Fertilizer Nitrogen Use Efficiency Determined using Enriched Isotope Tracers and Residue Decomposition of Irrigated Spring Malt Barley

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Authorization to Submit Thesis

This thesis of Grant D. Loomis, submitted for the degree of Master of Science with a major in Plant Science and titled “Fertilizer Nitrogen Use Efficiency Determined using Enriched Isotope Tracers and Residue Decomposition of Irrigated Spring Malt Barley,” has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Fertilizer nitrogen (N) use efficiency (FNUE) of barley (*Hordeum vulgare* L.) can be determined by using ^{15}N stable isotopes as a tracer. Understanding of FNUE is important when establishing fertilizer management guidelines to improve the sustainability of production practices and for quantifying the effect of N movement within the soil profile on the surrounding environment. Three malt barley cultivars were investigated during the 2017 and 2018 growing seasons, in Aberdeen, Idaho, USA where ^{15}N labeled fertilizer was applied to the soil surface or incorporated. Tissue samples were taken throughout the growing season at Feekes 4/5, 10.0, 11.2 growth stages, and at maturity. Plants were isotopically analyzed to determine accumulation and partitioning of N throughout the plant, as well as assimilation throughout the growing season. Overall, total system recovery resulted in fertilizer recovery of 61 and 72% of applied fertilizer N for surface applied as compared to incorporated fertilizer. In addition to FNUE, decomposition of remaining barley residue after harvest is an important component of nutrient cycling. Decomposition rates and quantities can be determined by capturing carbon dioxide (CO_2) lost as residue is broken down. Barley residue was collected from field trials and used in a laboratory experiment observing decomposition over 50 days. Treatments included residue placement (surface v. incorporated), residue size (sieved v. coarsely chopped), and soil types (sandy loam v. loam). Variation in the pattern of decomposition among residue size and placement occurred where the predicted time for 50% of residue to breakdown was greater for the incorporated-sieved treatment. Results of the current study provide important information concerning FNUE and residue decomposition of barley resulting in an improved understanding of nutrient cycling in barley-based cropping systems.

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Dedication

I dedicate this thesis to my family who have provided their love and support during my life. In particular, to my mother and father Jan & Leroy Loomis. Countless hours of support given to me by both in my youth and as an adult. Many hours of getting to ride along with my father in his truck gaining a love for agriculture and gaining perspective in life. I acknowledge the good faith and encouragement from my siblings Joel, Benjamin, Stephanie, Rayne, Logan, and Evan in pursuing my continued education.

I hope to pass on the good qualities that have developed as I have pursued my M.S. degree to my children.

Finally, I dedicate this thesis to my wife Adilynne, who has been supportive the entire time during my education.

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Chapter 1

Introduction

Barley (*Hordeum vulgare* L.) is an important cereal grain grown in Idaho on over 200,000 hectares resulting in 1.1 million metric tons (MMT) of production annually, which represents a third of total production in the United States (IBC, 2017). Improving fertilizer nitrogen (N) management and uses in the state of Idaho is critical to increase the marketability of the crop. In a changing climate where increased scrutiny is now placed on sustainability related to the movement of nutrients that can cause potentially negative effects to the surrounding environment. Additionally, residue management is an important component of nutrient cycling in the plant-soil ecosystem to support sustainability and soil health for subsequent growing seasons. Thus, investigation of nutrient cycling occurring under current management practices will provide evidence of the sustainability of barley production under high-input, irrigated conditions in southeastern Idaho.

Background

Understanding the movement of N in the plant-soil system is vital to the development of improved fertilizer N management practices, as well as to understand the potential effects these practices have on the surrounding environment in southeastern Idaho. Increased data on management practices of barley residue in the field and potential implications to soil microbial communities will enhance our understanding of nutrient cycling. This improved knowledge in terms of nutrient cycling will be beneficial to Idaho production as it will provide evidence of effective best management practices (BMPs) for both fertilizer-(N) use as well as crop residue management.

Fertilizer nitrogen use efficiency

Building an understanding of N accumulation patterns along with redistribution within the barley plant would provide key information in terms of nutrient cycling that are important for improving fertilizer N management (Bashir et. al, 1997). Additionally, determining applied fertilizer N recovery is important for determining fertilizer nitrogen use efficiency (FNUE) of barley production systems. Nitrogen management is critical in production of barley to meet specific quality expectations. Managing fertilizer losses from the production system is vital to finding the best solution to reducing movement into other environments. Another important consideration to barley producers is the type of residue management that should be conducted to maintain optimum yields. Recent findings showed that additional N applied had no significant effect on the breakdown of corn stalks in Iowa soils (Al-Kaisi et al., 2017).

The rate of decomposition of barley residues in the field can be greatly affected by tillage practices, and manipulation of residues in the field i.e. chopped or finer particles of barley residues as a part of mulching practices, soil type, and associated soil properties (Angers et al., 1997). Given this background, a study was designed to determine barley straw breakdown with regards to methods of residue management (surface vs. incorporated), residue size (ground and chopped), and soil type (loam and sandy loam). These experiments will be foundational to the development of revised residue management BMPs.

The following research gaps have been identified based on the literature available on barley:

1. Investigation on the effects of fertilizer-N management practices (surface and incorporated application) on FNUE of cultivars widely grown in southeastern, Idaho under high-input, irrigated conditions.
2. Effects of management practices on residue decomposition in southeastern, Idaho soils where barley is produced.

Based on the research gap the following research objectives have been identified:

1 Investigate the effects of fertilizer-N management practices (surface and incorporated application) on FNUE of the plant-soil system for three widely grown cultivars (ABI-Voyager, Moravian 69, and Harrington) in southern Idaho.

2 Determine the effect of residue size (chopped (4 cm to 6 cm) vs. sieved (2 mm)), methods of residue management (surface vs. incorporated), and soil type (sandy loam vs. loam) on barley residue decomposition.

Thesis Organization

This thesis is organized into five chapters, which address all components of this research. Chapter one is a general introduction outlining the relevance of this research with a brief background and introduction of the research, while the second chapter identifies the studies relevant to this research via a literature review. The third and fourth chapter outline the materials, methods, results, discussion, conclusions, and references for both the studies concerning FNUE of irrigated spring malt barley determined using enriched isotope tracers, and the laboratory evaluation of the effect of simulated post-harvest management practices on barley residue decomposition in Idaho soils. The fifth chapter, includes general conclusions of the thesis, highlights the implications of the research finding on FNUE and

residue decomposition as affected by simulated post-harvest management practices. Finally, future direction of research work based on the findings of the current studies is provided.

Chapter 2

Literature Review

History and Uses of Barley

Barley (*Hordeum vulgare* L.) is a valuable plant to mankind primarily due to the varied end-uses of its seeds. Globally, barley can be found growing throughout diverse regions, including the high plateaus of Tibet and Ethiopia, the Andes Mountains of Peru, oases of the Sahara, and even north of the Arctic Circle (Ullrich, 2011). In North America, the leading producers of barley are in northern latitude and high elevation areas where the majority of production is in the states of Idaho, Wyoming, Montana, and North Dakota as well as the plains of Canada (USDA-NASS, 2017). The most common uses of barley are feed for livestock, food for human consumption in the form of pearled grain, flour, or partially ground grain, and malting for beverages and food production.

Barley was among the first domesticated plants used in the transition from hunting and gathering to agrarian lifestyle in the "Fertile Crescent" of the Near East starting at least 10,000 years ago (Smith, 1998). Many studies have been conducted to find the origin of barley, but in short the studies have not definitively solved the question. Over time, studies began to focus on the origin of the different rowed cultivars rather than the origin of all barley. It is difficult to trace the path that barley took to arrive in the Americas, but the most commonly accepted explanation is the early explorers and settlers that were first documented to travel across the seas. In the western hemisphere, one of the first groups of people to introduce barley into the Americas was also the first group documented to explore the Americas, those who traveled on the expedition with Columbus (Harlan, 1968). During this time, it was common for explorers to bring seeds from crops of their home country to

establish agricultural production. In the early stages of European settlement of North America, immigrants from England would likely have cultivars that were late-maturing two-rowed barley such as Chevalier and Thorpe (Harlan,1968). However, the climatic conditions of the eastern coastal area of the United States were not favorable for these cultivars, whereas the eastern provinces of Canada were. Thus, a selection process began to determine appropriate cultivars that could be grown in the region.

The center of barley production in the United States remained the Atlantic coast until around 1849 when New York became the leading producer (Reid et al., 1968). As western expansion occurred, major brewing industries were established in areas near Cincinnati and St. Louis and thus, barley production was established near these areas. As railroads were developed, barley production expanded into areas where land prices and climatic conditions were more favorable for barley production (Reid et al., 1968). Upper Midwestern states were a primary source of barley, and barley was also being produced in Washington, Oregon, and California by the late 1800s. A major movement of production into the northern and western states occurred during the 20th century due to several key factors including; corn (*Zea mays*, L.) and soybean (*Glycine max*, L.) rotations proliferating in historical production areas, and the development of irrigation in the Pacific intermountain west. Areas such as southern Idaho were in a drier climate where reduced pest pressures and improved harvest conditions ensured high quality grain production.

Current Predominate End-uses of Barley

Currently, the most significant use of barley is for malting, which is primarily used for the production of beer and as an additive in bread flour made from wheat (*Tritcum aestivum* L.). Other cereals that are commonly added to barley malt to add flavor or taste to

beers are: sorghum (*Sorghum bicolor*, L.), corn, millet (*Pennisetum glaucum* L.), and rice (*Oryza sativa* L.). Malting is the process of controlled germination of grain followed by drying (Schwarz and Li, 2011). This is accomplished in specialized malting facilities where the final malt is distributed to breweries. The malting process results in a large increase of hydrolytic enzymes, partial degradation of endosperm cell walls and protein, and structural changes within the grain tissues that render starch and protein substrates readily extractable (Ullrich, 2011). Malt quality is usually deteriorated if barley germinates (i.e., sprouts) in the field uncontrolled. Hence, the intermountain west has large acreages of barley due to favorable weather conditions, such as dry summers and ample irrigation. Barley as a feed is also used by ruminant and non-ruminant livestock, poultry, and fish production systems. In feed rations, barley can be used like other cereals as a source of starch-based calories. Lastly, barley as a food for humans has historically represented a small portion of the market; however, recent releases of cultivars with high β-glucan content have resulted in an expanding market niche (Obert et al., 2011). Until recently, the health benefits of barley were not as well-known as other grains, particularly as it is high in dietary fiber, low in fat, especially saturated fatty acids and trans-fatty acids, and rich in antioxidants making it an excellent nutrient source as part of a well-balanced diet.

Nitrogen in the Environment

Nitrogen (N) cycling in the environment is an important part of living systems due to the continuous movement of N in various forms in the plant-soil-atmosphere system. Nitrogen is the primary component of the Earth's atmosphere as N_2 and is one of the most important reserves of N in the global N cycle (Foth and Ellis, 1988). The only naturogenic processes where N is transferred from the atmosphere to terrestrial ecosystems is through

biological or non-biological N fixation. These processes include fixation by cyanobacteria as well as by rhizobia infected roots of legumes. In contrast, anthropogenic N fixation was developed by Haber and Bosch (1917) in a process that converts atmospheric N_2 to NH_3 gas under high pressure using methane gas and iron-based catalysts. Fixation of N by the Haber-Bosch process is largely used to produce synthetic N fertilizers where the first commercial plant was constructed in 1917 in Oppau, Germany (Foth and Ellis, 1988). Synthetic N fertilizer production is the primary mechanism by which human activity has made dramatic changes to the global N cycle. Additionally, synthetic N fertilizer was a primary driver of the green revolution that ensured increased crop production and stability that in turn led to rapid human population growth in the preceding century (Ullrich, 2011).

Nitrogen cycling focuses on the conversion from organic to inorganic forms and vice versa, as well as changes in inorganic forms of N through a multitude of pathways. Soil N cycling is reliant on the activity of microbes that convert organic N into mineral forms (i.e., ammonium, NH_4) by the process termed mineralization (Stevenson, 1999). Following mineralization, aerobic microbes carry out nitrification where NH_4 is converted to nitrite (NO_2) by nitrosomonas bacteria and subsequently nitrate (NO_3) by nitrobacter where the conversion from NO_2 to NO_3 is typically rapid in upland soils. These inorganic-N forms (NH_4 and NO_3) are the primary forms taken up by plants when they become available in the soil solution and plant roots assimilate the nutrients. In contrast to the process of mineralization, immobilization occurs when microbial activity shifts the process to convert inorganic-N to organic-N. These processes are largely regulated by C:N ratios where a ratio of 20:1 or less favors mineralization and a ratio of 30:1 or greater favors immobilization (Brady and Weil, 2008). Leaching of N occurs primarily as NO_3-N is mobile in the soil and

is moved through the soil profile by water. Ammonium-N can be fixed by clay due to the negative charge associated with clay particles that attract cations in the soil. The pathways by which N is lost to the atmosphere in gaseous phases are through NH_3 volatilization and denitrification. These processes help complete the N cycle from the atmosphere to soil and back again to the atmosphere.

Nitrogen is the nutrient used in the greatest quantities in agricultural productions worldwide and in Idaho (Mahler, 2004). With increased mechanization in agricultural production systems and reliance on synthetic N fertilizers to secure yield goals, the impact on the N cycle by human activity has increased since the advent of the Green Revolution. Modern agricultural production is largely dependent on the usage of synthetic N fertilizer produced by the Haber-Bosch process. This reliance on synthetic-N fertilizers has led to changes in agricultural production, which have led to an approximate doubling in the amount of N that is put into the terrestrial pool of N as compared to that prior to the development of synthetic-N fertilizers (Vitousek et al., 1997).

