), biodiversity of organisms, including plant species and pollinators, increase with the presence of organic agricultural land, allowing farmable land retain fertility for longer periods of time (Gabriel et al., 2010).

Though organic farming is moving towards more sustainable and less destructive practices with many positive benefits, there are many unique challenges that do not affect conventional systems. For example, while conventional systems are able to utilize various advances in technology including new pesticides, herbicides, and fungicides, organic systems are limited to using only biological controls and applications that are deemed natural and approved for organic farming. Because organic agriculture is prohibited from using many applications available to conventional farmers, organic farmers must approach their systems from a much different perspective, a focus that centers itself on working with the land and the resources available to control diseases in a natural way.

This literature review will focus on controlling disease and promoting soil health in organic agroecosystems, particularly addressing the issues of treating soil borne diseases that affect many cereal crops in North America. In this case, the fungal seed disease, *Tilletia controversa*, commonly known as dwarf bunt, will be focused on and treatment methods suitable for organic agriculture will be reviewed. Furthermore, a strong emphasis on promoting soil health and biodiversity in the field will be focused upon, in order to broadly introduce methods that may aid in the reduction of dwarf bunt in organic North American cereal crops. This paradigm will also be employed to shed light on how other diseases that are usually controlled through conventional chemical application can be limited or prevented.

Effects of Biodiversity on Terrestrial and Agricultural Ecosystems

Maintaining biodiversity has been a key component of ecological science for many decades, and began with work on agricultural systems, after it was noticed that monocultures in agriculture and small island systems were more susceptible to invasion by pests and non-native species (Elton 1958). Since the first studies on biodiversity began, it has been well documented that systems with higher biodiversity are more productive (Tilman 1997), more resistant to invasion (Quijas et al., 2010), and are more stable over long periods of time (Haddad et al., 2011). The long term benefits that diverse systems sustain make it worthwhile to revisit how biodiversity can affect plant communities, particularly in agriculture, where system productivity and stability are key to successful yields each growing season.

Plant diversity, therefore, may affect productivity and stability of ecosystems in a number of ways. For the purposes of this review, primary productivity will be defined as the total of all materials produced by the growth of plants over a period of time (Tilman 1999), while stability will be defined as how well a system can respond to stress or disturbance-induced changes over time (Van der Putten et al., 2000). Current research has hypothesized that increased species diversity affects both primary productivity and stability in ecosystems. As mentioned earlier, research has focused on how plant species richness affects productivity, which can be used as proxy to measure stability over time. Early research has hypothesized that by increasing biodiversity in an ecosystem, interspecific interactions, or interactions between each species will increase, contributing to overall ecosystem functioning (Elton 1958; McNaughton 1977). As well, it has also been hypothesized that ecosystems with higher diversity should be more productive due

to increased and alternative nutrient cycling and nutrient flow (Odum 1970; Schulze and Mooney 1993). In addition, with more diversity, it is expected that more species will be able to capture more limiting resources present in a system, due to differences in life history strategy, morphology, and physiology (Lehman and Tilman 2000). With this increase in utilization of limiting resources, more niche space is exploited, allowing more available resources to be used and recycle back into the ecosystem, and in turn, increasing productivity (Lehman and Tilman 2000). Thus, the relationship between productivity and biodiversity has been described as a positive, asymptotic relationship, with productivity positively increasing with plant biodiversity until it reaches a plateau, where the addition of plant species does not affect the productivity of the system (Lambers et al., 2004; Tilman 2011).

To understand the relationship between diversity and productivity mechanistically, Lehman and Tilman (2000) proposed two main ideas that aim to explain this relationship. The first is known as the sampling effect and postulates that with increasing plant diversity, there is an increasing chance that a system will contain a highly productive species, therefore increasing the productivity of the entire system (Hector et al., 2001; Macquard et al., 2009). The second idea is known as niche complementarity and suggests that with increasing plant diversity, more niche space will be utilized due to interaction between different species. This mechanism suggest that each species in the community possesses unique traits that interact and complement the other species' traits, resulting in more resource utilization, saturating resource use and thus productivity in the system (Tilman 1996; Montes et al., 2008; Schmidke et al., 2010).

To break down niche complementarity down even further, Tilman et al. (1997) described three theoretical models that explain potential inherent mechanisms within the niche complementarity idea. The first model involves competition between plant species for one limiting resource and suggests that the species with the lowest requirement for that resource will dominate at equilibrium. In this case, productivity increases with biodiversity because the best competitor produces more biomass as it requires the least amount of a limiting resource, increasing the overall productivity of the system. The second model, however, involves competition between species for two limiting resources and suggests that there is no species that is competitively superior. Instead, this model postulates that any resources that deviate from each species' optimum utilization range are left unconsumed and thus provide an opportunity for new species to enter the system and take advantage of these unused resources. The arrival of new species and the increase in utilization of resources causes an increase of productivity in the system. Finally, the third model suggests that two or more factors act to limit the species abundance due to functional tradeoffs and interspecific interaction between species. These tradeoffs and the combinations of these tradeoffs between different species allow species to occupy different portions of the habitat, with no single species dominating the entire environmental range of the habitat. With greater exploitation of a habitat, resource utilization also increases, resulting in higher nutrient cycling and carbon storage, increasing overall productivity.

