POTENTIAL FOR AND IMPLICATIONS OF COVER CROPPING AND GRAZING COVER CROPS IN WHEAT AGROECOSYSTEMS IN MONTANA

by

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ABSTRACT

Growing interest in cover cropping may provide a way to recouple crop and livestock production in semiarid Montana. This two-year field study examined edaphic and agronomic implications of cool- vs warm-season cover cropping, with and without grazing, compared to the grower standard practice of chemical-fallow. After one year of cover cropping/grazing, Olsen-P and acid phosphatase activity were higher in cover cropped/grazed treatments than the fallow treatment. Potentially mineralizable Nitrogen was higher in spray-terminated cover crop treatments than graze-terminated treatments, while soil Nitrate-N was statistically lower in cover cropped/grazed treatments than in the fallow treatment. Wheat yields were not statistically different between cover cropped/grazed and the fallow treatments; however, the fallow treatment had higher wheat seed protein than cover cropped/grazed treatments. This research also utilized the Land Suitability Analysis approach to examine four exemplary Montana counties for: 1) warm-season cover crop adoption; 2) integrated crop-livestock adoption; and, 3) warm-season cover crop use as forage in an integrated crop-livestock adoption. Fergus and Fallon Co.'s both contain portions of land highly suitable for warm-season cover crop production, while all four counties have areas where integrated crop-livestock systems appear to be a logistical possibility. The conclusions taken from this research - both the agricultural field experiment and land suitability analysis – will help inform land managers across Montana's agricultural community about these emerging practices in sustainable agriculture.

CHAPTER ONE

INTRODUCTION TO THESIS

It is a truly daunting task to meet the food, feed, fiber, and fuel needs of the world’s growing population while protecting environmental quality (NASP, 2010). Agriculture is the single biggest land use across the world and in the United States (Robertson and Swinton, 2005). Many agricultural systems are highly specialized and require multiple inputs (i.e. fertilizers, herbicides, pesticides, etc.) to maximize production and profit (Robertson and Swinton, 2005). Such systems often lead to environmental degradation and may negatively impact public health (NASP, 2010).

The northern Great Plains (NGP) of North America is a semiarid farming region historically known for large, cereal crop monocultures (Tanaka et al., 2010). A need exists in the NGP to optimize agricultural inputs and diversify highly specialized systems in order to increase systems resistance and resilience to uncertain climate scenarios while maintaining production and yield levels (Ortiz et al., 2008).

Summerfallow and No-till in the Northern Great Plains

In the NGP, summerfallow has been used as a tactic for soil moisture conservation since the early twentieth century (Ford and Krall, 1979; Tanaka et al., 2010). Large portions of the NGP receive less than 400 mm of annual precipitation which often peaks in mid to late spring, leaving the latter months of the summer season dry (Tanaka et al., 2010). Low annual precipitation and unimodal spring distribution of that precipitation make soil water conservation in the NGP imperative for high cash crop yields. Wheat (*Triticum aestivum* L.) is the most commonly planted crop in much of the NGP (USDA – NASS, 2007) and for many dryland wheat producers in the NGP and Montana, water availability is the limiting factor for wheat production, making summerfallow an attractive practice.

Summerfallow is an effective but inefficient way of preserving valuable soil moisture the NGP (Peterson et al., 1996). Tanaka et al. (1989) noted that in no-till spring wheat systems, summerfallow soil water storage ranged from 32% - 42%, making it a valuable practice in terms of increasing soil water for optimal wheat yields. However, summerfallow has several negative consequences that impact cropping systems' sustainability. Summerfallow leads to long-term soil degradation via increased erosion (Tanaka et al., 1997), loss of soil organic matter (Campbell et al., 2000), decreased soil biological activity (Acosta-Martinez et al., 2007), increased saline seepage (Tanaka et al., 2010), and increased nitrogen leaching (Jones and Olson-Rutz, 2011). Over decades, the practice of summerfallow diminishes soil quality and therefore increases the need for synthetic fertility inputs in order to sustain yields in a system.