The wide-spread production and usage of synthetic-N fertilizers has led to changes in N cycling that have occurred by adding more N into the terrestrial pool by anthropogenic atmospheric N fixation. This has resulted in a transfer of atmospheric N into the soil. That has adjusted the equilibrium between the terrestrial and atmospheric pool of N as it has shifted towards the terrestrial side where additional soil N can be lost to the surrounding environment. In specific areas, increased levels of NO_3 have been measured in groundwater that are believed, at least partially, to be from nonpoint agricultural sources (Moody, 1990; Paerl, 2016). A major concern with higher levels of NO_3 in groundwater is the potential health hazard it poses to humans and other animals. For example, excess groundwater NO_3

concentrations can lead to negative human health effects including conditions such as methemoglobinemia (i.e., blue-baby syndrome), which were reported as recently as the year 2000 when babies were fed with formula reconstituted from private wells in Columbia County, Wisconsin (Knobeloch et al., 2000). In relation to this, N use efficiency in the plant-soil system is an important factor for improving water quality by limiting the downward movement of N in the soil profile (Mahler, 2007). In addition to issues with groundwater that have risen in certain environments, surface water eutrophication primarily in coastal regions are affected by N loading in a watershed (Howarth et al., 1996). Eutrophication in freshwaters has historically been considered to be primarily controlled by phosphorus (P) as cyanobacteria can fix atmospheric N (Schindler, 1977); however, recent work has indicated the balance of N and P are both of importance (Howarth et al. 1995; Paerl, 2009; Paerl, 2016; Vitousek et al., 1997). As concerns of anthropogenic eutrophication have risen, actions have been taken to limit off-site losses from crop N application and improve the fertilizer recommendation process including collecting soil samples and recommending only the fertilizer rate that is needed to meet realistic yield goals for a specific crop.

Sustainable fertilizer-N management can be achieved by managing applications as per the crop demands. While the use of synthetic fertilizers to produce efficiently large quantities of food cannot be substituted at this time, there is evidence that the efficiency of N fertilizer can be improved (Vitousek et al., 1997). Split applications, fertilizer incorporation, and application to meet crop demands are several examples of practices to improve N-fertilizer use efficiency in cropping systems (Girma et al., 2005). Additionally, crop rotations can be designed to maximize assimilation of N applied to the soil, which can aid in efforts to minimize the impact of human N use. Nitrogen demands in crop production are

location-specific and depend on the crop type. Few soils have sufficient N supplies that are available at the correct timing to produce high-yielding, and high-quality cereal crops. Proper approaches must be developed that maximize agronomic production while minimizing potentially negative environmental impacts.

Nitrogen in Crop Production

Nitrogen is one of the most important nutrient elements for crop production as it is a primary component of chlorophyll and essential for photosynthesis. Therefore, N is an essential plant nutrient as no other nutrient can substitute for its functions within the plant's life cycle. Nitrogen is found in the greatest quantity of the essential mineral nutrients within plant tissues. The source of plant N is either from soil reserves, supplemental fertilizer, or amendment applications. However, often N is insufficient to produce optimal yields, thus, applications of organic or inorganic sources of N to the soil are common in agricultural production. The Green Revolution was a period of time where discoveries lead to the use of synthetic fertilizers and pesticides, increasing agricultural production. Since the Green Revolution the application of synthetic- as well as other sources of N-fertilizers to the soil has increased (Brady and Weil, 2008). Determination of the correct rate of N to maximize production, while limiting the impact on the environment, is a goal that has improved due to the continued studies focused on optimizing N in cropping systems. When developing fertilizer management practices, it is important to understand the processes and forms of N, as well as the potential movement throughout the environment that can occur and have significant interaction with the soil-plant-atmosphere.

Nitrogen is found in nature in a range of forms which result in different reactions with the surrounding environment. Plants contain 1 to 6 percent N by weight and will absorb

N primarily in the inorganic form either as NO_3 or NH_4 (Gardner et al., 1985). Depending on the conditions of the soil, the availability of the various forms of N can change in concentration. Plants take up NH_4 most readily as compared to NO_3. This is due to the plant needing to metabolize NO_3 into NH_4, which requires an additional metabolic step (Brady and Weil, 2008). Soil conditions may favor higher amounts of one form of N over the other, which can affect crop production (i.e., anaerobic conditions in a field will stop conversion of NH_4 to NO_3) (Gardner et al., 1985; Havlin, 2014). For agricultural sustainability and optimization in crop production, application of N to the soil should be at levels to achieve optimal plant growth and yield. Elevated N rates can result in production of a greater amount of NH_4 which in turn can reduce the growth of plants at levels considered toxic (Bennett, 1996). While plants have metabolic pathways that allow the assimilation of NH_4 rapidly when needed, most often NH_4 is converted to nitrite (NO_2) then to NO_3 in the soil solution through nitrification reducing availability of NH_4. Fertilizer applied NH_4-N can influence the pH of the top soil, which can influence loss mechanisms as well as be partially responsible for changes in pathogenic activity. Conversely, nutrient deficiencies in a plant can influence the susceptibility to diseases over the growing season, and N is the macro nutrient considered to have the most interaction effects with plant pathogens (Schumann and D'Arcy, 2013). The reason for this is that when N is deficient the plant cannot assimilate normal compounds essential to the development of the plant leading to weak plant tissue, and thus, allowing easier invasion by pathogens.

The main uses of N within the plant are the development of amino acids, proteins, adenosine diphosphate (ADP; a compound that is essential to the movement of energy), and adenosine triphosphate (ATP; a chemical that participates in many functions within the

plant, and an integral part energy transfer which occurs in chlorophyll in leaves) (Voet and Voet, 2011). During the formation of amino acids that are used in the production of proteins, NO_3 must be reduced to NH_4 for the plant to utilize it. This reduction occurs in a two-step process where harmful NO_2 is not allowed to accumulate into amounts that would damage the plant. The proteins formed in the plant are critical building blocks of cells within the plant and are needed for biochemical reactions that occur in the plant's life cycle (Havlin, 2014).

Nitrogen in Barley Production

Nitrogen fertilizer is an important input for the production of barley that must be managed based on crop end-use, as soil and applied-N directly affect final grain yield, grain protein, and test weight (Robertson and Stark, 2003). Production of barley is primarily for feed, food, and malt production where production practices must focus on the specific need of each end-use (Rogers et al., 2017). In Idaho, 80% of barley production is for malting and the resulting grain must meet specific criteria in order to produce a consistent quality of malt (IBC, 2017). The application of N in the field to grow barley is an important determinant to the final yield and quality. In general, as application of N to barley fields increases, the protein content within kernels will also generally increase in a linear fashion (Robertson and Stark, 2003). If N is over applied the level of protein may become unacceptable, which results in rejection or reduced compensation based upon contracted terms met between grower and buyer. In addition to protein, appropriate application rates of N are required to maintain the quality and quantity of plumps (Robertson and Stark, 2003). Plump kernels are defined by federal grain grading guidelines and are defined for two-row barley as the percentage of grain that remains on top of a 6/64 x ¾ slotted-hole sieve after sieving

(USDA, 1997). Grain protein is directly correlated while Plump kernels are inversely correlated to N available for assimilation via soil and fertilizer-N applied. As barley assimilates more N, protein percentages increase and the volume of plumps decreases. The greater the amount of Plump kernels harvested from a plant the better market value that crop has with respect to malting. Therefore, barley must be managed not only for yield, but in a manner that keeps proteins at acceptable levels in the crop with a high volume of plumps. The current general recommendation of N for barley under an irrigated environment is 112 to 157 Kg ha^{-1} (Robertson and Stark, 2003). Fertilizer-N applications after tillering are not recommended to avoid excess grain protein. Four factors are important to consider when determining the appropriate rate of N fertilizer to apply for barley to reach an optimum yield goal: the available soil inorganic N, mineralizable N, previous crop residues, and realistic yield estimates. Current recommendations are for a soil test (i.e., 2M KCl extraction) to be performed to determine inorganic soil N status (NH_4 and NO_3) (Robertson and Stark, 2003). Previous research has indicated that inorganic-N is well correlated to crop response in barley production (Brown and Stark, 1989). Soil organic matter has typically failed to forecast available mineralizable N from organic content in southern Idaho (Robertson and Stark, 2003). Microbial activity in the soils will vary resulting in a range of mineralizable N soils in southern Idaho (e.g. 33.6 to 67.2 kg ha^{-1}), but the average mineralizable N value used is 50.4 kg ha^{-1}, unless a known rate of mineralization is established in a specific area (Robertson and Stark, 2003). Further, previous crops in the rotation to barley will have a considerable effect on the production of barley. Potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), and onion (*Allium cepa* L.) residues are readily decomposed, and the plant tissue rapidly releases N into the soil during decomposition, and are accounted for by

spring soil inorganic-N testing. This decomposition is facilitated by the breakdown of the macromolecules (e.g., proteins, nucleic acid, amino-polysaccharide) within organic tissue. These substrates that are higher in N content are used in microbial activity liberating N as NH_3 (Stevenson, 1999). For every metric ton of cereal grain residues remaining in the field additional fertilizer-N is recommended at a rate of 17 kg ha^{-1} of N per metric ton not to exceed 56 kg ha^{-1} of N (Brown and Stark, 1989). Therefore, the residue management of straw remaining in the field after the grain has been harvested is a major consideration in maintaining soil fertility and nutrient cycling for subsequent crops.

Nitrogen in Barley Physiology

Barley plants are autotrophic meaning they are able to synthesize inorganic nutrients obtained from the soil into organic compounds utilized by the plant. Specifically, N is assimilated into vital organic substances such as pigments, enzyme co-factors, lipids, nucleic acids, amino acids and, chlorophyll (Taiz and Zeiger, 2002). In the plant, NO_3 is converted to a higher-energy form in NO_2, then to a higher-energy form NH_4, and finally into the amide N of glutamine (Bloom et al. 1992). Amino acids are the building blocks for proteins and N is critical in the production of amino acids. Assimilation of N throughout the growing season results in a shift of N from the source of available N in the plant that will transfer to the sink where the N is needed. It has been observed that the sink location in the plant will change throughout the growing season based on the development of fruiting parts of the plants (Gardner et al., 1985). Additionally, vegetative growth occurs before production of the fruiting structures during the growing season. Studies reported that N accumulation occurs mostly during the early growth stages in barley where accumulation is reduced in the later stages of maturation, and partitioning is the primary method of change at this time

(Gardner et al., 1985; Bloom et al., 1992). Studies have shown that N fertilization increases the amount of dry matter remobilization (Dordas, 2012). Fertilization of barley will affect the N accumulation and partitioning in barley, which can affect grain quality, yield, and protien (Dordas, 2012). After anthesis the grain of barley becomes the sink for nutrients causing movement of the N in barley.

Fertilizer Nitrogen Use Efficiency

The process of utilization of applied fertilizer-N in the field is important to understand with respect to the output from a field as an agroenvironmental indicator of the barley production system. One such indicator is FNUE. Fertilizer N use efficiency can be defined as the ratio between the amount of fertilizer N removed from the field by the crop and amount of fertilizer N applied expressed in percentages. Information on FNUE provides information about the relative utilization of supplemental fertilizer-N applied to an agricultural production system. Primary methods to measure FNUE are the difference method and the use of enriched or depleted ^{15}N (i.e. isotope tracer method).

The difference method measures a fertilized plot in comparison to a non-treated check. Fertilizer nitrogen use efficiency is then calculated as described in Equation 1 (Moll et al., 1982; Raun and Johnson, 1999):

(Equation 1) PFR = (NF)-(NC) / R

Where,

NF = total N uptake by the crop from the fertilized plots,

NC = total N uptake by the crop in unfertilized plots,

R = rate of fertilizer applied to the individual plot,

PFR = percent fertilizer recovery

The difference method often provides different results as compared to the isotope tracer method, unless the amount of soil N that the crop uptakes is the same for the plots that are fertilized and non-fertilized (Harmsen, 2003). Stable isotope tracer (^{15}N) methods can account for N that may not create a response in a crop as ^{15}N from applied fertilizer can be differentiated from N taken up from the soil. When enriched ^{15}N isotopes are added to the system, they can be measured in the soil where they are assimilated into the soil N pool giving a higher percentage of ^{15}N in the plant-soil system. Thus, this method more accurately accounts for N within the experiment when compared with the difference method. Sampling at different growth stages allows determination of which growth stage has the highest amount of N recovery. Typically, a higher percent N recovery is documented within the soil, microbial community, and plant system when using the isotope method (30 to 70% used by plant and up to 40% found in soil) as compared to the difference method (Stevenson, 1999).

Use of ^{15}N Tracers to Measure FNUE

Measurement of FNUE using ^{15}N isotope tracers in laboratory or field experiments provide insight into the movement and transformations occurring in the plant-soil-atmosphere system. Isotopes are common in studies observing the movement of specific elements. For example, labeled C, sulfur (S), P, and N have been used in studies that observed organic matter decomposition releasing nutrients into the soil (Stevenson, 1999). Isotope selection is important when designing a tracer study. Selection must take into consideration whether a radio or stable isotope is most appropriate, and whether increased

safety protocols and an understanding of the half-life of radioisotopes must be taken into consideration. Carbon tracer studies use both ^{13}C and ^{14}C which are stable and radioactive isotopes, respectively, to trace the fate of crop residues (Stevenson, 1999). Among the many known N isotope forms, only two are stable and naturally occurring (i.e., ^{14}N and ^{15}N). Due to the radioactivity and short half-lives of the other N isotopes they are not applicable for long term studies. For example, the radioisotope ^{13}N has a half-life of 10.05 minutes which would be unusable in a study done over a period of months (Norman et al., 1965; Bremner and Hauck, 1982). The majority of the N found on earth appears as ^{14}N (99.634% atmospheric N), and the natural abundance of ^{15}N is 0.366% (Stevenson, 1999). Usage of ^{15}N in agricultural studies is advantageous compared to ^{13}N as ^{15}N is a stable isotope that does not go through radioactive decay making it safe to handle and use in an environmental setting. Due to the relatively low natural abundance of ^{15}N, its movement can be measured in both the plant and the soil as the isotope moves through the plant-soil system making it an ideal tracer for field experiments. No special permitting is required to obtain or use stable ^{15}N isotopes, unlike ^{13}N which requires special permits and must be used in a controlled environment with the proper safety precautions due to radioactivity.