A study conducted by Tilman (1996), also illustrates the importance of biodiversity in ecosystems. This study investigated total community biomass variation over many years in 207 plots planted with different levels of plant diversity and found

that biomass variation in low diversity plots was significantly greater than the variation in biomass within high diversity plots, suggesting that the higher diversity treatments had more consistent productivity over time, compared to the low diversity treatments. This illustrated sustained increases in productivity over time in high diversity plots, as well as sustained stability at high diversity plots due to lower variation in production. While this trend has been shown many times throughout ecological research, of the two overarching models that explain this relationship between productivity and diversity, niche complementarity has garnered the most empirical support. In another study, Tilman et al. (1998), investigated productivity and biodiversity in a variety of study plots to determine whether the sampling effect or niche complementarity had stronger effects on ecosystem functioning. In this study, abundances of 24 plant species were measured (abundance estimated by measuring percent cover) in both low diversity plots (monocultures and 2 species plots) and high diversity plots. The abundances of the 24 species in the low diversity plots were plotted against their abundances in the high diversity plots. It was found that the most abundant species in low diversity plots also had higher abundance in high diversity plot. However, at high diversity levels, the abundances of all species were greatly reduced, sometimes up to 40 fold less productive. This suggests that the presence of other species greatly reduced the percent cover of the most abundant species in low diversity plots, but the overall increase of plant species contributed to increased overall percent cover in the high diversity plots. This study provides support for niche complementarity as a mechanism that drives biodiversity/productivity relationships in terrestrial ecosystems. A study conducted by Hector et al., (1999) also showed evidence for niche complementarity. In this study, species loss was investigated in European

grasslands. This study showed a linear relationship between reduction of biomass and species loss, while also illustrating that communities with fewer functional groups were less productive. In another study, Tilman et al., (2001) measured productivity in high diversity plots versus monocultures. It was found that high diversity plots had 2.7 times greater biomass than monocultures and also had greater productivity than the most productive monoculture, indicating that niche complementarity has more of an effect on ecosystem functioning. Carbon stores were also measured, and a similar pattern was observed, showing increased carbon storage at high diversity levels.

Understanding these mechanisms are also useful when investigating agricultural systems. Holistic approaches to agriculture have recently advocated for species rich and functionally diverse cover crop mixtures in order to improve soil nutrient conditions and begin to reduce the number of inputs required in these managed systems (Altieri 1999) At the core, agricultural systems essentially reduce biodiversity, creating large stands of crop monocultures, which are more susceptible to disease, pest, and other harmful outbreaks (Cox and Atkins 1979; Altieri 1999). Furthermore, conventional agriculture can also disrupt many naturally controlled ecosystem functions, including decomposition, seed dispersal, insect and pathogen control, and terrestrial genetic evolution (Swift and Anderson 1993; Altieri 1999). These issues that come with conventional agriculture not only negatively affect the agroecosystem, but also have negative economic and societal impacts, including disruption of valuable ecosystem services and degradation of the environment (Altieri 1999). Maintenance of biodiversity within agro-ecosystems is an essential way to reduce negative results of monocultures, and also to maximize productivity and stability in agriculture. Similar to natural, unmanaged ecosystems,

increases in biodiversity have been shown to reduce pest outbreak and create positive interactions between plant species, contributing to more stability in agricultural systems (Altieri 1994). Historically, biodiversity in agriculture had to be well understood in order to maximize interactions between plants and the soil interface, in order to yield the most productive and stable system (Miller and Rossman 1995), while resisting disease and pest outbreaks. In today's society, biodiversity theories must be applied to agricultural management in order to successfully understand a sustainable agroecosystem. Currently, it is known that with more intensive agricultural input, biodiversity in both agroecosystems and surrounding areas is lost (Swift and Anderson 1993).

Using Soil Microbiology and Diversity to Promote Soil Health

Though conventional farming is highly productive, this is only due to exorbitant amounts of chemical and synthetic inputs, of which can drastically alter plant communities, insect-plant interactions, soil microbial communities, and soil nutrient cycling (Cox and Atkins 1979). This in turn, has a negative effect on agricultural system, as over time, these essential resources are degraded, requiring more input from the farmer to maintain high levels of productivity. In natural ecosystems, systems that are more diverse have also been shown to have resistance to disease and invasion (Naeem et al., 2000), while sustaining increased productivity and stability. In agriculture, these same biodiversity theories apply. Many of these ideas focus on top down and bottom up approaches, highlighting that biodiversity in agriculture not only enhances the presence of natural enemies, but also regulates soil health and microbiota, encouraging healthy soil cycling and biology (Finch and Collier 2000; Gurr et al., 2003). Maintenance of

biodiversity in agricultural systems is important in order to preserve diversity in both insect and microbial populations, which often help control agricultural pests and diseases due to natural trophic interactions (Tilman et al., 2002; Gurr et al., 2003). Current research on creating biodiversity in agriculture focuses on creating habitat patches or utilizing crop cover to attract pollinators, provide niche space for natural pest enemies, and to improve soil fertility (Clapperton et al., 2007; Lammerts van Bueren et al., 2011).