Summerfallow acreage has declined in the NGP from a peak of approximately 17 M ha in 1971 to fewer than 4 M ha in 2010 (Tanaka et al., 2010), and even lower in 2016 (USDA-NASS, 2016). In part, this decline is due to increased soil water storage efficiency through no-till practices which were first spread throughout the region in the 1980's and became extremely popular in the 1990's (after the patent on Glyphosate expired; Bacarra et al., 2003; Tanaka et al., 2010). No-till increases soil water storage efficiency when compared to conventional or conservation tillage, via enhanced soil structure and soil organic matter accumulation, allowing for more intensive cropping systems (Tanaka and Aase, 1987; Peterson et al., 1996).

Increased cropping intensity in no-till systems has had major implications for soil quality. Intensely cropped no-till systems have been shown to increase soil C levels leading to enhanced soil structure and water infiltration as well as water storage capacity via increased crop residue which enhances soil organic matter accumulation (Campbell et al., 2000; Shrestha et al. 2013; Engel et al. 2017). Increased soil C correlates strongly with soil organic matter (SOM), which is an important metric influencing many soil properties including soil nutrient pools and soil biological activity (Tiessen et al. 1994; Acosta-Martinez et al., 2007). With advances in soil water storage, much of the NGP has moved away from summerfallow and toward more diverse and intensely cropped no-till systems. However, some of the driest parts of the NGP, including the ‘Golden Triangle’ (i.e. north central) region of Montana, have yet to move away from summerfallow.

North central and northeastern Montana accounted for approximately 25% of the ha still under summerfallow in the NGP in 2007 (USDA-Nass, 2007). This area receives, on average, less than 350 mm of precipitation per year making non-fallow cropping systems risky to implement. One potential fallow improvement practice being studied across the NGP and specifically in Montana is the adoption of cover cropping. While cover crops decrease short-term cash crop yields due to soil water depletion (Miller and Holmes, 2005; Tallman, 2014), some research suggests that long term cover cropping may actually help buffer economic uncertainty for farmers via increased soil quality and timely N provisioning (Miller et al., 2015).

A Summerfallow Alternative: Cover Crops

The use of cover crops during the fallow period may enhance soil properties in dryland wheat production systems. Cover crops can be single species or mixtures of species (i.e. polyculture) that benefit soil properties by enhancing nutrient cycling (Lu et al., 2000), increasing soil organic matter and soil structure (Zentner et al., 2004), increasing bioturbation (Williams and Weil, 2004), decreasing erosion (Tanaka et al., 1997), and suppressing weed growth (Fisk et al., 2000). Although cover crops offer many potential benefits to producers, one of the largest barriers to adoption of cover crops is soil water usage (Jones et al., 2015).

Depletion of soil water and subsequent declines in cash crop yields associated with cover crop usage increases short-term economic risk for producers (O’Dea et al., 2013, Miller et al., 2014). However, Miller et al. (2011, 2015) showed that with proper termination timing, soil water use can be minimized while maximizing the edaphic benefits of a legume cover crop. What may offset the negative implications of soil water usage by cover crops is their ability to build soil quality. Over the long-term, cover crops can enhance SOM (McDaniel et al., 2014) leading to increased soil water storage (Hudson, 1994). Enhanced SOM and soil quality are tied directly to cash crop yields and quality. Therefore, cover crops’ ability to build soil organic matter and enhance overall soil quality may be a means of offsetting the economic risks of cover cropping over the long-term (Parr et al., 1992, Biederbeck et al., 1998). Research in the NGP has shown that, in the long run, the economic trade-off between soil water depletion and improved soil nutrient cycling and soil quality may produce overall economic gains for producers

(Zentner et al. 2004; Allen et al. 2011; Miller et al. 2015). Further research is needed to understand economically viable alternatives to both summerfallow and wheat-cover crop systems that offset the marginal costs associated with cover crop incorporation in the short run and improve soil quality in the long run.