While ^{15}N is widely used, experiments using ^{15}N must make the following assumptions: (i) natural abundance in the soil is at the average across environments (0.366%), which should be verified by analysis, (ii) living organisms (e.g. plants, microorganisms etc.) cannot differentiate between the different isotopes present in the soil and ^{15}N will be assimilated no differently than the other available isotopes in the soil, (iii) biochemical reactions remain the same with the ^{15}N atoms, and (iv) physical interactions remain constant over time (Stevenson, 1999). After testing the experimental soil for ^{15}N

status, the use of these tracers can produce valuable data that can help discern the most valuable use of N fertilizers. Determination of FNUE and ^{15}N recovery are based on the following equations:

(Equation 2) % plant N derived from the fertilizer = (Nu - Nt)/(Nu - (Nf/n))

Where,

Nu = atom % ^{15}N in unfertilized plants,

Nt = atom % ^{15}N in fertilized plants,

Nf = atom % ^{15}N in the fertilizer (for example 2.405%),

n = the plant discrimination factor between ^{14}N and ^{15}N – (assumed as 1)

Studies using N isotopes began about five decades ago with the intentions that it would give valid information on FNUE (Stevenson, 1999). This technique has been found to be a great method to monitor the movement of N in the soil, including dynamics of different fertilizer sources. The results that are produced from these experiments aid in understanding dynamics of soils, and the succession of N in terms of amount of N that is mineralized or immobilized by microbial activities within the soil environment, as well as the amount of N that assimilated by the plant. The ^{15}N method is a more powerful method than the difference method as it provides basic information on N in the soil. The difference method records the fertilizer assimilated by plants, but it fails to account for the mineralization- immobilization or turnover in the soil, as fertilized plots and the untreated plots may provide a higher recovery than the tracer method. Current research practices using ^{15}N are used to follow the

N transformation in the soil and distinguish between pools of N in the soil (Stevenson, 1999).

Long term studies that acquire multiple years of data in a single location where the isotope tracers have been applied, have reported that the availability of the tracer declines rapidly from the first year (Stevenson, 1999). Thus, in order to acquire the most accurate data the location of the trial must rotate to other locations where the abundance of the isotopes is known to be at natural abundance levels. This will ensure that when application of tracers is conducted, they will enrich the soil making ^{15}N available to the plant to assimilate the N applied through fertilizer, and no recovery of previously applied ^{15}N is available to interfere with the current study results (Stevenson, 1999). The % fertilizer-N recovered (20%) from a barley production system in Alberta, Canada tissue samples taken at the grain filling stage indicates functionality of the tracer method (Haugen-Kozyra et al., 1993) which was applied at planting. This shows that studies using the method of ^{15}N can give effective and clear information on plant physiological changes. With an appropriate method to observe movements of fertilizer-N a study than can observe differences in placement of fertilizer will better identify ideal management practices.

Surface vs. Incorporation of N Fertilizer in Barley Production

Nitrogen fertilization through different application methods can lead to the loss of N fertilizer through the naturally occurring mechanism of volatilization and nitrification. The charge of soil particles and organic matter is negative allowing NO_3^- form to move into the soil easily because an anion does not bind to another anion allowing it to move via diffusion or in soil water. Studies have reported that when fertilizer-N is incorporated into the soil, less N_2O (typically 28% less), a potent greenhouse gas, is released into the atmosphere when

compared to surface application (Nash et al., 2012). Nitrogen undergoes substantial movement and transformations in the soil system due to the processes of mineralization, immobilization, denitrification, nitrification, volatilization, leaching, and interaction with other elements or soil particles. Thus, it is important to consider whether fertilizer-N is surface applied or incorporated e.g. when applied to the soil surface as loss is more likely from surface applications (Rogers et al., 2018; Engel et al., 2011). In some extreme cases approximately 50% of fertilizer-N applied to the soil surface was lost without incorporation (Jones et al., 2013). Comparing these two types of fertilizer-N management practices, it is estimated that more N will be recovered through the plant-soil system rather than being lost when incorporated compared to surface applied. Hence, proper understanding of these two methods of fertilizer application can lead to better knowledge of barley production, productivity, and environmental sustainability.

Residue Management in Barley

In Idaho, barley is grown on 200,000 hectares resulting in approximately 6,716 kg ha^{-1} of organic residues, where residues from barley can vary in their C: N ratio (i.e. 80 to 54:1) depending on the growing condition, cultivar, and location (IBC, 2017; Rogers et. al., 2017). After grain is harvested, barley residue either remains in the field or is bailed and removed. Remaining residue in the field is an important source of soil organic carbon (SOC) (Al-Kaisi et al., 2017). In semi-arid regions of southern Idaho and other parts of the Pacific Northwest (PNW), soils are highly susceptible to soil organic matter (SOM) loss, and thus, SOC levels may be low (Rasmussen et al., 1998). In addition to building SOC, residue reduces soil erosion, retains plant nutrients in the soil, and provides energy for soil microbial processes (Malhi et al., 2006, Ertl, 2013, Hossain and Puteth, 2013; Al-Kaisi et al., 2017).

Soil microbial communities are the primary regulators of soil C and nutrient (e.g. N) cycling, where the C: N ratio of residue is an important factor determining decomposition. A C:N ratio of 24:1 is a balanced ratio for soil microorganisms where addition of residue at this ratio would result in little to no excess C or N left in the soil after decomposition. Greater ratios would result in net immobilization, and lesser ratios would result in net mineralization. Current recommendations are based on the knowledge that residues affect the cycling of C and N and thus, the availability of crop nutrients in the soils. Decomposition under varying management practices needs to be quantified and understood so that the management practices are developed on the basis of nutrient cycling.

Trends in the United States have moved towards no-till practices that leave residue on the surface of the soil (Uri, 1998; Busari et al., 2015). Soil aggregates have shown to improve structure and fertility in the soils in these no-till management systems after four years of residue left on the soil surface in the field (Rhoton, 2000). These findings help to encourage crop producers to make management changes to convert tillage practices to no-till. However, researchers have reported that no-till soils often have an increased emission of greenhouse gases when they are poorly-aerated and fine textured (Rochette, 2008).

Management of Barley Residue Decomposition

Current recommendations in Idaho and parts of the PNW recommend supplemental N applications to breakdown cereal straw; however, application of fall-N to facilitate residue breakdown is not widely practiced. Additionally, field tillage practices vary widely in the state from no-tillage, direct-seed operations to intensive conventional tillage operations that affect residue breakdown differently. Conventional tillage incorporates residues into the soil, and surface soil is turned over into the sub-surface soil. Incorporated residues result in more

contact between the soil and the residue, typically resulting in increased rates of residue breakdown. Therefore, the depth of the residue placement and C loss of straw buried in the soil is usually related to the rate of decomposition (Christensen, 1986). Further, the top soil becomes more stable and suitable to decomposition when residues are placed under the soil surface (Vigil and Sparks, 1995). Incorporation of crop residues has shown that net mineralization is typically greater than residues left on the soil surface in a study that observed wheat residue exposure to soil after 26 months with placement above, on, and in the soil with losses at 25, 31, and 85% respectively (Douglas et al., 1980), resulting in changing C:N ratio of the soils. Conversely, no differences in decomposition rate of corn residues over an extended period of time were observed in a silty clay loam soil in Iowa when residues were incorporated versus unicorporated (Al-Kaisi et al., 2017). The effects of residue placement in the process of barley residue decomposition as mentioned above showed mixed results based on the literature available. This indicates the need for more investigation into the factors that influence decomposition.

Manipulation of residues in the field i.e. chopped or finer particles of barley residues as a part of mulching practices could aid breakdown by increasing the surface area contact between the soil and remaining residues (Vigil and Sparks, 1995). Another study indicated increased mineralization of C from rye and wheat residues were obtained with larger particle size (>6 mm) of residues in a laboratory incubation study at 25°C (Angers and Recous, 1997). Studies have varied in expressing the effects of particle size in the process of barley residue decomposition based on available literature. Changes in top soil with respect to mulching and combination with soil types specific to a region has an influence on residue breakdown by impacting the activities of microbial communities (e.g. bacteria, fungi,

actinomycetes, etc.). Mulching could be considered for increasing barley residue breakdown e.g. microbial activity increased typically under warm conditions (32-35°C) (Douglas et al., 1980) and when the soil pore-space is filled (~55%) which facilitate the decomposition (Al-Kaisi et al., 2017). Conversely mulching is not a common practice in barley production in the region due to its effect on increased immobilization which reduces nutrient availability (McCalla and Army, 1961).

Soil type and associated soil properties exert an important effect on decomposition patterns of barley residues by affecting the quantity and quality of microbial communities and their interactions with associated flora and fauna present in the soil (Gilmour et al., 1998). Barley residue decomposition is affected by soil texture: for example, a greater adsorption of organic N by clay soils has been reported as compared to sandy soils (Van Veen et al., 1985) and decreased SOM decomposition has been reported in highly aerated sandy soils upon addition of barley residues (Christensen, 1986; Thomsen et al., 1999). Studies have shown that different soil textures affect the rate of decomposition more than the composition of residues in the soil (Christensen, 1986; Al-Kaisi et al., 2017). Recycling of barley residue is another important factor in the nutrient cycling in barley production systems. Remaining straw is decomposed and nutrients are either lost to the surrounding environment or assimilated into the soil for use by future crops. A wide-range of practices are present in Idaho for cereal residue management including, incorporating remaining residue from the previous crop, leaving residue on the soil surface, or removing residue by bailing. Little work has been conducted investigating the rate of decomposition of residues under varying management practices such as tillage (no-till (surface applied) vs. incorporated into soil) and mechanical residue size reduction (fine-sieved v. coarsely

chopped) in irrigated barley production in southern Idaho. These studies are needed to provide more insight to the best management practices in barley production.

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Chapter 3

Nitrogen Partitioning and Fertilizer Nitrogen Use Efficiency of Irrigated Spring Malt Barley Determined using Enriched Isotope Tracers

Abstract

Management of nitrogen (N) fertilizer in irrigated two-row malt barley (*Hordeum vulgare* L.) is critical in a high-input agricultural production system such as southern Idaho. Understanding fertilizer N use efficiency (FNUE) by using isotope tracers increases our understanding of crop uptake and will lead to improved fertilizer N management strategies for economic and sustainable barley production in the western United States. Stable isotope tracer (^{15}N) methods can account for N that may not create a response in a crop as ^{15}N from applied fertilizer can be differentiated from N uptake from the soil. A research study was conducted at the Aberdeen Research and Extension Center, Aberdeen, Idaho to investigate the effects of fertilizer-N management practices (surface and incorporated application) on FNUE of the plant-soil system for three widely grown cultivars (ABI-Voyager, Moravian 69, and Harrington). Across time, plant recovery was lowest at Feekes 4/5 due to the small plant biomass, and increased to a maximum at soft dough where fertilizer recovery from that point declines until senescence. Partitioning between plant and spike was significantly different between soft dough and harvest stages, as more N was allocated to the spike as the plant matured. Fertilizer recovery in the soil was primarily from the top 30 cm. Surface application resulted in only 60.9% recovery of applied N, which was less than that from incorporated fertilizer.

Introduction

Nitrogen is essential for crop production where barley and other cereal grains largely rely on synthetic fertilizer N applications to meet the demands of production. Judicious use is an important factor in ensuring optimal economic yields while minimizing negative environmental impacts (Vos et al., 1993). Thus, an understanding of N accumulation patterns along with redistribution within the barley plant would provide key information in terms of nutrient cycling that are important for improving fertilizer N management (Bashir et. al, 1997). Additionally, determining applied fertilizer N recovery is critical for determining FNUE of barley production systems.

Previous research on fertilizer nitrogen recovery of barley globally has indicated variation in the amount of recovery within the plant as well as the plant-soil system (Bronson, 1991). Research in Canada indicated 23 to 53% recovery of ^{15}N labelled fertilizer in the plant where 82 to 95% was accounted for in the soil-plant system at the culmination of the study (Tomar and Soper, 1981). Other research has reported approximately 20% recovery in the plant where the plant-soil system recovery was 60 to 67% (Smith and Gyles, 1989). Research from Switzerland indicated 31% of added N was recovered in the barley plant where 87% was recovered in the plant-soil system where the majority of the labelled N recovered in soil was in the top 0 to 30 cm (Vos et al., 1993).

In the United States, barley production is largely concentrated in higher latitude and/or elevation areas with shorter growing seasons including the Upper Midwest and western states (USDA-NASS, 2017). Leading producers include Idaho, Montana, and North Dakota where Idaho represents 30% of total grain production on 200,000 ha annually or 20% of the total hectarage (USDA-NASS, 2017). In contrast, Montana and North Dakota

represent 23% of production on 32% of the hectarage and 22% of production on 24% of the hectarage, respectively. In Idaho, the state average yield is approximately 5000 kg ha^{-1}, including both irrigated and dryland production, ranking third for all states and nearly 30% greater than the United States average (Rogers et al., 2018). Production in Idaho is dominated by irrigated malt (80%) where a price advantage occurs for malt barley (IBC, 2017).

Strict quality specifications must be met to receive the premium that is associated with the production of malt barley (e.g., protein concentrations, Plump kernels) (IBC, 2017). Application of N to barley factors in both yield and quality goals as application of N to barley to increase yield also leads to increases in protein and decreases in Plump kernels (Brown and Stark, 1989; Robertson and Stark, 2003). If N is over applied, quality of the barley can be reduced where protein and plumps may become unacceptable, plants may lodge leading to increased disease pressure. Failure to meet the demands (quality) of the buyer can result in rejection or reduced compensation based upon contract specification agreed upon between the grower and buyer.

In Idaho, malt barley fertilizer management practices were developed with both yield and quality in mind (Robertson and Stark, 2003). Lower fertilizer rates are prescribed as compared to feed barley or other small grains, such as wheat (*Tritcum aestivum* L.) (Brown et al., 2001). For malt barley, specific guidelines have been incorporated including the recommendation to avoid fertilization after tillering to avoid excessive grain protein. Additionally, fertilizer N placement (i.e., surface vs. incorporation) can greatly impact N losses via ammonia volatilization where fertilizer is applied both via surface broadcasting as well as by incorporation via tillage in the state (Dari et al., 2018; Rogers et al., 2018).