Increasing biodiversity below ground is also an important factor to take into consideration for improving sustainable agricultural practices. Soil management is a key component to creating healthy agroecosystems and promoting sustainability within agriculture. In natural systems, research has indicated that soil microbial communities are integral components of accepted ecological relationships, including the relationship between diversity and productivity. The idea that productivity increases asymptotically with biodiversity was first explored by looking at above ground relationships between varying plant species and most of the earlier theoretical models focused on how plant interactions above ground caused increased productivity in terrestrial ecosystems. However, research has also shown that microbial communities and below ground dynamics play an integral role, or can even drive this relationship (Schimel 1995; Dybzinski et al., 2008; Wagg et al., 2011). Since the majority of terrestrial plants form some type of symbiosis with soil microbes, particularly with mycorrhizal fungi (Smith and Read 2008), it is of critical importance to acknowledge the role that soil microbial communities play in determining plant community structure and how they can influence plant communities in both natural and agricultural settings.

One major group of soil microbes that impart immense benefits into an agro-ecosystem is arbuscular mycorrhizal fungi (AMF). AMF form a symbiotic relationship with over 80% of land plants (Smith and Read 2008) and are known to take up limiting nutrients in the soil (mainly phosphorus) and transmit these nutrients to their host plant (Schulze & Mooney 1993; Smith and Read 2008). The nature of this symbiosis allows AMF to limit or promote the presence of particular plant species, influencing plant community assembly (Grime et al., 1987; Gange et al, 1990; van der Heijden et al., 1998a,b; Hartnett et al., 1999). A study by Schnitzer et al., (2011) investigated the role of host specific soil microbes in driving the positive relationship between plant diversity and ecosystem productivity. In this experiment, plant productivity and plant disease rates were measured in the presence of soil microbes when trained with conspecific and heterospecific plant species. When plants were grown in the presence of soil microbes, productivity and the prevalence of disease was significantly decreased with increasing diversity. The results of this study illustrate the importance of soil microbes in driving the pattern between productivity and biodiversity. A study by Maron et al. (2011) also showed the importance of soil microbial communities in establishing the relationship between biodiversity and productivity. In this experiment, the role of soil fungal pathogens was investigated. Plots of varying plant species diversity were either treated with fungicide or were left untreated. Productivity of these plots was then measured. In the control plots, a positive, linear relationship was observed between plant diversity and shoot biomass. However, in plots treated with fungicide, this relationship disappeared. In low diversity plots treated with fungicide, productivity increased 131%, while productivity only increased by 33% in high diversity plots treated with fungicide,

flattening the productivity/biodiversity relationship. These results indicate that fungal pathogens and other soil microbes may be the drivers of the positive, asymptotic relationship between biodiversity and productivity in grassland ecosystems, which has been traditionally explained by niche complementarity and plant competitive interactions. While patterns between biodiversity and productivity can be linked to competitive interactions between plant species and niche complementarity in communities, there is strong evidence to support the importance of soil microbial communities, particularly AMF communities, in establishing plant community structure, biodiversity, and productivity relationships. Many other aspects of soil biology have also been shown to improve the health and diversity of agro-ecosystems. For example, Clapperton et al. (2007) suggest the importance of increasing diversity in the entire food web, promoting an increase in macro soil biota, including earthworms, while also aiming to create a soil habitat that is rich in resources and nutrients. Through promoting sustainable soil habitats, macro and micro soil biota, such as AMF and earthworms, are able to flourish and provide more benefits to crops above ground.

From an agricultural perspective, maintaining the health of soil microbial communities is essential to capturing the many benefits these communities can provide to plant communities. Particularly, the presence and utilization of microbial symbionts, such as AMF is a sustainable way to confer direct health benefits to crops. It is estimated that AMF make up anywhere between 5-50% of soil microbial biomass in agricultural soils (Olsson 1999). Benefits of AMF on crops have been most extensively shown in cereal crops, where mobilization and uptake of phosphorus is imperative in maintaining robust health of these crops and avoiding macro and micronutrient deficiencies, which lead to

disease (Thompson 1991). As well, studies have also shown that AMF can have positive effects on crops that are grown in soils that have low fertility, that are low in essential micronutrients, or are highly alkaline or acidic (Kahiluoto et al., 2012). Furthermore, phosphorus uptake in agriculture is also highly dependent on AMF communities. Long-term studies carried out in Ontario showed that cereal crops grown in no tillage systems absorbed more phosphorus from AMF inoculum, and was more likely to be colonized by AMF than crops in tilled systems (Miller 2000; Galvez et al., 2001). Due to the lesser amount of inputs in organic agricultural systems, AMF play an even larger role in contributing to the health of agroecosystems. Studies have illustrated that organic farming systems have increased AMF colonization and diversity compared to conventional farming systems (Ryan and Graham 1999; Mader et al., 2000; Oehl et al., 2004), mediating phosphorus uptake and crop health. AMF also help maintain soil structure in agricultural systems. AMF hyphal networks in the soil allow soil aggregates to form around these hyphal networks, creating more diverse soil structure. As such, research on modern agricultural practices not only recommends increasing biodiversity in farming techniques, but also provides it as a solution for sociological issues like projected food shortages, and for management practices, where pest control and disease management are on-going and continually evolving problems.