Cover crops can be an additional source of nutrients and carbon for soil, especially in no-till systems (Sainju et al., 2002; O'Dea, 2011). Species in the *Fabaceae* family fix atmospheric nitrogen and increase total nitrogen levels in soil, while fibrous rooted species in the *Poaceae* family often have higher C to N ratios (C:N) and may increase total soil carbon levels (Fornara and Tillman, 2008). Tap-rooted cover crop species (of the *Brassicaceae* family in this study) may increase bioturbation while also increasing soil nutrient retrieval and decreasing nitrate leaching at soil depths below cash crop rooting zones (Dunbabin et al., 2003). The addition of biologically-fixed N, diverse C and nutrient inputs, and bioturbation and nutrient redistribution from cover crops may lead to increased cash crop yields through mechanisms which improve soil quality and require further regional- and local-scale investigation.

While diversity of root structure and function may help improve soil quality, diversity of soil litter inputs may also play a role in changing soil parameters related to cash crop yield. Cover crops with different C:N ratios decompose at different rates and influence soil organic matter mineralization rates (Hendrix et al., 1990, Dunbabin et al. 2003). Diverse litter inputs to soil also lead to diverse soil microbial populations and increase soil microbial activity (Calderon et al., 2015). Acosta-Martinez et al. (2011) noted a correlation between increased soil microbial activity and cash crop yields implying that, in some systems, cover crops may lead to increased cash crop yield via multiple mechanisms directly related to soil quality and biological activity.

A second barrier to cover crop adoption is the marginal cost associated with cover crop seed costs, equipment use, and additional management time which are not offset by the production of marketable commodity crops (Jones et al., 2015). Using cover crops as a source of livestock fodder may help offset the cost of cover crop production for producers – especially over the short-term before the benefits of improved soil quality manifest themselves. Fraase et al. (2010) noted that, in North Dakota, a late-season foxtail millet cover crop was approximately 7% cheaper on average than grazing native range over the same period, indicating the potential utility of using cover crops as a cost-effective source of additional forage source. While cover crops may prove to be a cheap alternative to perennial pasture, they may also prove to be a critical source of forage in areas where traditional forage sources are in decline. Conservation Reserve Program (CRP) land can be hayed and grazed (with authorization from the National Resource Conservation Service) to provide additional livestock forage in years when drought or other natural disasters cause a shortage. CRP hectarage went from 1,409,528 ha in 2006 to 570,325 ha in 2016 (after several years of record high wheat prices) in Montana alone (USDA-FSA, 2017), thus creating a large decline in available ‘emergency’ forage supplies for livestock producers. This decline in CRP hectares has led to increased interest in cover crops as a forage source to increase regional forage supplies. Annual cover crops require a relatively short growing season and may hold high forage quality late in the season when many perennial ranges reduce quality (Wang and Danzl, 2014).

Along with providing additional livestock forage, cover crops may also provide an opportunity to engage the warm-season plant growth period which adds key diversity to no-till wheat-based cropping systems (Snapp et al., 2005; Florence, 2016). Capitalizing on warm-season cash crops is not economically viable along the northern Rocky Mountain Front due to a spring-centric rainfall pattern. Most often there is adequate biomass yield that does not translate to grain yield due to insufficient late season rainfall (Miller and Holmes, 2005). However, there may be sufficient precipitation for cover crops to be used as forage whereby offering an economically viable route to engaging warm-season plant diversity in the NGP and Montana.

Integrated Crop Livestock Systems

Integrated crop-livestock systems (ICLS) – in this case referring to grazed cover crops in a dryland wheat system – offer a diversified and sustainable means of crop production in many regions (Hilimire, 2011; Sulc and Franzluebbers, 2014). The addition of livestock to a cropping system can have important implications for soil quality and crop yield including enhanced nutrient cycling. Studies have shown increased available nitrogen (N; Tracy and Zhang, 2008; Assmann, 2014), phosphorous (P; Costa et al., 2014), and labile carbon (Acosta-Martinez et al., 2004; Tracy and Zhang, 2008). Livestock grazing may reduce the need for external chemical inputs by increasing labile nutrient availability and enhancing nutrient cycling and may be an important step toward enhancing the sustainability of cropping systems (Sulc and Franzluebbers, 2014).