Despite the amount of information available concerning barley response to fertilizer N application in Idaho, we are unaware of any work that has directly assessed the fertilizer nitrogen recovery in irrigated spring malt barley. Thus, the objectives of this study were to: i) determine the total and percent fertilizer N accumulation of several malt barley cultivars when fertilizer was surface applied versus incorporated, ii) determine accumulation and redistribution of fertilizer N within the barley plant, and iii) determine the amount and distribution of fertilizer N within the soil profile at barley maturity.

Materials and Methods

Plot Management and Experimental Design

The field experiment was conducted during the 2016 and 2017 growing seasons at the University of Idaho Aberdeen Research and Extension Center (42°58'29"N 112°48'55"W) on a Declo loam soil (Coarse-loamy, mixed, superactive mesic Xeric Haploacaldics) in neighboring fields. Initial soil fertility levels are shown in (Table 3.1). Samples were oven-dried at 40°C, and crushed and sieved to pass a 2-mm sieve. Soil pH was determined potentiometrically using a 1:1 soil to deionized water ratio, ammonium and nitrate were determined by 2M KCl extraction and spectrophotometric analysis, and soil P was determined by $NaHCO_3$ extraction and spectrophotometric methods per Miller et al. (2013).

Three malt barley cultivars commonly grown in irrigated production in southern Idaho were selected: Anheuser Busch InBev Voyager (ABI-Voyager), Miller Coors Moravian 69, and Harrington. ABI-Voyager and Moravian 69 represented greater than 35% of the malt barley acreage in Idaho in recent surveys (AMBA, 2016). ABI-Voyager was released in 2011 by Busch Agricultural Resources and had an average yield of 7330 kg ha^{-1},

protein of 112 g kg^{-1}, and an average plant height of 97 cm in irrigated performance trials in Idaho, USA (Marshall et al. 2017). Moravian 69 is a short-statured cultivar that was released by Coors Brewing Co. in 2000 and has an average yield of 7903 kg ha^{-1}, protein of 113 g kg^{-1}, and an average plant height of 86 cm in the same performance trials. Harrington released by the University of Saskatchewan in 1981, is considered the industry standard for malt quality, and had an average yield of 6397 kg ha^{-1}, protein of 116 g kg^{-1}, and an average plant height of 91 cm (Mckenzie et al., 2005).

Plots were 3.0 m long by 1.26 m wide planted with seven rows at 18-cm row spacing, with a 1.2 m gap between plots. Due to the destructive nature of tissue sampling, plots treated with the tracer would not accurately represent the yield. Barley trials followed oats that were harvested fully (grain and straw) with a small-plot planter on April 7, 2016 and April 8, 2017 at a rate of 2 million seeds ha^{-1} following the recommendations for irrigated spring barley in Idaho (Robertson and Stark, 2003; Marshall et al., 2017). The source of fertilizer N was prilled ^{15}N-labeled urea (3.34180 atom % ^{15}N, 2.4 by 3.0 mm). Fertilizer N was broadcast by hand on April 7, 2016 and April 8, 2017 at a rate of 115 and 109 kg N ha^{-1} in 2016 and 2017, respectively to achieve a total N rate (i.e., soil inorganic-N + applied N) of 214 kg N ha^{-1} (Robertson and Stark, 2003). Two methods of fertilizer N applications (surface and incorporated), which are commonly used in Idaho for barley production were used for this study. Surface broadcast applications occurred immediately prior to planting, while incorporated fertilizer treatments were applied and incorporated with a plot-size spring-tooth harrow to a depth of 5 to 6 cm in individual plots. Irrigation was applied using a hand-line irrigation system sourced from a groundwater well (Robertson and Stark, 2003; Neibling et al., 2017). Plots were managed to be weed and insect free according

to current University of Idaho recommendations (Robertson and Stark, 2003). The experiments were each arranged as a randomized complete block with cultivar (ABI Voyager, Moravain 69 and Harrington) by fertilizer placement (surface and incorporated) with four replications.

Collections and Processing of Tissue and Soil Samples

Samples of aboveground dry matter were collected by cutting a 1-m row section from the second, fourth, and sixth rows of each plot at the soil surface, at least 30 cm from the edge of the plots to avoid any potential edge effects. Four separate samplings occurred based on Feekes growth stages (Table 3.2) (Miller, 1999). Whole plant analysis was conducted for the Feekes 4/5 and boot stage samplings, and for the remaining samples plants were separated into stems with leaves (plant) and spikes allowing for determination of N partitioning. Native atom % ^{15}N was verified on barley planted adjacent to the study.

Tissue samples were dried at 65°C until a constant weight was achieved. Samples were separated into vegetative tissue (stems plus leaves) and spikes, and weighed for dry matter. The sum of dry matter of vegetative tissue and spikes was defined as biological yield and was converted to an area basis (kg ha^{-1}). The plant samples were treated as a whole plant sample for the first and second sampling (Feekes 4/5 and boot), whereas the last two samplings were separated into plant and spike portions. Weights of the tissue was recorded, and the samples of vegetative tissues and spikes were ground to pass a 2-mm sieve using a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA) for determination of total N and atom % ^{15}N. The grinder was cleaned between each sample to prevent ^{15}N cross contamination. Four soil cores (2.5 cm diameter) were collected from each plot and composited as one representative sample from 0 to 30, 30 to 60, and 60 to 90 cm following

barley harvest on August 14, 2016 and August 10, 2017 and analyzed for atom % ^{15}N. Samples were dried at 40°C and crushed using a mortar and pestle to avoid ^{15}N contamination between samples.

^{15}N Analyses

Total nitrogen (TN) for each ground plant and soil sample was measured by high-temperature combustion using a VarioMax CN analyzer (Elementar Americas, Inc. Mt Laurel, NJ) in the Idaho barley agronomy laboratory. Atom % ^{15}N was determined by the University of California Davis Stable Isotope Facility (Davis, CA) via an elemental analyzer interfaced to a continuous flow isotope ratio mass spectrometer (Europa, Sercon, Ltd., Cheshire, UK).

Statistical Analyses

The experiment was a randomized complete block design with cultivar (ABI Voyager, Moravain 69, and Harrington) and fertilizer placement (surface and incorporated) completely randomized as treatments with 4 replications for each treatment (n = 24). Total N uptake, % fertilizer-N recovery and partitioning (spikes v. plant), as well as yield and quality parameters were analyzed by analysis of variance (ANOVA). Stage of sampling was treated as a repeated measure and plant part was treated as a split-plot factor where appropriate. Year and block were treated as random factors in all analyses (Carmer, et al., 1989; Moore and Dixon 2015). Statistical analyses were performed in JMP 13.0 (SAS Institute, Cary, NC, USA). All mean separations were performed using Fisher's protected least square differences (LSD) as a post-hoc multiple comparisons analyses at the $P < 0.05$ level.

Results and Discussion

Soil Characteristics

Analysis of initial soil samples indicated that the N fertility status of the soil was similar between growing seasons. The pH of the soils was alkaline in both years where in 2016 the 0 to 30 cm pH was 8.3 and the 30 to 60 cm depth pH was 8.2, and in 2017 both depths had a pH of 8.2 (Table 3.1). The NH_4-N level in the soil was similar over both years in all depths ranging from 4.0 to 4.3 mg kg^{-1}. The NO_3-N in the 0 to 30 cm depth was similar in both years at 2.9 and 3.0 mg kg^{-1} in 2016 and 2017, respectively. However, the initial NO_3-N level at the 30 to 60 cm depth in both years was 8.0 and 9.2 mg kg^{-1} in 2016 and 2017, respectively. The amount of soil P extracted with Olsen extractant was 17 and 19 mg kg^{-1} respectively, in 2016 and 2017. The low amount of available N in the soil warranted additional fertilizer-N to be applied to the soil to meet yield goals. Background analysis of ^{15}N in the soil was used to find natural atom % of ^{15}N in the soil.

Total N Accumulation

The ANOVA results indicated that there were significant differences in ^{15}N accumulation for plant part, and there were significant growth stage x plant part interactions (Table 3.3). There were no significant effects of cultivar on total accumulated N in our study. Similarly, the higher order interactions among cultivar, fertilizer placement, growth stages, and plant parts were all non-significant for total accumulated N.

Effects of Growth Stages on Total N Accumulation

Total N accumulation between growth stages was significant with the first sampling stage (Feekes 4/5) having the smallest amount of N (37.3 kg-N ha^{-1}) accumulated. Feekes 4/5 stage was significantly different from all other growth stages. Boot (140.7 kg-N ha^{-1})

and harvest (154.2 kg-N ha^{-1}) stages were not significantly different for total N accumulated, whereas the soft dough (160.6 kg-N ha^{-1}) was significantly different from boot stage, but not the harvest stage (Table 3.4). This indicates that through the growing season the peak N accumulation occurred from boot to soft dough stage. After soft dough stage the accumulation of N was lost from the plants. Possible explanations come from high temperatures and low humidity during grain filling stage to maturity, as well as leaf senescence and losses of N from the plant leaves once mature. It has been well established that losses of N occur at plant heading to maturity (Bashir et al., 1997; Schjørring et al., 1989; Smith and Gyles, 1989; Tomar and Soper, 1981), thus our findings are supported by previous research. As the plant begins to senesce it has been observed that plants will lose NH_3 at a constant rate. As the plant approaches final plant senesce the rate of N lost from the plant increases (Parton et al., 1988). These losses occur through the shoots of the plant releasing NH_3 gas. An important regulator of the rate of release is the ambient NH_3 concentration in the atmosphere.

Plant parts at the last two growth stages (GS) had significant differences as the accumulation pattern changed over time between soft dough and harvest. At soft dough accumulation in the plant (73.4 kg-N ha^{-1}) and spike (87.2 kg-N ha^{-1}) only differed by 13.8 kg N ha^{-1}, which was statistically significant (Table 3.5). The distribution which was closely balanced between the two plant parts was allocated differently as the plant reached maturity. Development of the kernel in the spike led to more demand on N for development of amino acids which are the building blocks of proteins. Nitrogen was translocated to the spike leading to a large difference in total accumulated N between plant parts to meet the need of seed development. At harvest samples in the plant differed where 31.1 kg-N ha^{-1} was

measured in the plant and 123 kg-N ha^{-1} in the spike, which is a difference of 91.9 kg N ha^{-1}. Our findings provide critical information on the movement of N over the growing season of barley, which is linked with the final crop yield from the plants.

Fertilizer N Recovery in Plants

The ANOVA results indicated that the fertilizer placement, plant part, and growth stage x plant part interactions have significant effect on % fertilizer N recovery (Table 3.3). There were no significant effects of cultivar on % fertilizer N recovery in our study. Similarly, the higher order interaction among cultivar, fertilizer placement, growth stages, and plant parts were all non-significant for % fertilizer N recovered.

Effects of Growth Stage and Fertilizer Placement on Percent Fertilizer N Recovery

Throughout the growing season the % fertilizer-N recovery varied between sampling times. Similar to Bashir et al. (1997), the first sample resulted in the lowest % fertilizer-N recovered, and the difference between Feekes 4/5 (16.6 %) and boot (53.0 %) stage was significant where boot stage sampling was the highest % fertilizer-N recovered. The % fertilizer-N recovered in the soft dough (43.2 %) and into the harvest (43.2 %) was significantly less than the boot stage (Table 3.4). The last two stages had different partitioning patterns within the plant being significantly different (Table 3.5).

The whole plant sample values for % fertilizer recovery averaged over cultivar and growth stage had significance between the two methods of fertilizer placement (Table 3.4). Surface placement (37.2%) of fertilizer-N was significantly less than the incorporated (40.8%) on amount of fertilizer-N recovered. It is well established that more soil to fertilizer-N contact reduces losses of N from the soils (Haugen-Kozyra et al., 1993).

Effects of Growth Stages and Plant Parts

In the first sampling the observations showed that at Feekes 4/5 (16.6 %) the % fertilizer-N recovered was lowest (Table 3.4). This is due to the small plant size and the developing root system as the secondary roots begin to develop and tillers will shortly begin to form prior to any development of reproductive structures that requires an increased amount N from the soil (Egle et al., 2015). Samples from the boot stage resulted in the highest amount (53.0 %) of percent N recovered. As the barley plant transitioned into grain production more N was needed for the production of the reproductive structure (spike) (Bashir et al., 1997). As proteins are created in the seeds, N is critical to the formation of amino acids which are building blocks in proteins, which is why it is necessary for the plant to accumulate N in this growth stage (Egle et al., 2015). In the boot stage the head was fully developed resulting in the maximum amount of % fertilizer-N recovered. In the last two stages of sampling the % fertilizer-N recovered remained the same between soft dough and harvest. The location of the N in the plant was significantly different in the soft dough sample from the harvest sample (Table 3.5). At soft dough, the distribution % fertilizer-N recovered between spike and plant were similar. In the harvest sample more of the N was partitioned into the spike than the plant (Perby and Jensén, 1984). As the plant matures into anthesis N is redistributed to the spike from other plant parts such as the leaves and stem (Schjørring et al.,1989).

Fertilizer N Recovery in Soils

The ANOVA indicated that only the depth (of samples) had a significant effect on the % fertilizer N recovered from the soil where cultivar or higher order interactions were not significant ($p \geq 0.05$) (Table 3.6). All other sources of variance such as cultivar and

fertilizer placement in the soil were found to be non-significant on the % fertilizer N recovered. The sampling depth over the two seasons was significant where all other treatments were not significant on the % fertilizer-N recovered in the soil (Table 3.6). Approximately 18.4 % of the fertilizer-N was recovered in the top 0 to 30 cm soil (Engel et al., 2011; Nash et al., 2012; Rogers et al., 2018). For the 30 to 90 cm depth, only 4.8 % was recovered which indicated that movement of fertilizer N was limited from top layer of soils to lower depth (Table 3.7). It is likely that leaching losses of fertilizer-N from the soil are likely minimal. This finding was similar to what was observed in another study performed on winter wheat, 18 % was recovered in the top 20 cm of soil at the end of the first year in a two-year study (Bashir et al.,1997; Egle et al., 2015). These results provide evidence that under the current study conditions minimal fertilizer-N losses to leaching over the growing season were measured.