Practices to Promote and Sustain Terrestrial and Soil Diversity in Organic Farming

Promoting biodiversity and an effective microorganism community in the soil may prove to be beneficial in controlling plant disease, as these practices not only improve soil fertility and nutrient cycling, but also increase the presence of beneficial soil

microflora, which may be instrumental in reducing plant disease in agriculture (Sangakkara and Weerasekera 1999; Borgen and Davanlou 2012). There are practical methods in which farming practices can be amended to promote biodiversity both in plant and soil microbial communities. The first major practice that is currently being advocated in sustainable agroecosystems is low to no till farms and promotion of diverse cover crop and native habitat patches within agricultural fields. Furthermore, promotion of a healthy soil microbial community, with the presence of arbuscular mycorrhizal fungi and other soil microbes, will help to maximize nutrient cycling in the soil, but can also provide highly beneficial attributes to above ground plants, including increased nutrient uptake, drought tolerance, increased biomass, and pathogen protection. Through promoting these types of attributes through sustainable agricultural practices, agricultural areas can be transformed to disease susceptible monocultures, which require maximal inputs and interventions from humans, to more self-sustaining, ecologically aware agroecosystems.

Dwarf Bunt and Impacts on Cereal Crops

While maintaining biodiversity both above and below ground and practicing minimally invasive and sustainable farming techniques allows for land preservation, longer sustainability for agricultural land, and improvement in soil and crop quality, this is not always effective in dealing with diseases that have already established in an area. Among such diseases is dwarf bunt, a grass pathogen that can cause drastic losses to infected fields, and one that has plagued North American agriculture for decades. The

remainder of this literature review will focus on control of dwarf bunt in sustainable and organic agroecosystems. Dwarf bunt is a disease that affects winter wheat crops and is caused by the soil borne fungus, *T. controversa*. This fungal pathogen causes severe crop damage in wheat heads, as they become infected with black fungal matter and lead to a disturbing, stinking smell on the wheat (Figure 1), rendering it unusable for grain production and even for animal feed (Jespersen 1994). Wheat heads also appear ragged, unruly, and generally less healthy than unaffected plants. As well, diseased plants are often stunted in growth, and cannot be exported due to trade embargos that prohibit the export of contaminated seed or crop into other countries.

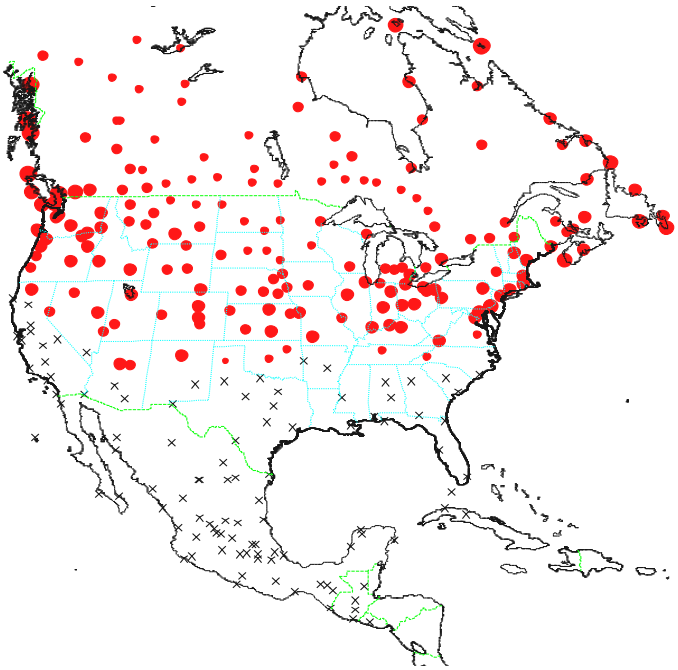
A. 

B. 

C. 

Figure 1. A: Wheat head with in tact bunt balls. **B:** Wheat head with disrupted bunt ball. The black pigmented area is exposed *T. controversa* spores. **C:** Infected wheat head with exposed bunt balls. Note the ragged appearance of the wheat head, a common symptom of *T. controversa* infection. Pictures courtesy of Gayle Jespersen.

This is disease is prevalent in particular areas of Canada, but is widespread across North America and Europe (Figure 2). In Canada, the most affected areas are in Ontario and British Columbia, where the climate remains at a sufficient temperature, allowing spores to remain viable over the winter and infect winter wheat crop (Jespersen 1994).



A.

B.