While many soil nutrients are affected by the presence of grazing in a cropping system, one of the most critical is N. Livestock deposit N-rich waste throughout a pasture or cropland (Marchao et al., 2010; Bardgett and Wardle, 2010; Assmann et al., 2014). This influx of animal excrement may lead to enhanced levels of N cycling (Bardgett et al., 1998). Although an increased rate of cycling does not necessarily mean increased levels of total soil N, Assmann et al. (2014) noted significant gains in soil N in an ICLS in Brazil. Tracy and Zhang (2008) observed significant gains (approximately 45%) in soil N in a corn-oat pasture rotation in Illinois after only four years. However, Acosta-Martinez et al. (2004) noted that a wheat-fallow-cotton-rye rotation with grazing in Texas had statistically similar levels of soil N and microbial N when compared to a continuous cotton rotation with no grazing after five years. Although livestock excrement is N-rich and deposited in grazed croplands, N is also removed from the system by livestock in the form of animal tissue (Hatfield et al., 2000). Therefore, further investigation is needed to track changes in soil N pools in order to better understand soil N dynamics associated with ICLS in Montana.

Although conventional wisdom holds that livestock add P to most systems, several studies have produced conflicting results, indicating a need for region-specific studies. For example, Powell and Mohammed-Saleem (1986) noted a net loss of P in grazed croplands in West Africa, but also found that 33% of P deposited in cattle manure was utilized by a subsequent maize crop, indicating a high level of labile P. Costa et al. (2014) examined the effects of grazing on the dynamics of soil P in a no-till soybean-cereal cover crop rotation in southern Brazil. Under no-till, total soil P increased in the top 20 cm of soil in both grazed and non-grazed treatments although the non-grazed treatment accumulated more P over the six years. Further, Costa et al. (2014) also noted that the addition of grazing increased the P cycling and led to a surplus of labile P. On the other hand, Assmann et al. (2014) noted that P release from wheat stubble at the soil surface was enhanced in grazing treatments compared to nongrazing treatments. These studies suggest that grazing livestock in certain crop rotations may be beneficial in terms of P cycling and availability despite a potential net loss of nutrients in a system from harvest of crop and nutrient removal via livestock tissue. Further research is needed to understand soil P pool dynamics in grazed, dryland wheat systems in Montana.

While evidence suggests that the incorporation of livestock in a cropping system enhances nutrient cycling in various ways, little published research examines how the addition of grazing to croplands affects nutrient timing and delivery to cash crops. Increased nutrient levels and enhanced cycling may promote higher crop yields and quality (Assmann et al. 2014a, b); however, the mechanisms involved are not yet fully understood. Study of edaphic parameters, including soil enzyme activity and microbial biomass, in tandem with tracking of soil nutrient pools, may further shed light on this relationship – especially as it pertains to systems in the semi-arid NGP and Montana.

One issue of concern when grazing livestock on cropland is the potential for increased soil compaction, which may hinder root growth and decrease crop yields (Hamza and Anderson, 2005; Bardgett and Wardle, 2010). Grazing livestock after soil freeze-up may mitigate compaction (Clark et al., 2004; Hamza and Anderson, 2005). It should be noted that even with soil compaction, some studies have found no significant effects on cash crop yield (Schomberg et al., 2008; Tracy and Zhang, 2008), especially in regions with freeze-thaw cycles like Montana.

A second issue of concern when grazing on cropland is the risk of too much crop residue removal resulting in a dry, hard soil surface and decreased water infiltration (Shaver et al., 2002). Crop residue is an important source of soil C and plays a pivotal role in increasing SOM and soil structure in no-till systems (Blanco-Canqui and Lal, 2007). Appropriate management of livestock can negate the potential for over-grazing and subsequent losses in crop residue. However, this may require additional time and effort on behalf of the farmer or rancher as frequent monitoring may be needed to ensure that enough plant biomass is left on the field to keep residue, crop residue, and soil inputs high.

While current evidence suggests potential benefits and drawbacks to ICLS, further research at regional and local scales is needed to fully understand the implications of livestock integration (Russelle et al. 2007; Sulc and Tracy 2007). Little work involving ICLS in wheat-cover crop systems has been done in Montana, leaving an important step toward increased sustainability unexplored.