Total Fertilizer N Recovery in Soils-Plant System

The total soil-plant recovery from the fertilizer placement component of the study was significant on the amount of fertilizer held in the plant and soil. This analysis was using the three depths of soil sampling at the time of harvest and the entire barley plant nutrient composition at harvest. With the surface application resulting in only 60.9% recovery of applied N, which is significantly different from the incorporated fertilizer (71.5%) (Table 3.8) (Guindo et al., 1994; Bashir et al., 1997). These results further show the limited movement of N through the soil profile in the incorporated treatment. Losses from the surface treatment are likely to be from volatilization.

Conclusion

Across time, fertilizer N recovery was lowest at Feekes 4/5, due to the small biomass of barley plant, and increased to a maximum at soft dough where fertilizer recovery from that point declines until senescence. Partitioning between plant and spike was significantly different between soft dough and harvest stages, as more N was allocated to the spike as the plant matures. In total soil-plant recovery the fertilizer management was significant on the amount of fertilizer held in the plant and soil. With the surface application resulting in only 60.9% recovery of applied N, which was significantly different from the incorporated fertilizer (71.5%). No significant differences between cultivars were found when averaged across two years. Results of the study provide evidence of the high N recovery in the plant-soil system of irrigated malt barley in Idaho when fertilizer N is incorporated into the soil, a practice that is optimal for FNUE.

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Tables

Table 3. 1 Initial soil fertility levels in neighboring field sites for studies conducted during the 2016 and 2017 growing seasons at the Aberdeen Research and Extension Center, Aberdeen, ID.

Year	Depth	pH	NH_4-N	NO_3-N	Olsen-P
	---cm---		----------mg kg^{-1}----------		
2016	0-30	8.3	4.1	2.9	17
	30-60	8.2	4.0	8.0	
2017	0-30	8.2	4.3	3.0	19
	30-60	8.2	4.0	9.2	

NH_4-N; ammoniacal nitrogen, NO_3-N; nitrate nitrogen, Olsen-P; Olsen extracted phosphorus.

Table 3. 2 Plant sampling times and description of Feekes growth stages (GS) for studies conducted during the 2016 and 2017 growing seasons at the Aberdeen Research and Extension Center, Aberdeen, ID.

Sampling Time	Feekes GS	Description
1	4.0/5.0	Pseudostem erection (tillering)
2	10.0	Boot
3	11.2	Soft dough
4	11.4	Maturity (Harvest)

Table 3. 3 Analysis of variance (ANOVA) values for total nitrogen (N) accumulated (kg-N ha^{-1}) and fertilizer recovery (%) in barley plants for the field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Sources of variation	Total N Uptake (kg-N ha^{-1})	Fertilizer-N Recovery (%)
Cultivar (C)	0.06	0.58
Fertilizer Placement (FP)	0.08	0.04
Growth Stage (GS)	<0.01	<0.01
Plant Part (PP)	<0.01	<0.01
C*FP	0.02	0.41
C*GS	0.49	0.75
C*PP	0.68	0.92
FP*GS	0.35	0.41
FP*PP	0.12	0.06
GS*PP	<0.01	<0.01
C*FP*GS	0.64	0.98
C*FP*PP	0.74	0.85
C*GS*PP	0.45	0.99
FP*GS*PP	0.46	0.16
C*FP*GS*PP	0.65	0.89

Table 3. 4 Effects of fertilizer placement and growth stages averaged across cultivars on total nitrogen (N) accumulated (kg-N ha^{-1}) and fertilizer recovery (%) in barley plants for the field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Treatments	Total Accumulated N (kg-N ha^{-1})	Fertilizer Recovery (%)
Growth Stage		
F4.0/5.0	37.3c[†]	16.6c
Boot	140.7b	53.0a
Soft Dough	160.6a	43.2b
Harvest	154.2ab	43.2b
Fertilizer Placement		
Surface	118.9	37.2b[‡]
Incorporated	127.6	40.8a

[†]Different letters for each parameter indicate significant differences in growth stages as compared using Tukey's Protected honest significant difference (HSD) test at $p<0.05$, respectively.

[‡]Different letters for each parameter indicate significant differences in fertilizer placement as compared with Fischer's Protected LSD at $p<0.05$.

Table 3. 5 Effects of growth stage and plant parts averaged across cultivars and fertilizer placements on total nitrogen (N) accumulated (kg-N ha^{-1}) and fertilizer recovery (%) in barley plants for the field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Growth Stages	Plant Parts	Total Accumulated N (kg-N ha^{-1})	Fertilizer Recovery (%)
Soft Dough	Plant	73.4c[†]	21.1b
	Spike	87.2b	22.1b
Harvest	Plant	31.1d	9.5c
	Spike	123.1a	33.7a

[†]Different letters for each parameter indicate significant differences between growth stages and plant parts as compared using Tukey's Protected honest significant difference (HSD) test at $p<0.05$.

Table 3. 6 Analysis of variance (ANOVA) values for fertilizer recovery (%) in soils for the field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Source of variation	Fertilizer Recovery (%)
Cultivar (C)	0.95
Depth (D)	<0.01
Fertilizer placement (FP)	0.56
C*D	0.92
C*FP	0.94
D*FP	0.39
C*D*FM	0.59

Table 3. 7 Effects of soil depth averaged across cultivars and fertilizer placements on fertilizer recovery (%) in soil for the field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Soil Depth (cm)	Fertilizer Recovery (%)
0-30	18.4a[†]
30-60	3.3b
60-90	1.5b

[†]Different letters for each parameter indicate significant differences among soil depth as compared using Tukey's Protected honest significant difference (HSD) test at $p<0.05$.

Table 3. 8 Effects fertilizer placement on total fertilizer recovery (%) (recovered in soil-plant system) averaged across cultivar at harvest in a field study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Fertilizer Placement	Total Fertilizer Recovery† (%)
Incorporated	71.5a‡
Surface	60.9b

† The values were calculated including three soil depths (i.e. 0 – 90 cm) at harvest.

‡Different letters for each parameter indicate significant differences between residue management, residue size and their interaction, as compared with Fischer's Protected LSD at $p<0.035$. respectively.

Chapter 4

Evaluation of Effect of Residue Management Practices on Barley Residue Decomposition in Idaho Soils

Abstract

Barley (*Hordeum vulgare* L.) production with an optimum yield goal in Idaho and other parts of Pacific Northwest (PNW) needs attention on farm resource management. Little is understood of post-harvest residue management practices on barley residue decomposition. The objective of this study was to determine the effect of residue placement (surface vs. incorporated), residue size (chopped vs. ground and sieved) and soil type (sand vs sandy loam) on barley residue decomposition. Further, a Markov-Chain Monte Carlo (MCMC) modeling approach was applied to investigate the first-order decay kinetics of barley residue. A 3-month laboratory incubation experiment was conducted at a temperature of 25 to 30°C at the Aberdeen Research and Extension Center, Aberdeen, Idaho, USA using field collected soil samples (0 to 15 cm depth). The amount of cumulative CO_2-C released over 50-d was greatest when residues were chopped and incorporated in soils. However, a higher initial flush of C-mineralization was measured at days 2 to 5 for all treatments. The only exception was sieved residues regardless of placement (surface vs. incorporated) showed the highest volume of CO_2 release on days 1 to 2. There was no significant difference in C-mineralization from barley residue for the two soil types under current study. The highest decay constant value ($k = 0.0083\ d^{-1}$) with a predicted residue half-life to mineralize barley residues of about 80-d was measured for residues when chopped and applied at the soil surface, whereas incorporated-sieved treatments would need an additional 48-d to decompose 50% of the residue. However, residue decomposition under field

conditions with barley residues, along with soil microbial community, is warranted to verify the study results.

Introduction

Barley (*Hordeum vulgare* L.) is an important cereal crop grown in Idaho on over 200,000 hectares resulting in 1.1 million metric tons (MMT) of production annually, which represents a third of total production in the United States (IBC, 2017). Common practices of barley production involve harvesting of barley grains, and afterwards barley residue either remains in the field or is bailed and removed. Remaining residue in the field is an important source of soil organic carbon (SOC) (Al-Kaisi et al., 2017). In semi-arid regions of southern Idaho and other parts of the Pacific Northwest (PNW), soils are highly susceptible to soil organic matter (SOM) loss, thus, SOC levels may be low (Rasmussen et al., 1998). In addition to building SOC, residue reduces soil erosion, retains and recycles plant nutrients in the soil, and provides required energy for soil microbial processes (Malhi et al., 2006, Al-Kaisi and Guzman, 2013; Ertl, 2013, Hossain and Puteth, 2013; Al-Kaisi et al., 2017). Soil microbial communities are the primary regulators of soil C and nutrient (e.g. N) cycling, where the carbon (C) to N (C:N) ratio of residue is an important factor determining decomposition. A C:N ratio of 24:1 is a balanced ratio for soil microorganisms where addition of residue at this ratio would result in little to no excess C or N left in the soil after decomposition, whereas greater ratios would result in net immobilization and lesser ratios would result in net mineralization. Sustainable fertilizer recommendations for barley production in Idaho and other parts of PNW are based on the knowledge that residues affect the cycling of C and N and availability of crop nutrients in the soils. Thus, critical factors in

barley residue breakdown includes soil type, tillage management, and managing the post-harvest barley residue.

Barley residue can vary in its C:N ratio (54 to 80:1) depending on the growing condition and locations (Angers and Recous, 1997). Further, field tillage operations in Idaho and other PNW regions vary widely from no-tillage, direct-seed operations to intensive conventional tillage operations that subsequently can affect residue breakdown. The rate of decomposition of residues in the field can be greatly affected by tillage practices. Conventional tillage incorporates residues into the soil where surface soil is turned over into the sub-surface soil (Angers et al., 1997) and the top soil becomes more stable for residue breakdown (Christensen, 1986; Vigil and Sparks, 1995). Incorporation of crop residues in a wheat field in Oregon over a 26-month field study showed that the net mineralization was typically greater when residues were plowed under soils (85%) than that left on the soil surface or above (25% and 31%, respectively) (Douglas et al., 1980). This resulted in the variation of C:N ratio in the soils, and greater nutrient dynamics for subsequent crops. However, the opposite trend of increased breakdown of corn residue occurred when residues remained on the surface of the soils (no tillage) compared to incorporated in recent studies in Iowa (Al-Kaisi et al., 2013; de Kok-Mercado, 2015). The method of residue placement (surface vs. incorporated) and consequently, the contact between the soil and the residue have had no conclusive finding, and both positively and negatively affected the residue breakdown rate in soils.

Residue particle sizes in the field (chopped or finer sizes of barley residues as a part of mulching practices) could favor either faster or slower breakdown by various mechanisms (Vigil and Sparks, 1995). In general, finer sized residue would allow more surface area for

microbial activities along with improved, nutrient and/or water retention in the surface of the soil to facilitate residue breakdown (Al-Kaisi et al., 2013, 2017). In contrast, the application of larger residues (chopped condition) would reduce soil to residue contact. Less contact between soil and residue could lead to a consistent rate of breakdown for the entire period. Smaller sized residues may favor C mineralization i.e. residue breakdown of barley by either increased microbial activities which occurs typically under warm conditions (32-35°C) (Douglas et al., 1980) or by filling the soil pore-space (55%) which facilitate the decomposition (Al-Kaisi et al., 2017). However, another study indicated increased C mineralization (8% more) from rye and wheat residues with the application of larger sized residue as compared to smaller sized residues for a 65-day laboratory incubation study at 25°C (Angers and Recous, 1997). Conversely, a neutral effect of grinding the cereal crop residues (adoption of various particle sizes of residue) with lower C:N ratio on C mineralization have been reported (Bremer et al., 1991). However, mulching is not a common practice in barley production in the region due to its effect on increased immobilization which reduces nutrient availability (Mccalla and Army, 1961). Thus, the effect of residue breakdown under prevalent weather conditions and soil types in the study region is considered to be critical for sustainable barley production.

Soil types and associated soil properties (organo-mineral interactions in a soil) specific to a region are modified when the plants roots interact with microbial organisms. Plant interactions with other flora and fauna present in that soil has an influence on residue breakdown (Gilmour et al., 1998). Barley residue decomposition is affected by soil texture. Clay soils showed a greater adsorption of organic N, as compared to sandy soil which resulted in less breakdown (Van Veen et al., 1985). Additionally, a reduced rate of SOM

decomposition has been reported in highly aerated sandy soils (Christensen, 1986; Thomsen et al., 1999) upon addition of barley residues. Soil type has a more prominent effect on the rate of decomposition than the composition of straw type with respect to N content (Christensen, 1986). However, no differences in decomposition rate of corn residues over an extended period of time were observed in a silty clay loam soil in Iowa after addition of N to the soil (Al-Kaisi et al., 2017). Other associated soil properties such as soil moisture in addition to soil type significantly influences the breakdown of the residue (Christensen, 1986).

The effects of various factors in the process of barley residue decomposition as mentioned above showed mixed results based on the literature available. Thus, management practices effect on C mineralization from post-harvest barley residues needs to be quantified and understood in irrigated production systems of Idaho so that sustainable barley production can be achieved with higher amounts of nutrient availability (C, N etc.) for subsequent crop production. Our objectives were (i) to determine the effect of residue management i.e. residue placement (surface vs. incorporated), residue size (chopped vs. ground and sieved) and soil type (sand vs sandy loam) on barley residue decomposition, (ii) to quantify the barley residue decomposition with a modeling approach to guide proper resource management for barley or cereal production in Idaho and other parts of PNW.

Materials and Method

Site Description

Two common soil types were collected from southeastern Idaho (Rogers et al., 2018; Table 4.1). Both of the soil samples were from the same series (Coarse-loamy, mixed, superactive, mesic Xeric Haplocalcids) but differ in textural classes i.e. sand and sandy loam

(USDA-NRCS, 2006). Within a sampling site, an approximately 0.1 ha area was sampled by collecting and compositing four sub-samples using a 7.6-cm bucket auger from depths of 0 to 15 cm. Following a crop of oats with all of the crop residue being removed from the field. Collected soil samples were dried in a forced-convection oven at 40 °C, and subsequently crushed and passed through a 2-mm sieve.