Figure 2. **A:** Predicted distribution of *T. controversa* in North America, using temperature parameters in CLIMEX model generator. Red dots indicate a matching area and black x symbols indicate that the area is not a temperature match for *T. controversa* (Figure from Murray and Wright 2007). **B:** Distribution of *T. controversa* in British Columbia. (Figure from the British Columbia Ministry of Agriculture http://www.agf.gov.bc.ca/cropprot/dbunt.htm).

As Jespersen (1994) describes, this disease is particularly difficult to control because of its' life cycle. During harvest, spores are released from bunt balls present in the wheat heads, infecting both wheat seed and the soil. Spores that infect the soil are usually the most likely to transfer the disease as spores can remain viable in the soil for up to 7 years. Infection of dwarf bunt occurs over longer periods of time, taking up to approximately six weeks for spores to germinate. Germination will only occur at ambient soil temperatures (just a few degrees above freezing), and is usually favored by the presence of large amounts of non-melted snow cover. Infection usually occurs at the soil surface, where temperatures are warmer (ideal temperature for infection is ~5ºC) and there is the presence of light, which is also a key component to rapid infection (Figure 3).

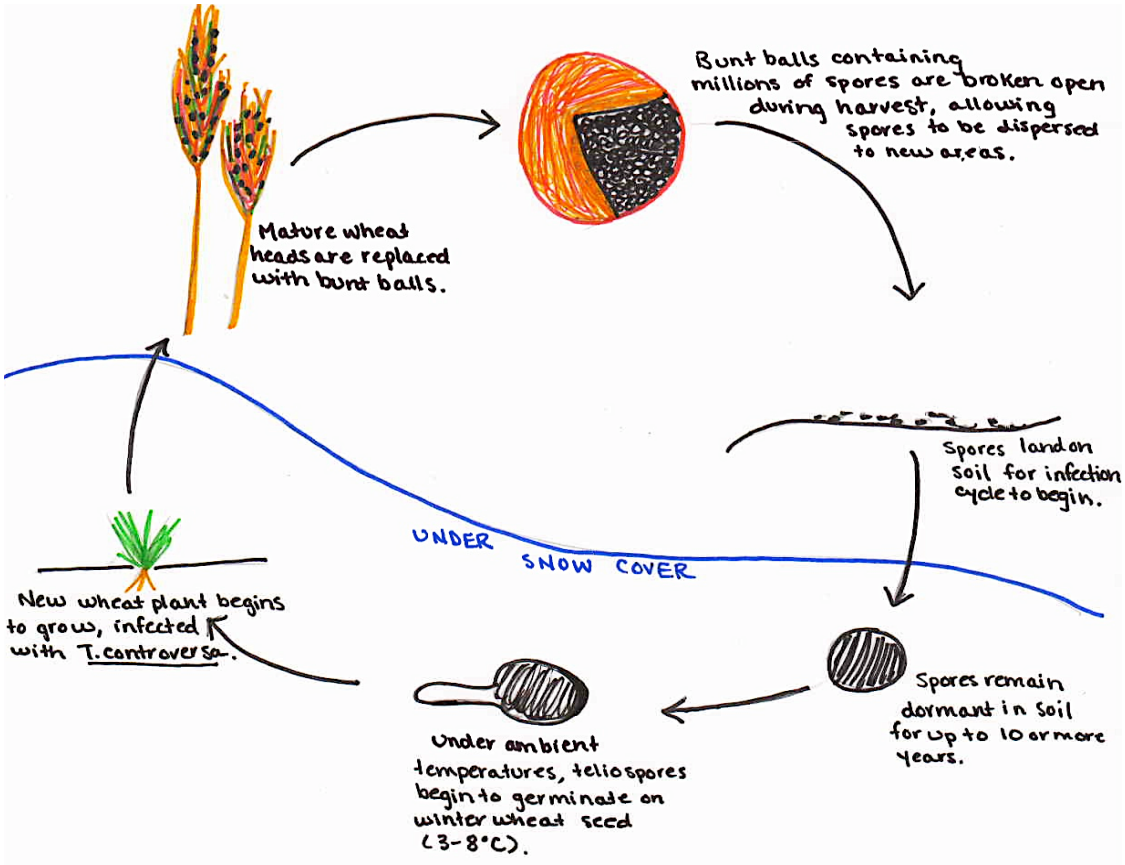


Figure 3. Life cycle of *T. controversa*. Figure adapted from Sitton et al., 1993.