Furthermore, increasing the complexity of cropping systems may ultimately lead to more sustainable food production systems (Sulc and Franzluebbers, 2014). Implementing no-till methodology, adding cover crops, and incorporating livestock grazing into dryland wheat production systems in Montana could increase farm-scale resilience and robustness as well as regional-scale environmental quality (Fiskel, 2003). Studying the edaphic and agronomic implications of these cropping systems methods is only part of the story. An equally important part of the story is devising economically feasible ways to facilitate re-coupling livestock and crop production across the NGP and Montana.

Mapping ICLS and Warm-Season Cover Crop Adoption Potential in Montana

Two relatively simple sustainable on-farm practices that may increase the diversity of cropping systems in Montana are: 1) building integrated crop-livestock systems; and 2) utilizing warm-season cover crops as fallow replacement. The first of these practices involves re-coupling crop and livestock systems which may reduce the need for external inputs (i.e. fertilizers, herbicides, etc.) and help increase systems-level complexity and sustainability (Sulc and Franzluebbers, 2014). However, many producers in the NGP and Montana may struggle to overcome the financial barriers and learning curves associated with diversifying their production systems in the short-term. Building among-producer partnerships between livestock and crop producers may offer an effective work-around to this problem and allow the construction of ICLS between producers of different commodities, in situations where it is not possible to do so within a single enterprise. Geographic Information Systems (GIS) technology may offer an efficient means of identifying opportunities for, and planning, integrated crop-livestock systems in Montana, regardless of within or among agricultural production enterprises.

Many applications in agriculture increasingly use GIS. At the regional and national scales, GIS is used for mapping soil conditions, crop type and yield potential, range conditions, pest infestations, weed invasions, and a host of other environmental factors surrounding agricultural production (Wilson, 1999). At the field scale, GIS can be used for equipment guidance, pesticide and fertilizer rate control, and mapping agronomic parameters (Yousefi and Razdari, 2015). For example, modern seeders and combines are routinely equipped with high accuracy GPS units used to help operators seed and harvest in precise patterns. Similarly, tractors GIS technology is used to regulate the rate of pesticide and fertilizer application based on former and current pest problems and historical yield maps. The final products of these analyses assist farmers and other land managers to make more informed management decisions based on real-time data collection.

GIS land suitability analysis (LSA) is a common approach used across multiple disciplines to identify optimal location(s) for particular land uses. In a broad sense, LSA examines spatial relationships between multiple data layers to search for or predict land-use potential of a landscape based on pre-determined criteria for a particular activity (Hopkins, 1977; Malczewski 2004). Land suitability analysis is increasingly being used in agricultural land-use planning practices including land suitability for specific crop production (Akinci et al., 2013; Lkadivko et al., 2014; Boitt et al. 2015) and grazing potential (Barbari et al., 2006; Amiri et al., 2012). However, no published research has utilized the LSA approach to select regions with high potential for crop-livestock integration among ranchers and farmers.

Some research has been conducted using GIS approaches other than LSA to help facilitate manure exchange-based ICLS among producers. A good example of this is the University of Missouri - Center for Applied Research and Environmental Systems;

nutrient management tracker (http://nmtracker.missouri.edu/) which is a web-based GIS platform that can be used to locate sources of manure from livestock operations. While the nutrient management tracker is useful for local producers and land managers in Missouri, where large numbers of livestock are housed and fed on a relatively small area of land, it is less useful in Montana, where livestock operations are often supported by large tracts of pasture and grazing land. In most Montana livestock systems, manure does not accumulate in pens or corrals to the degree that it does in other systems with smaller livestock containment areas. To facilitate crop-livestock integration in Montana, it may be most economical to graze livestock directly on cropland. This project seeks to utilize the LSA approach to identify regional farming and livestock operations within four exemplary counties of Montana in order to create a spatial database to assist producers and land managers in building ICLS opportunities.

Currently, the potential for ICLS synergy in Montana is frustrated by a significant knowledge gap. Put simply, there is little knowledge about where in Montana the geographies of crop and livestock production are in adequate proximity to support ICLS. A first step in addressing the logistical knowledge gap would be to examine the spatial relationships between livestock and wheat production in Montana. Assessing distances between crop and livestock operations may offer insight for producers and land managers on how to re-couple livestock and crop production.