Soil Description

Soil particle size analysis was performed using the hydrometer method (Table 4.1) (Miller et al., 2013). Soil pH and electrical conductivity (EC) were determined potentiometrically using a 1:1 soil to deionized water ratio (Miller et al., 2013) using a soil pH meter (Orion Star^{AM} A215 pH/Conductivity Benchtop Multiparameter meter, Thermo Fisher Scientific Inc., Waltham, MA, USA). The loss on ignition (LOI) analysis was conducted on samples where 10 g of the sample was dried at 105°C for 2 h and placed in a desiccator for 1 h. Samples were then combusted in a muffle furnace at 360°C for 2 h, dried for 1 h at 105°C and equilibrated in a desiccator for 1 h. The LOI was determined based on the difference in initial and final weights (Storer, 1984; Miller et al., 2013) and organic matter (OM) content calculated. Total nitrogen (TN) was measured by high-temperature combustion using a VarioMax CN analyzer (Elementar Americas, Inc. Mt Laurel, NJ) based on Bremner (1996).

Residue Description

The residue used in the experiment was obtained from a common malt barley cultivar (Harrington) which is typically grown as a malt quality standard (McKenzie et al., 2005). Residues were collected in 2017 after harvest of a barley crop grown under standard production practices at the Aberdeen Research and Extension Center, Aberdeen, ID

(Robertson and Stark, 2003). The average dry matter production for barley excluding grain (8000 kg ha^{-1}) was chosen as the rate of residue added for the study (Rogers et al., 2018) based on variable post-harvest residue management in Idaho. The residue was characterized for cellulose, hemicellulose, lignin, and ash content. The cellulose (ADF) content (ash-free) was determined using the analytical process detailed in the 'Fiber (Acid Detergent) and Lignin in Animal Feed protocols (973.18), 2000'. The hemicellulose (NDF) content (ash-free) was determined using the method described by Van Soest and others (1991). Lignin, a critical factor influencing digestibility of the plant cell wall, was analyzed by the method outlined by Goering, 1970. Followed by fiber (ADF and NDF) and lignin analyses, the ash content in the residue samples were analyzed using the methods detailed in the 'Ash of Animal Feed (942.05), 2000'.

Laboratory Incubation Experimental Approach

A 50-day laboratory incubation experiment was conducted at a constant temperature of 25 to 30°C at the Aberdeen Research and Extension Center, Aberdeen, Idaho, USA. The experiment was arranged as a randomized complete block (RCB) design with two types of residue placement (surface vs. incorporated), two residue sizes (chopped vs. sieved), and two soil types (sand vs. sandy loam) with four replications of each treatment combination (Table 4.3). Surface applied residue was evenly spread on the surface of the soil and incorporated residue was thoroughly mixed into the soils in a 500 mL capacity wide-mouth Mason jar. Residue size included chopped (2cm to 5cm) and sieved (ground to pass a 2-mm sieve) treatments. Barley residues (4.1 g) were mixed with or placed on the surface of soil (100 g) in the mason jar for each treatment combination.

A 60 mm petri dish containing 5 mL of 1 M NaOH solution was placed in each Mason jar to capture CO_2 evolved from the soil-residue mixture during the incubation. The amount of CO_2 evolved from residue decomposition was trapped in NaOH solution at specific time intervals. Evolution of CO_2 was immediately determined by titration by adding 5 mL of 2 M barium chloride ($BaCl_2$) solution and 2 to 3 drops of phenolphthalein indicator to each petri dish. The pH endpoint was found by titration with 1 M HCl solution using a digital auto-titration (848 Titrino Plus, Metrohm Lts., Herisau, Switzerland) until the pH endpoint was reached (Al-Kaisi et al., 2017). A new petri dish with 1 M NaOH was used at each time interval after taking the previous petri-dish from individual mason jars. Three mason jars containing only soil of each types without any residue were included as a control in the study to monitor CO_2 release from the soil. Additionally, three empty Mason jars without any soil or residue were also included as an experimental control (control Mason jars), which were used to calculate the total CO_2-C evolved from each treatment in the atmosphere. The total number of Mason jars used were 48 including blank Mason jars devoid of any soils and residue samples and four Mason jars with soils and no residue to allow determination of ambient CO_2 at each sampling period. The readings were taken to measure the amount of CO_2-C released on every day of the incubation study at a specific time of the day, and titration was performed at the same time.

The soil was maintained at 60% water-filled pore space in the soil-residue mixture in each Mason jar throughout the entire experiment (Al-Kaisi et al., 2017). The Mason jars were weighed initially with the soil-residue mixtures without a petri dish in it and each Mason jar was weighed each time the petri-dish was changed for taking readings. Additionally, the amount of CO_2 evolved from each jar via. absorption by (NaOH) in petri

dish was taken into account for weight reduction in each jar. Based on the above parameters, the overall reduction in the weight of the Mason jar was calculated and compensated by sprinkling the exact amount of double deionized water in each jar during the entire experiment.

Calculations

CO_2-C decomposed

Once the endpoint in titration was achieved, the amount of CO_2 retained in each petri dish was determined by using the following formula (Stotzky, 1965).

$CO_2 = (X-Y) \times N \times W$ (Equation 4.1)

Where,

X = volume of acid needed to titrate the petri dish solution from the Mason jars with soil sample only to the end point i.e. 'blank', (mL)

Y = volume of the acid needed to titrate the petri dish solution from the Mason jars with soil-residue sample to the end point i.e. 'blank', (mL)

N = normality of the acid, (mL^{-1})

W = the equivalent weight of C in CO_2; W would be 6 if data is to be expressed in terms of C, (mg CO_2-C).

The data were presented on a unit mass basis of dry residue and soil (CO_2-C mg kg^{-1} residue d^{-1}). The amount of residue C mineralized from each Mason jar was estimated by deducting the amounts of CO_2-C evolved from the jars without residue from those with residue and soil for each treatment. The difference between amounts of residue C mineralized and amount of residue C of the original mass used in the experiment was used to estimate residue C remaining.

First-order Decay Constant and Decay Time

The initial rates of residue decomposition and First-order rate constants (k) was calculated using a simple First-order decay (Equation 4.1, see Murwira et al., 1990 for more details) within a Bayesian Markov Chain Monte Carlo (MCMC) framework (Equation 4.2).

$C_t = C_0 (1\text{-}e^{-kt})$ (Equation 4.2)

Where,

C_t = carbon content at time t (day)

C_0 = initial C content (mg)

k = first-order rate constant (day^{-1})

t = time (day)

The joint probability distribution of the Bayesian MCMC model is as follows (Equation 4.3):

$$\left[C_0, k, \sigma_p^2 | C_t\right] \propto \prod_{i=1}^{n} \text{gamma}\left(C_{ti} \left| \frac{(C_0 * (1-e^{-kt_i}))^2}{\sigma_p^2}, \frac{(C_0 * (1-e^{-kt_i}))}{\sigma_p^2}\right.\right) \times \text{beta}(k|\alpha, \beta) \times \text{gamma}(C_0|\alpha, \beta) \times \text{gamma}\left(\sigma_p|\alpha, \beta\right) \quad \text{(Equation 4.3)}$$

Where, C_0, C_t, and σ_p (aka process model uncertainty) followed uninformed gamma prior distributions and k followed an uninformed beta prior distribution.

We implemented the MCMC method using the *rjags* package in R (version 3.4.3). Posterior distributions of k were estimated with 10,000 model iterations after discarding the first 5,000 runs. Model convergence was diagnosed with the Gelman–Rubin diagnostics, and model suitability were determined with Bayesian p value.

Using decay coefficient k values, time required for 50, 75, and 99% residue C mineralization from barley residue was estimated by:

$t_{0.50} = \ln(2/k)$ (Equation 4.4)

$t_{0.75} = \ln (4/k)$ (Equation 4.5)

$t_{0.99} = \ln (100/k)$ (Equation 4.6)

Statistical Analyses

The experiment was carried out as a completely randomized block design with residue placement, residue size, and soil types as three treatments with four replications. Cumulative C mineralization rate (i.e. residue breakdown), the percentage of residue decomposed, and First-order decay kinetic parameters such as decay constant and days to complete the certain percentage of residues were analyzed using an analysis of variance (ANOVA). Statistical analyses were performed in JMP 13.0 (SAS Institute, Cary, NC, USA). Tukey's multiple comparison procedures was used to compare the treatment means as post-hoc multiple comparisons where $P \leq 0.05$.

Results

Characterization of soils

The soils used in the experiment are common soil types in southeastern Idaho, USA. The sandy soil had higher sand content (898.2 g kg^{-1}) compared to the sandy loam (661.2 g kg^{-1}) (Table 4.1). The average silt content for sandy and sandy loam soils were 57.4 and 238.7 g kg^{-1}, respectively. However, the clay content of both the soils was low (44.4 g kg^{-1} for sand and 100 g kg^{-1} for sandy loam). Both soils have alkaline pH which was higher in the sandy loam (pH of 8.4) than sandy soils (pH of 8.1). The average EC for sandy and sandy loam soils were 101.8 and 148.0 μS cm^{-1}, respectively. The OM content was low in both the soils (9 and 15 g kg^{-1} for sand and sandy loam soils, respectively). The TN content was similar for both the soils. The TN content represented very low values in both the soils (0.46 and 0.69 g kg^{-1} for sand and sandy loam soils, respectively).

Characterization of Residue

The barley residue (cultivar Harrington) had a TN of residue of 41 g kg^{-1} whereas, the TC was greater (392 g kg^{-1}) which gives a high C:N ratio of 96:1 for this cultivar. In general, a higher C:N ratio is expected for barley residue than for other cereal crops which is consistent with our data. The cellulose and hemicellulose content of the barley residue were 447 and 670 g kg^{-1}, respectively. The lignin content was low (64 g kg^{-1}) whereas, the ash content was 120 g kg^{-1} for the barley residue used under current study (Table 4.2).

Daily and Cumulative Decomposition of Barley Residues

The daily response of C mineralization rate (residue breakdown) with respect to the residue placement (surface vs. incorporated) and residue size (chopped vs. sieved) was variable. Both the soils showed similar pattern in daily residue decomposition breakdown (Fig. 4.1A and B). In general, an initial C mineralization flush (initial greater flush of CO_2-C release) by individual treatments for both soils was variable within a range of 2 to 5 days (Fig. 4.1A and B). However, the accelerated initial mineralization rate at the beginning of the experiment was obtained rapidly for the sieved residues (1 to 2 d) than chopped (3 to 5 d) for both surface application and incorporation with the highest evolution of CO_2-C (8.3 g kg^{-1}) from the incorporated-sieved application for both soils (Fig. 4.1A and B). The pattern of cumulative decomposition of barley residues over a period of 50-d were similar to the pattern of daily C mineralization (residue decomposition) for both soils (Fig. 4.2A and B).

Effects of Residue Management on Barley Residue Decomposition

The ANOVA results indicated that the residue placement and residue size and their interaction have significant effect on the cumulative CO_2-C release, percent of residue decomposed, and residue decay constant over a period of 50-d (p <0.001) (Table 4.4). There

were no significant effects of soil type (sandy vs. sandy loam) on any of the measured output in our study, although two soils were textually and chemically different. Similarly, the higher order interaction among residue placement, residue size, and soil types were all non-significant for cumulative CO_2-C release, decay constant, and percent of residue decomposed. Based on the ANOVA, averaged across soil types the cumulative CO_2-C released (over 50-d decomposition period) were significantly higher for chopped and sieved residues when surface applied (107 and 98 g kg^{-1}, respectively) compared to incorporated (101 and 69 g kg^{-1}, respectively) (Fig. 4.3A).

The highest amount of cumulative C mineralization (amount of cumulative CO_2-C released) when averaged across soil types after 50-d incubation occurred when residues were chopped and surface applied (107 g kg^{-1}) compared to the sieved and incorporated (69 g kg^{-1}), which resulted in the lowest magnitude of C mineralization. No significant difference in CO_2-C release between surface-sieved vs. incorporated-chopped treatments were measured under current study. Similarly, the percentage of residue decomposed followed the same pattern as the C-mineralization rate for various treatments. The highest and lowest amount of residue decomposed over a 50-d decomposition period were observed in surface-chopped (27%) and incorporated-sieved (18%) respectively when averaged across soil types (Fig. 4.3B). The surface-sieved vs. incorporated-chopped treatments showed non-significant differences in their mean values of percentage of residue decomposed (25% for both the treatments).

First Order Decay Kinetics and Half-life of Barley Residues

The ANOVA results indicated that the residue placement, and residue size, and their interaction have significant effect on the decay constants and times (in days) required for 50,

75 and 99% of barley residue carbon mineralized over a period of 50-d (p <0.001) (Table 4.4). There were no significant effects of soil types on any of these calculated parameters. The first order decay kinetics parameters as calculated using MCMC modeling approach were well aligned with model parameter uncertainty and sensitivity analyses, and model predictions were satisfactory as shown in Fig 4.4. The highest k value (0.0083 d^{-1} with a 95% CI of 0.0078 to 0.0088 d^{-1} and goodness of fit R^2 of 0.997) with a predicted residue half-life to mineralize barley residue (i.e. $t_{(0.5)}$) of about 80-d (95% CI of 73 to 83 d) was obtained for residues when chopped and applied at the soil surface when averaged across soils (Table 4.5). This value was not statistically different than surface-sieved (k = 0.0080 d^{-1}; CI = 0.0074 to 0.0086 d^{-1}) and incorporated-chopped (k = 0.0079 d^{-1}; CI = 0.0072 to 0.0086 d^{-1}) treatment combinations. The lowest k value (0.0054 d^{-1} with a confidence interval; CI of 0.0049 to 0.0059 d^{-1} and goodness of fit R^2 of 0.988) was calculated for sieved residues when incorporated in soils and averaged across soils types. Incorporated-sieved treatments would need 48-d to decompose 50% of the residue. These k and $t_{(0.5)}$ values differ significantly from the other three treatment combinations (surface-chopped, surface-sieved and incorporated-chopped treatments) under current study. Similar trends were found for $t_{(0.75)}$ and $t_{(0.99)}$ for all the treatment combinations under current study (Table 4.5).