Temperature of germination is a key factor in the spread of this disease, as colder climates where the soil actually freezes do not develop dwarf bunt problems, resulting in the lack of dwarf bunt infection in primary cereal producing regions like the prairies. Spores that are found within the soil are often brought to the surface after tillage and other agricultural disturbance, presenting more opportunities for infection. Throughout the growing season, dwarf bunt systemically grows throughout the crop and replaces the kernels with bunt balls by harvest time, starting the cycle again. Kernels are replaced with approximately 5-12 million spores of *T. controversa* encased by bunt balls, which are easily disturbed, infecting healthy grain, soil, and agricultural equipment (Sitton et al., 1993). *T. controversa* primarily infects winter wheat and perennial grasses, but may also affect other crops such as rye and barley (Sitton et al., 1993). It was first described in 1935 in wheat grown in Montana, however the earliest records of dwarf bunt in winter wheat can be traced back to 1847 in Czechoslovakia (Mathre 1996). To date, it has been documented that systemic infections of dwarf bunt can reduce crop yields by up to 70%, creating devastating economic losses for farms infected with this disease (Mathre 1996). Winter wheat is most susceptible to dwarf bunt infection when young wheat plants are planted in unfrozen soil, beneath the snow (Mathre 1996).

Due to the life cycle and mode of infection of dwarf bunt, it has been traditionally difficult to control. In conventional agriculture systems, fungicide and seed treatments have been developed to eradicate this fungus and have been effective. Unfortunately, seed treatments are unable to protect seeds planted in soils infected with dwarf bunt (Jespersen 1994). Seed treatments are mostly effective against preventing the spread of

dwarf bunt into new, uninfected areas. Resistant varieties also exist, but most varieties are still somewhat susceptible to infection by dwarf bunt. Resistance to dwarf bunt is an ongoing dilemma, as new strains of dwarf bunt evolve, making many formerly resistant wheat varieties susceptible to this disease once again (Sitton et al., 1993). However, resistant wheat varieties are currently the best method available for eradicating the disease in areas with previously devastating rates of dwarf bunt (Sitton et al., 1993). Resistant varieties vary in their resistance to dwarf bunt and to other cereal diseases. Some varieties are resistant to both dwarf and common bunt, while others may also be resistant to other plant diseases including rusts, viruses, and even snow molds (Sitton et al., 1993).

As mentioned, fungicides are also available to control dwarf bunt. However, common fungicides, including Vitavax 200 and Bayan that control common, loose, and flag smut are ineffective against dwarf bunt (Sitton et al., 1993). Gustafson LSP, which contains 30% thiabendazole is currently registered for dwarf bunt, but this fungicide also has variable results. Another systemic fungicide, CIBA Dividend (difenoconazole) has also been used to treat dwarf bunt and has been shown to be highly effective in the field (Sitton et al., 1993). This fungicide is now common in conventional agriculture and has nearly eradicated dwarf bunt infection in systems using this product.

Farming practices can also be useful in reducing the potential for infection. Practices including the timing of seeding can be very effective in preventing infection of dwarf bunt. Since germination of spores requires specific conditions, early or late seeding of winter wheat can effectively reduce the severity of dwarf bunt infection (Sitton et al., 1993). Young plants are most susceptible to dwarf bunt when they have developed 3 – 8

leaves prior to snow cover and dormancy (Sitton et al., 1993). If seeds are planted to time growth to less than 3 leaves prior dormancy (usually in late autumn), the probability of dwarf bunt infection is greatly reduced. As well, late autumn seeding also gives fungicide seed treatments time to be more effective against this disease. However, disease risk has to be assessed when alternate seeding times will be used, as this can also pose problems. For example, if winter wheat is seeded early, this may interfere with late maturing crop, and may also face lower soil moisture, which increases the likelihood of diseases such as, Cephalosporium stripe, barley yellow dwarf, and strawbreaker foot rot (Sitton et al., 1993). On the other hand, late seeding may lead to an increase in soil erosion and weed infestation (Sitton et al., 1993). Determining whether to seed earlier or later should therefore depend on the level of infection of dwarf bunt and the risks associated with altering seeding time.

Other mechanical practices may also help reduce the level of infection of dwarf bunt, including deep seeding, depth of seed furrows, destruction of heavily infected wheat, removal of grassy weeds, sowing spring wheat, placement of quarantines, and integrating various methods of dwarf bunt control (Sitton et al., 1993). Deep seeding and depth of seed furrows help control dwarf bunt by removing the seed from the direct line of infection, which is usually near the soil surface (Sitton et al., 1993). Seeding approximately 2.5cm below the soil's surface tends to protect seeds from direct exposure to dwarf bunt spores. As well, using very deep seed furrows may encourage infection of dwarf bunt, as deep seed furrows collect moisture and retain snow for longer periods of time, creating an ideal environment for dwarf bunt to persist and infect seeds (Sitton et al., 1993). Along these lines, preventing persistent snow cover, or planting winter wheat

away from areas that retain snow will also help reduce the levels of dwarf bunt infection. Studies have shown that dwarf bunt is most persistent on north-facing slopes and in lower areas where snow persists for longer periods of time (Sitton et al., 1993). Selecting a suitable site to plant winter wheat on, away from fences, wind breaks, and barriers that may trap snow may also reduce systemic infection of dwarf bunt (Sitton et al., 1993). Destruction of heavily smutted wheat may also reduce transmission of spores and prevent widespread infection. When smutted wheat is harvested, the easily disturbed bunt balls release millions of spores, contaminating soil, uninfected fields, and agricultural equipment, causing the disease to spread and create dwarf bunt inoculum for future infection (Sitton et al., 1993). Though destroying crop through burning may increase soil erosion and reduces organic matter, this may be necessary to prevent future, uninfected soils from becoming infested with the disease. Elimination of grassy weeds may also reduce dwarf bunt by reducing the number of available dwarf bunt hosts, and therefore reducing the potential inoculum to infect winter wheat (Sitton et al., 1993). Finally, planting spring wheat may also reduce the potential for dwarf bunt infection in winter wheat, as spring wheat is unaffected by dwarf bunt. Planting in areas that are prone to dwarf bunt infection will prevent future infection of dwarf bunt in the desired area by reducing the inoculum of dwarf bunt over time.