Historically, one potential obstacle to using LSA to identify areas with high potential for ICLS adoption at a state- or regional-level has been a general lack of publicly available data. However, in recent years, public geospatial data has become increasingly available via local and federal governments, public universities, and non-governmental organizations. Before the mid 2000's, large-scale geospatial datasets were difficult to find and often quite expensive (Berry, 2013). With this influx of freely available geospatial data and user-friendly data downloading interfaces, producers and land managers now have access to geospatial data that can be used for a variety of land-use planning and land suitability analysis. An excellent example of this is the Montana State Library's Geographic Information Clearinghouse (http://geoinfo.msl.mt.gov/), which houses Montana-scale data from a variety of local, state, and federal agencies from both the public and private sectors.

There are two key publicly available datasets that could support ICLS-oriented LSAs in Montana. The national Cropland Data Layer (CDL; USDA-NASS, 2016) shows crop type, pasture and hay production, and other natural land cover at a 30-m resolution. This dataset offers producers and land managers access to information about local and regional crop and livestock production. Such information could be integrated into an LSA to identify regions with a high level for potential crop-livestock integration based on the density of, and distance between, farming and ranching operations in an area.

A second important public dataset is cadastral (land ownership) data, such as the Montana Cadastral Data Layer (MCDL; State of MT, 2016). The MCDL contains parcel boundaries, land ownership, and property value data as well as information about the number of acres used for agricultural production and grazing for each land parcel. Integrating these data into an LSA may offer useful insights as to where in Montana there are sufficient densities of both farming and ranching operations to support among-producer ICLS. A Montana specific LSA tuned to identify areas where conditions are suitable for ICLS would integrate the following information:

- agronomic factors (i.e. commodities produced),
- logistical factors (i.e. distances between producers), and
- environmental factors (i.e. climate data)

The final product of such an LSA would be maps with associated databases showing the locations of wheat growing operations that are: 1) close enough to livestock grazing operations to permit ICLS experimentation; and, 2) have environmental characteristics that would support ICLS integration via grazing cover crops.

The second sustainable on-farm practice for increasing systems diversity involves replacing the fallow period with warm-season cover crops. The LSA approach can also be applied to identifying areas with a high potential for warm-season cover crop adoption based on environmental parameters conducive to warm-season plant growth. Traditionally, producer surveys have been used to measure interest in and adoption of cover crops in the USA (Arbuckle Jr. and Roesch-McNally, 2015; Jones et al., 2015); however, little published work has utilized GIS to map areas of high cover crop adoption potential based on environmental and agronomic parameters.

Interestingly, several studies have utilized GIS in place of a survey to identify areas for specific crop and other on-farm practice adoption (Mendas and Delali, 2012; Akinci et al., 2013; Kladivko et al., 2014; Boitt et al. 2015). Wade et al. (2016) used LSA to assess the potential for conservation tillage adoption in Iowa, while Kladivko et al. (2014) utilized GIS to highlight adoption potential of fall-planted cover crops in the

Upper Mississippi River Basin to reduce Nitrate leaching based on agronomic and edaphic criteria. While these studies utilized GIS to map potential adoption of on-farm practices, neither published a state-wide map showing specific farming operations where decisions could be adopted (note: Kladivko et al., 2014 selected five counties per state for analysis).

Publicly available environmental and agronomic data is readily accessible for the state of Montana. The Montana State Library's GIS Clearinghouse provides a plethora environmental data including average growing degree days and precipitation data. With this environmental data and the agronomic data from both the CDL and MDCL, LSA can be used to show regions of Montana suitable for warm-season cover crop growth and producer adoption.

GIS is a powerful tool that is increasingly being used in agricultural applications from field- to national-scale analysis. Further applications of GIS in agricultural planning in Montana may offer producers, land managers, and policy makers the ability to identify areas of high potential for producer adoption of sustainable on-farm practices including warm-season cover cropping and building among-producers ICLS.