Discussions

Daily and Cumulative Decomposition of Barley Residues

The initial flush of C-mineralization from any crop residues under laboratory, greenhouse, or field conditions is usually significantly different from the decomposition rate for the rest of experimental duration (Bremner et al., 1991; Angers and Recous, 1997; Al-

Kaisi et al., 2013, 2017). This occurs because the maximum decomposition occurs in this period due to soil nutrient dynamics, moisture availability, soil aeration status, and microbial growth. The initial higher flush of barley straw breakdown (greater C-mineralization) in our study was confirmed by the findings by other cereal residue decomposition studies (Bremner et al., 1991; Angers and Recous, 1997; Al-Kaisi et al., 2013, 2017; de Kok-Mercado, 2015). The barley residues that were chopped and applied to the soil surface had the overall highest cumulative C-mineralization as measured at the end of the experiment (107 g kg^{-1}; Fig. 4.3A), whereas, the overall lowest rate was measured from sieved residues when mixed with soils (incorporated-sieved treatment) irrespective of soils (Fig. 4.2A and B).

The labile C sources become more accessible to microbial activities as surface area is increased a likely explanation to the increase in sieved residues mineralization compared to the chopped (the higher rate of CO_2-C mineralized) in the initial phase days 1 to 2. Our results are consistent with the findings by Bremer and others (1991) who showed the greater mineralization by finer sized wheat straw at the initial phase of residue addition (1 to 2 days). Afterwards, the decreased rate of decomposition for sieved residues when applied in surface soils might be attributed to the exhaustion of those labile C sources, and possibly the stable association of C between decomposing residues and soil mineral particles (Angers and Recous, 1997). A similar pattern of decomposition was observed by Angers and Recous, (1997) who mentioned that finer sized rye and wheat residues (0.05 to 1mm sieved particles of residues) produced lower quantities of CO_2-C than other larger sized residues (7 mm) for the entire experiment when mixed with a silty soil at 25°C in a laboratory incubation study in France. The possible reason might be a physical protection developed over soil surface after an initial flush of C mineralization for sieved residues when applied onto the soil

surface in comparison to chopped residues when incorporated (Angers and Recous, 1997; Al-Kaisi et al., 2017).

Subsequently, the rate of residue decomposition declined after approximately Day 5 irrespective of any treatment combinations for both the soils. This pattern followed other studies conducted either in field or laboratory with residues from different cereal crops grown under variable soil types (Angers and Recous, 1997; Al-Kaisi et al., 2013, 2017, de Kok-Mercado, 2015). These decreased rates were followed by a slight increase at Day 8 to 9 for all treatments, and again decreased until the end of the experiment. The difference in the decomposition rate among treatment combinations remained consistent except for the surface applied sieved residues, which had higher mineralization rates (5.8 g kg^{-1}) in Day 10 to 12 compared to other treatment combinations for sandy loam soil. In general, rate of C mineralization by various treatment combinations followed the order of surface-chopped>incorporated-chopped> surface-sieved>incorporated-sieved for both the soils (Figs. 4.1 and 4.2)

The chopped residue always produced greater amounts of CO_2-C than sieved except during the initial flush of CO_2-C. It might be postulated that the longer availability of decomposable C in chopped residue was obtained due to physical protection of soil surface by larger sized residue particles. Chopped compared to sieved residues irrespective of residue placement resulted in a consistently higher rate of residue decomposition till the end of the experiment in (Angers and Recous, 1997). The daily decomposition pattern from our study suggests that surface applied barley residue has a higher mineralization rate, producing more CO_2-C than incorporated when comparing the two residue placement methods regardless of residue size. Although no microbial community (fungi) analyses were

performed under present study, it is expected that residues that were surface applied have more microbial interaction with soil-residue mixture than incorporated, an increased rate of C-mineralization in addition to higher k values (Fig. 4.3A and B).

Effect of Residue Management on Barley Residue Decomposition

Our laboratory incubation study showed that the surface application of residues, which is similar to no-tillage practices, promote residual breakdown faster than incorporated for both chopped and sieved residues. As supported by other findings one treatment was found to be statistically different (Sieved-incorporated) (Beare et al., 1993, Al-Kaisi et al., 2013). Our findings are also supported by the results of Beare and others (1993), that reported a reduced rate of residue breakdown due to the lack of fungal communities when sorghum (*Sorghum bicolor* L.) residues were incorporated as compared to the residue left on the soil surface. The results from our study can have value in promoting conservation practices and preserving residues on soil surface, rather than incorporation via conventional tillage practices in PNW where wind and water erosions are reasonable concerns for soil and water quality maintenance.

Our results provide evidence that the physical size of the barley residue (chopped vs. sieved) which mimic the mulching condition in the field had a significant effect on the C mineralization rate for both surface applied and incorporated residues. The residues that were chopped into bigger pieces than sieved were more conducive to decomposition and produced greater amount of CO_2-C via mineralization while applied on the surface soils, which resulted in approximately 27% decomposition of applied residues over a 50-d period. The application of chopped residues on soil surface possibly promoted soil aeration, retained more nutrients, and conserved more water. Together these factors help build soil biota which

resulted in consistently higher breakdown of residues for the entire period. Our results were supported by other findings which showed greater cereal residue decomposition by either surface application (de Kok-Mercado, 2015), or chopping or maintaining bigger particle size of residues in the field (Bremer et al., 1991; Angers and Recous, 1997; Al-Kaisi et al., 2013).

Our study did not show any significant differences in the cumulative CO_2-C release by the two soils. These soils were selected as they are representative of the relatively similar soils found in the study region (south-eastern Idaho) (Table 4.1). Additionally, other associated soil factors such as OM did not vary widely which could have possibly made a difference in microbial populations, nutrient dynamics, or organo-mineral association in these two soil types, and thus, differences in CO_2-C release from the soils.

Prediction of Barley Residue Decomposition: Modeling Approach

The results from the first-order kinetic model, with parameter sensitivity analysis prediction using the MCMC approach describes the C mineralization during the initial stages of barley residue decomposition in our laboratory incubation studies. As expected, our study showed that a higher rate of C-mineralization in chopped residues, when applied at soil surface, lead to higher percentage of residue decomposed. This resulted in higher values of k and lower number of days to decompose 50% of the residue added at the beginning of the experiment. Conversely, the residue that was sieved and incorporated into the soils showed slower breakdown of the barley straw by virtue of slower C-mineralization rate. Therefore, the incorporated-sieved residues under current study would take the longest time to decompose only half of the residues, and only 18% of the residues were decomposed during the 50-d time span of the experiment.

Although we did not perform any microbial community studies, differences in fungal growth and other associated microbial population among treatments may aid in explaining why the values of k were different for various treatment combinations.

The implication of the calculation of decay constant and predicting number of days to decompose certain percentage of residue have serious consequences on residues remaining in the field. We should aim towards a residue management practice which will facilitate residue decomposition and increase the nutrient availability-especially mineral C and N to subsequent crops. Our study indicated that we can achieve faster mineralization rate of C in residues when chopped and applied onto the soil surface under a controlled laboratory condition over a period of 50-d. However, the residue decomposition under field conditions during different seasons with barley residues is warranted to achieve a definite conclusion.

Conclusions

Our study considered some critical factors in barley post-harvest residue breakdown, such as residue management methods (tillage), residue size, and soil where the residues are applied. Our 50-d laboratory incubation study conducted at 25 to 30°C indicated residues that are chopped and applied at soil surface consistently resulted in greater C mineralization than sieved residue which were incorporated in soils. Results reported the magnitude of mineralizable C released from residue decomposition under various treatments were variable. Additionally, the effects of no-till or conventional tillage system on barley residue decomposition under laboratory condition were documented. The relevance and application of our findings would be critical in providing practical information on residue decomposition of a cereal crop (barley) for various residue application methods such as

surface vs. incorporation. Improved residue management practices would promote sustainable farm practices which are environmentally friendly and reduce the use of farms' resources. However, field studies involving residue decomposition during varying stages of the year with other soil types, along with microbial community analyses, would help to explain the process of residue decomposition under field condition.

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Tables

Table 4. 1 Basic properties of soil used in the laboratory incubation study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Properties	Sand	Sandy Loam
Sand (g kg^{-1})	898.2 (±4.9)†	661.2 (±5.6)
Silt (g kg^{-1})	57.4 (±15.1)	238.7 (±5.6)
Clay (g kg^{-1})	44.4 (±11.1)	100 (±0.02)
pH	8.1 (±0.04)	8.4 (±0.2)
EC (μS cm^{-1})	101.8 (±3.04)	148.0 (±5.9)
SOM (g kg^{-1})	9 (±0.6)	15 (±0.6)
TN (g kg^{-1})	0.46(±0.01)	0.69(±0.01)

†values in the parenthesis indicate standard errors.

EC; electrical conductivity, SOM; soil organic matter.

Table 4. 2 Basic properties of barley cultivar Harrington residue samples used in laboratory incubation study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Properties	Unit	Average	±Standard Error
Total N	g kg^{-1}	41	0.1
Total C	g kg^{-1}	392	1.4
C:N	NA	96	3.3
Cellulose††	g kg^{-1}	447	16
Hemicellulose	g kg^{-1}	670	16
Lignin	g kg^{-1}	64	2
Ash	g kg^{-1}	120	8

††The value of cellulose, hemicellulose, lignin and ash content were reported as percentage of dry matter which 92.7% for initial residue samples.

OM; organic matter, C:N; carbon to nitrogen ratio, NA; not applicable.

Table 4. 3 Experimental treatments used in evaluation of CO2-C released from soil over a 50-day laboratory incubation study conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Soil Types	**Residue Size**	**Residue Placement**
Sand	None	None
	Chopped	Incorporated
		Surface
	Sieved	Incorporated
		Surface
Sandy Loam	None	None
	Chopped	Incorporated
		Surface
	Sieved	Incorporated
		Incorporated

Table 4. 4 Analysis of variance (ANOVA) values for cumulative decomposition rate, percentage residue decomposed, decay constant (k) and associated parameters over 50-days' laboratory incubation study for barley residue decomposition† conducted at the Aberdeen Research and Extension Center, Aberdeen, ID, USA.

Sources of variation	Cumulative CO_2-C decomposition	Residue decomposed	Decay constant (k)	$t_{(0.5)}$§	$t_{(0.75)}$§	$t_{(0.99)}$§
Residue placement	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Residue size (RS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Soil type (ST)	0.09	0.09	0.34	0.07	0.23	0.09
RP x RS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
RP x ST	0.17	0.16	0.07	0.18	0.09	0.20
RS x ST	0.10	0.10	0.66	0.13	0.72	0.12
RP x RS x ST	0.24	0.27	0.09	0.35	0.10	0.41

†Barley residue decomposition in this study were evaluated using the first order kinetic model $Ct = C_0 (1 – \exp^{-kt})$; where, where C*t* is carbon content at time *t* (day), C_0 is initial carbon content, *k* is first-order rate constant calculated as d^{-1}, and *t* is time (day).
§Times (in days) required for 50, 75, 90, and 99% of barley residue carbon mineralized under current study were estimated as: $t_{(0.50)} = \ln 2 (k^{-1})$, $t_{(0.75)} = \ln 4 (k^{-1})$, $t_{(0.90)} = \ln 10 (k^{-1})$, $t_{(0.99)} = \ln 100 (k^{-1})$

Table 4. 5 First-order decay model parameters for sequential barley residue decomposition under residue placement and residue size treatment combinations averaged across soil types in 50-days' laboratory incubation study at 25-30°C.

Residue placement	Residue size	k-values (d^{-1})†		Goodness of fit statistics (R^2)	$t_{(0.5)}$§		$t_{(0.75)}$§		$t_{(0.99)}$§	
		Mean	95% CI		Mean	95% CI	Mean	95% CI	Mean	95% CI
Surface	Chopped	0.0083a††	0.0078 to 0.0088	0.997	80b	77-83	165b	159-171	552b	512-592
	Sieved	0.0080a	0.0074 to 0.0086	0.993	86b	81-91	171b	161-181	569b	535-603
Incorporated	Chopped	0.0079a	0.0072 to 0.0086	0.993	88b	80-96	175b	159-191	582b	529-635
	Sieved	0.0054b	0.0049 to 0.0059	0.988	128a	117-141	257a	235-279	853a	781-925

†Barley residue decomposition in this study were evaluated using the first order kinetic model $Ct = C_0 (1 – \exp^{-kt})$; where, where C*t* is carbon content at time *t* (day), C_0 is initial carbon content, *k* is first-order rate constant, and *t* is time (day).
§Times (in days) required for 50, 75 and 99% of barley residue carbon mineralized under current study were estimated as: $t_{(0.50)} = \ln 2 (k^{-1})$, $t_{(0.75)} = \ln 4 (k^{-1})$, and $t_{(0.99)} = \ln 100(k^{-1})$
CI; confidence interval; SL; sandy loam soils.
††Different letters for each parameter indicate significant differences between residue management, residue size and their interaction, as compared using Tukey's Protected honest significant difference (HSD) test at $p<0.05$, respective