While many of these controls will help to reduce dwarf bunt infestation in winter wheat crops, the most effective control for dwarf bunt is to take an integrated control approach, combining many different control methods in order to reduce and potentially eliminate dwarf bunt infection from an area. A combination of planting resistant varieties

in suitable planting areas, with seed treatments, and farming techniques offers more protection against dwarf bunt infection than any single method alone.

Dwarf Bunt Control in Organic Agriculture

Dealing with plant disease in organic agriculture is a unique problem because many technological advances in chemical control agents cannot be used. In the case of dwarf bunt, there have been some advances into biological control products that may help reduce dwarf bunt infection. These organic implementations, along with agricultural practices may help organic farmers combat dwarf bunt in their winter wheat crop.

Since dwarf bunt is a disease that infects the seed of winter wheat and other grasses, organic control has been focused on finding a suitable seed treatment that will deter or eliminate the infection of dwarf bunt at the seed level. In one study, Smilanick et al. (1992) examined the germinability of *T. controversa* spores after treatment with hydogren peroxide. In this study, three hydrogen peroxide treatments were used to test the germination of telispores in infected seeds of both wheat and barley. Hydrogen peroxide was chosen because it is considered a safe and natural chemical, being naturally produced in many food products including honey and dairy products, and escapes many dietary and environmental issues that other biocides face (Smilanick et al., 1992). To effectively test germination of teliospores in wheat and barley after treatment with hydrogen peroxide, the authors designed three hydrogen peroxide treatments. The treatments contained a dilution of 35% hydrogen peroxide in distilled water and were heated to 23, 45, or 50ºC. Approximately 300 infected wheat seeds were then placed in 10mL or 25mL of the solutions. After soaking the seeds in each hydrogen peroxide

treatment, seeds were rinsed with cold, distilled water for two minutes and teliospores were collected for further germination testing. Teliospores were also steamed with vapour from the hydrogen peroxide, and controlled moisture treatments. Teliospores were then collected for further germination testing. Teliospores treated with both hydrogen peroxide solution and vapour were then placed on agar dishes for germination, and were incubated at 20ºC for 3 weeks and at 10ºC for 6 weeks. On each plate, approximately 200 teliospores were analyzed. The results of this study showed that with seeds immersed in hydrogen peroxide, heated treatments were the most effective. Solutions heated to 50ºC for 6 min or more prevented germination of teliospores, while the germination of the seed was greater than 95%. Vapour steaming of seeds had no effect on germination and was ineffective in reducing or preventing germination of dwarf bunt teliospores. Finally, in the controlled moisture treatment, the reduction in germination of teliospores was greatly reduced, with little to no effect on the wheat seed. Treatments that exceed 3 minutes prevented germination of teliospores, illustrating the beneficial effect hydrogen peroxide can have on treating seeds for removal of dwarf bunt spores.

A similar study investigated the effect of fumigation with acetic acid on the treatment of common bunt in wheat. Sholberg et al. (2006) investigated how fumigating the seeds of a highly susceptible wheat cultivar, Laura, with acetic acid controlled the germination of common bunt spores. In this study, Laura wheat seeds were inoculated with common bunt spores and then fumigated with two different acetic acid treatments. One treatment contained 2 g kg^{-1} of acetic acid and the other contained 4 g kg^{-1} of acetic acid, both at 20ºC. The results of this trial showed, that in the field, acetic acid fumigation reduced infection levels of common bunt over 3 years (2000, 2001, and 2003). The

treatment with higher levels of acetic acid was most effective, although both treatments were at least as effective as the common fungicide, Vitavax. Though this trial shows promising results for common bunt, this has yet to be tested on dwarf bunt, though it may have similar results.