Figures

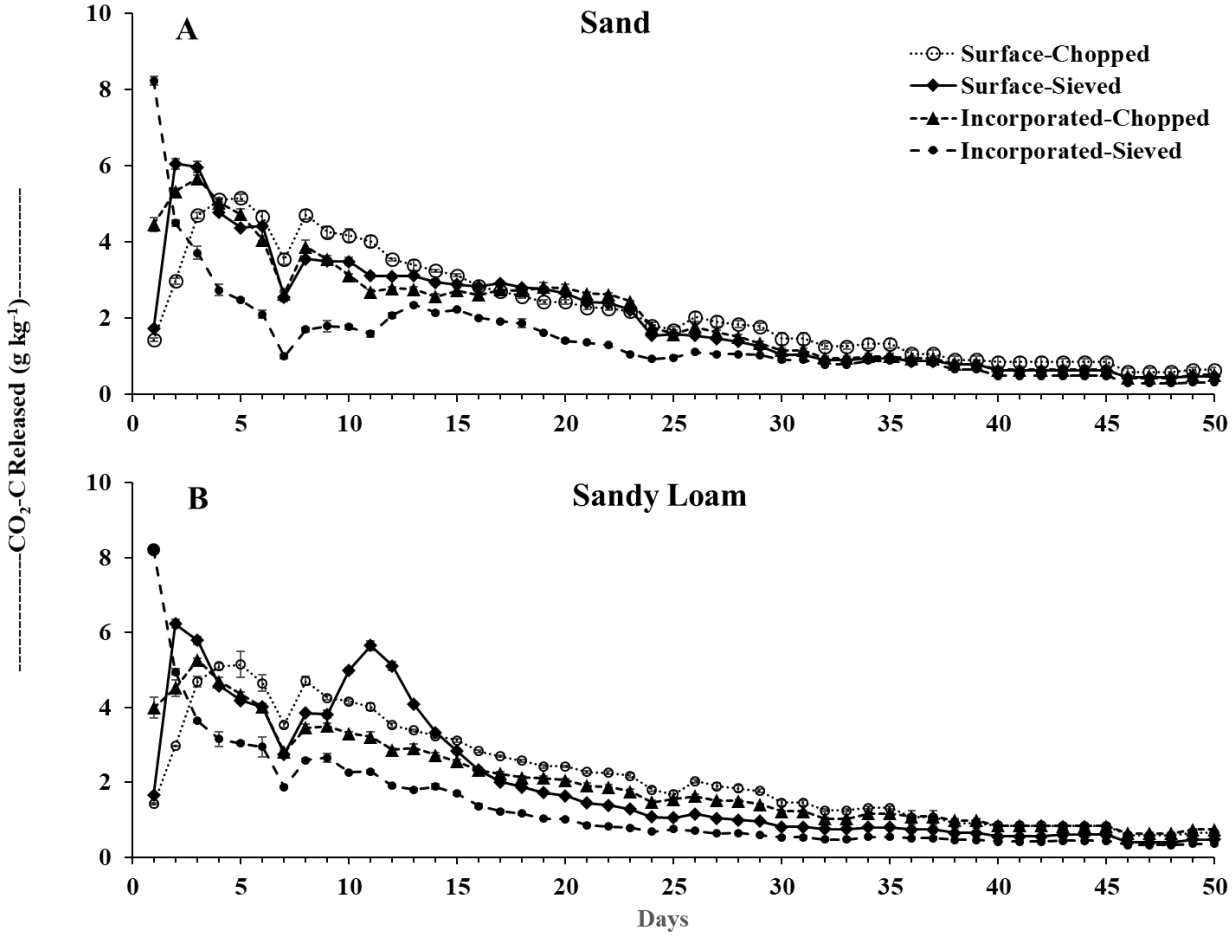

Figure 4. 1 Amount of CO_2-C released (rate as calculated per kg of residues) on daily basis for barley residue decomposition under residue placement and residue size treatment combinations for A) sandy and B) sandy loam soils in 50-days' laboratory incubation study at 25-30°C

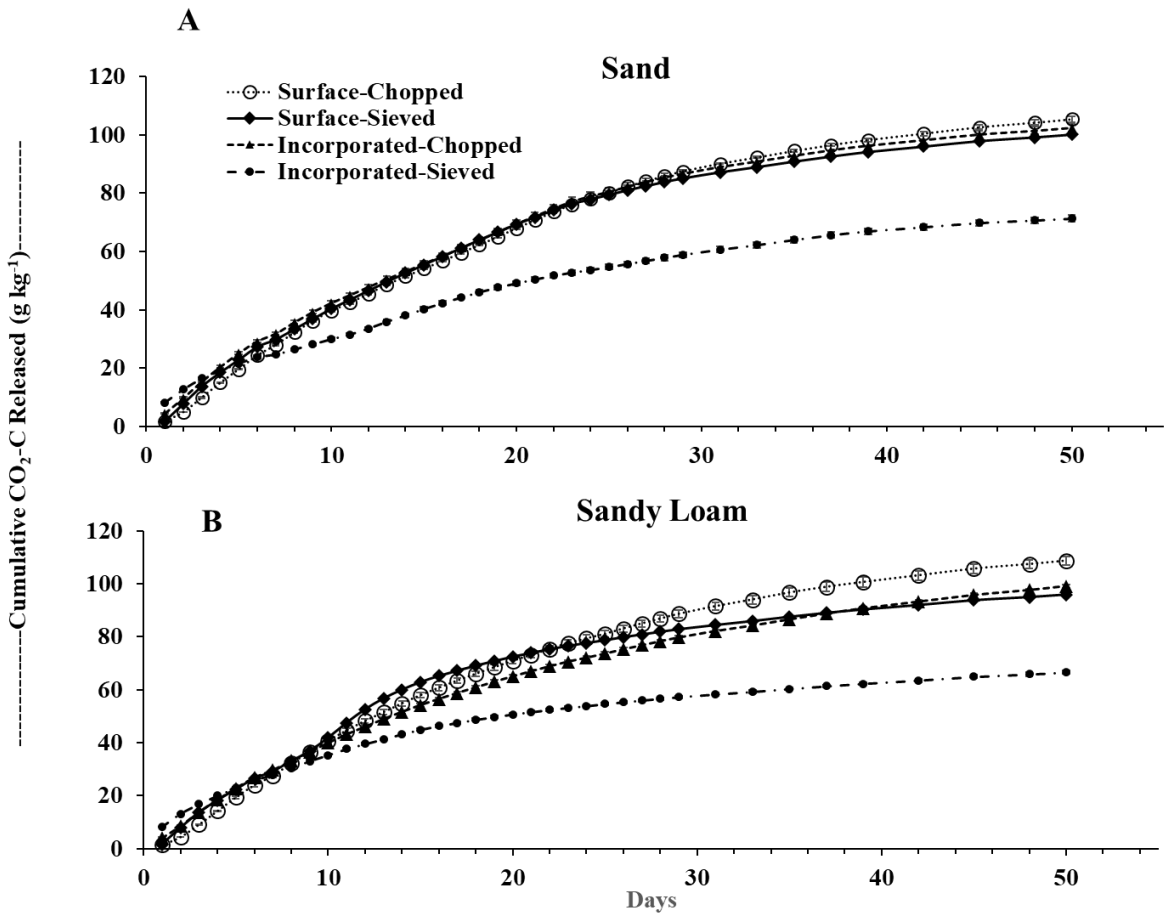

Figure 4. 2 Amount of cumulative CO_2-C released (rate as calculated per kg of residues) for barley residue decomposition under residue placement and residue size treatment combinations for A) sandy and B) sandy loam soils in 50-days' laboratory incubation study at 25-30°C.

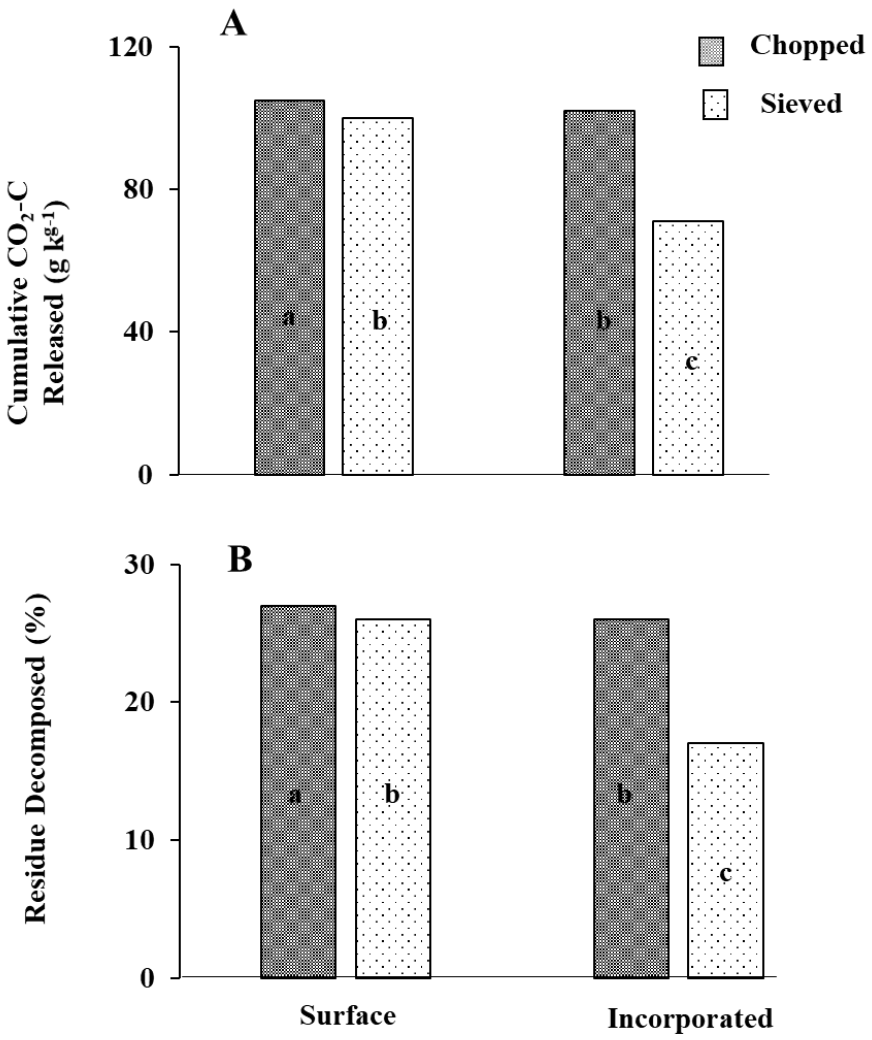

Figure 4. 3 Effects of residue placement and residue size on cumulative CO_2-C released (rate as calculated per kg of residues) and percentage of residue decomposed for barley residue decomposition under treatment combinations for A) sandy and B) sandy loam soils in 50-days' laboratory incubation study at 25-30°C.

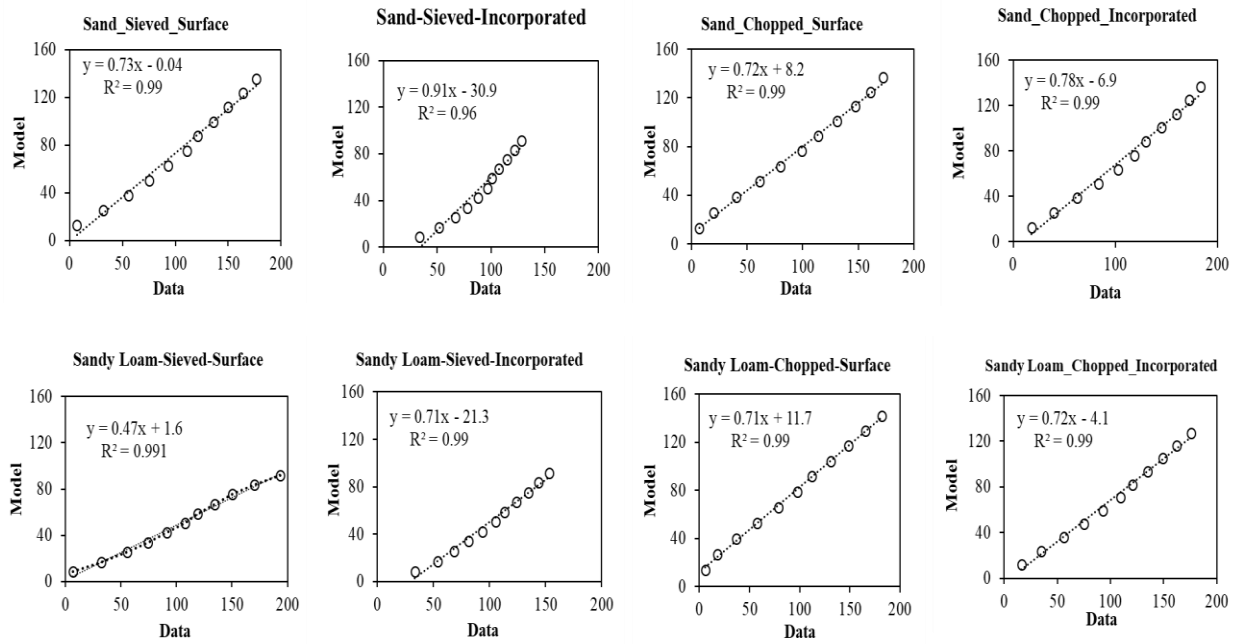

Figure 4. 4 Calibration and prediction of the first order decay constant for residue decomposed under barley residue decomposition study conducted in laboratory at 25-30°C.

Chapter 5

Conclusion and Suggestions for Further Work

Study results of the Chapter Nitrogen Partitioning and Fertilizer Nitrogen Use Efficiency of Irrigated Spring Malt Barley Determined using Enriched Isotope Tracers show that incorporation of N fertilizers will result in more fertilizer recovered in the soil-plant system. In a time where using resources effectively and efficiently is vital, it is critical to convey these important findings and confirmations with producers. Future research could focus on varying fertilizer-N, rates as well as the timing of N applications to refine accumulation and partitioning data under varying conditions. Experimenting with other fertilizers that are coated for slow release could show other differences inefficiencies. Application of fertilizer through irrigation systems or a liquid form fertilizer could show another method of management and its potential for being efficient. Interest has grown in improving fertilizer efficiencies and productivity as a result of this study. Specifically, interest from the Idaho Barley commission has grown on how fertilizer is needed in the breakdown of crop residues remaining in the field which lead to the development of the second study in this thesis.

Laboratory results of the Chapter Evaluation of Effect of Residue Management Practices on Barley Residue Decomposition in Idaho Soils showed that variation occurred based on residue size and method of incorporation. A complementary study done in the field to compare the results of the laboratory decomposition is needed to verify the study results in situ. Studies involving residue decomposition under the temperature and moisture regimes occurring during different times in the year, as well as studies with broader soil types, would improve our understanding of residue decomposition of barley. Additionally, microbial

community analyses would help to describe the mechanisms controlling the decomposition of residue. With many different management tools available to barley (cereal) producers more evidence is required to make clear and precise recommendations moving forward. More studies are needed to demonstrate the proper way to manage post-harvest residues to remain profitable and sustainable for ongoing years of production. With more scrutiny and negative opinions on agricultural production practices in the United States and the world, based on scientific evidence or not, our producers need the most current information to help them make the best decisions as stewards of the land.