Other studies have focused on testing other organic compounds for use as potential seed treatments to control bunt diseases. In a study by El-Naimi et al. (2000), several organic compounds were tested to see the effect on control of common bunt contamination. In this study, organic nutrients were tested as seed treatments for common bunt on two susceptible wheat cultivars. The organic nutrients used in this study were as follows: skimmed milk powder, hucket, and wheat flour and were used in a concentration of 160g per kilogram of seeds. This study was conducted over 4 years and was tested with two types of wheat cultivars, Bau and Sebou. To commence the study, seeds were inoculated with spores of common bunt and then subjected to seed treatments. Each cultivar was subjected to the following treatments: a fungicide treatment (Vitavax), a skimmed milk treatment, a hucket treatment, and a wheat flour treatment, which were prepared in a solution of distilled water. The results of this study showed that variety played a role in susceptibility to disease, with Bau cultivars more likely to become infected than Sebou cultivars. As well, all seed treatments reduced common bunt infection levels, though to varying degrees. Vitavax and skimmed milk treatments were the most effective in reducing common bunt infection, with a 97% and 96% reduction in bunt infection over the 4 year period. Hucket and wheat flour treatments were also highly successful, with a 93% and 62% reduction in common bunt infection over 4 years. These results have also been repeated in other studies and have found similar results, especially

in regards to skimmed milk seed treatment (Becker et al., 1994). The mechanism behind these treatments is the promotion of antagonistic soil-borne microorganisms, particularly the promotion of *Bacillus* and *Pseudomonas* species, which seem to directly inhibit common bunt spores on the surface of the seed.

Similar studies by Borgen and Davanlou (2012), investigated common organic seed treatments used to control common bunt. In this study, seeds were treated with a liquid manure solution and a powered milk treatment. In a second experiment, seeds were also treated with a commercially available product, known as Mycostop, which contains the bacterial species, *Streptomyces griseoviridis*. Other seed treatments were also used in the second year of planting, including a solution containing Pseudomonas chororaphidis. a commercial product, Effective Microorganisms, containing a mixture of microbes, mostly made up of yeast and lactic acid bacteria, and the commercial product Symbioplex, which contains a mixture of different types of antifungal bacteria. Other isolates of bacteria were also used, including *Trichoderma harzianum* and *Gliocladium roseum*, in solution for seed application. Finally, two types of compost were used (composted garden waste and fresh compost consisting of manure and straw, along with rumen juice from cows, and rumen juice combined with milk powder. The results of this study indicated that milk powder and a combination of milk powder and liquid manure had approximately a 98% reduction rate of bunted heads compared to the control. While, diluted manure and liquid manure alone had little to no effect on reducing bunted heads. Treatments containing *Streptomyces griseoviridis* reduced bunted heads by almost 46%, while effective microorganism, lactic acid bacteria, both types of compost, and rumen juice treatments combined with low quantities of milk powder had varying effects,

ranging from 45% to 73% reduction in bunted heads. The remaining treatments were not significant.

Finally, another study by Borgen and Kristensen (2001), investigated the effectiveness of mustard flour and milk powder for use in seed treatments to control both common bunt and stem smut in organic agriculture. This study tested both mustard flour and milk powder on wheat and rye seeds infected with common bunt. After planting, it was found that mustard flour treatments (10g/kg of seed) were effective in controlling common bunt without disrupting the vigor of the seed. Milk powder was also found to significantly control infection of common bunt (ideal application 80g/kg of seed), however, milk powder did seem to effect the germination vigor of the seed itself. Both mustard flour and milk powder, however, did reduce the percentage of diseased plants by 91% compared to control subjects.

Other research has moved away from seed treatments and has investigated breeding resistance into crops for a more long-term solution in dwarf bunt protection. In a study by Huber and Buerstmayr (2006), different genotypes of wheat cultivars were screened for resistance to bunt. Each cultivar was inoculated with either common bunt or dwarf bunt and was then measured for infection rate. Of the 98 genotypes screened for resistance of common bunt, 9 genotypes showed complete resistance with no infection present, while 25 genotypes showed low infection. For dwarf bunt, of the 29 genotypes screened, only 1 genotype showed complete resistance to dwarf bunt, showing no infection, and 1 genotype showed low infection rates. The remaining 27 genotypes ranged in infection level, with 11 genotypes showing very high infection rates. This study not only illustrates the variability between wheat cultivars to both common and dwarf

bunt, but also provides insight into breeding to provide resistant cultivars to these diseases.

Currently, research into preventing plant diseases, particularly in the area of bunts and smuts, has focused on finding effective seed treatments that follow organic regulations. Of different types of seed treatments researched, acetic acid fumigation and the application of mustard or milk powder seems to be most effective against common bunt, however these methods have yet to be tested on seeds infected with dwarf bunt. Future research should test these applications with *T. controversa* infected seeds to see if the same efficacy exists for control of teliospore germination.

Future Directions & Conclusion

While much research has been conducted into the areas of improving organic agricultural and sustaining low input, environmentally aware farming practices, more research is required to see how farmers can work with their land to preserve biodiversity, increase productivity, and prevent disease. Restricted by organic regulations, sustainable farmers must work intimately with their land and its' biological components in order to maximize yield and prevent detrimental diseases that are difficult to control in organic systems. In the instance of dwarf bunt, future directions should look into developing agricultural land that is rich in biodiversity and fertility, which will help reduce infection by invasive diseases, particularly in the soil. As well, research should look into developing resistant genotypes, which will provide organic farmers with long-term solutions to disease resistance, while also minimizing inputs in the future. Managing

disease in organic systems will continually be a challenge, however, it is important in order to ecologically maintain agroecosystems.

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