Research Objectives

Ch. 2 of this thesis aims to further our understanding of the edaphic and agronomic implications of cover cropping and ICLS adoption in Montana. Specifically, this study compared: 1) an ICLS to a chem-fallow wheat system; 2) an ICLS to a cover crop-wheat system; and, 3) a cover crop-wheat system to a chem-fallow wheat system.

Comparisons among systems were based on edaphic and agronomic parameters briefly summarized below:

Soil and Agronomic Objectives:

1. To investigate how grazing cover crop mixtures affects soil biochemical properties in comparison to using herbicide only for crop termination, or no cover crop at all (control).
2. To assess how changes in soil properties, catalyzed by grazing and cover crop growth, affect subsequent wheat yields, compared to no cover crop.

Livestock Grazing Objective:

3. To evaluate both cool- and warm-season annual cover crop polycultures for potential forage quantity and quality in dryland wheat-cover crop systems.

Ch.3 of this thesis identifies areas of Montana conducive to: 1) warm-season cover crop adoption to enhance crop diversity; 2) ICLS adoption via grazing wheat systems; and, 3) warm-season cover crop use as forage in and ICLS. This research provides land managers with critical information necessary for establishing ranch-farm relationships with local producers in an attempt to re-couple livestock and crop production.

Warm-Season Cover Crop Objective:

1. To investigate the suitability, based-on environmental and agronomic parameters, of four Montana exemplary counties for warm-season cover crop growth and adoption using LSA.

ICLS Objective:

2. To investigate the suitability for creating integrated crop-livestock production systems, based on distances between farming and ranching operations, of four exemplary Montana counties using the LSA approach.

References

Acosta-Martinez, V., T.M. Zobeck, and V. Allen. 2004. Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci. Soc. Am. J. 68: 1875-1884.

Acosta-Martinez, V., M.M. Mikha, and M.F. Vigil. 2007. Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat-fallow for the Central Great Plains. App. Soil Eco. 37:41-52.

Acosta-Martinez, V., R. Lascano, F. Calderon, J.D. Booker, T.M. Zobeck, and D.R. Upchurch. 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Bio. Fert. Soils 47: 655-667.

Akinci, H., A.Y. Ozalp, and B. Turgut. 2013. Agricultural land use sutability analysis using GIS and AHP technique. Comp. Elect. Ag. 97: 71-82.

Allen, B.L., J.L. Pikul, Jr., J.T. Waddell, and V.L. Cochran. 2011. Long-term lentil green-manure replacement for fallow in the semiarid northern Great Plains. Agron. J. 103:1292-1298.

Amiri, F., A.R.B.M. Shariff, and T. Tabatabaie. 2012. Monitoring land suitability for mixed livestock grazing using Geographic Information Systems (GIS). (pp.241-266). *In:* Application of Geographic Information Systems. ed: B.M Alam. InTech Publishing, Rijeka, Croatia.

Arbuckle Jr., J.G, and G. Roesch-McNally. 2015. Cover crop adoption in Iowa: The role of perceived practice characteristics. J. Soil Water Cons. 70: 418-429.

Arzanie, H., A. R. Mousavi, M. J. Shalamzary, G. Ajdary. 2014. Range suitability model for livestock grazing. Intern. J. Sust. Develop. 7: 105-112.

Assmann, T.S, M. A. de Bortolli, A.L. Assmann, A. B. Soares, C. S. Rocha Pitta, A.J. Franzluebbers, C. L. Glienke, J.M Assmann. 2014. Does cattle grazing of duel purpose wheat accelerate the rate of stubble decomposition and nutrients released? Agric., Ecosyst., & Envi. 190: 37-42.

Baccara, M., D. Backus, H. Bar-Isaac, L. Cabral, and L. White. 2003. Monsanto's Roundup®. New York Univ. L.N. Stern School of Business, Firms and markets mini-case. 14 July 2003. http://pages.stern.nyu.edu/~lcabral/teaching/monsanto.pdf.

Barbari, M., L. Conti, B.K. Koostra, G. Masi, F. Sorbetti Guerri, S.R. Workman. 2006. The use of Global Positioning and Geographical Information Systems in the management of extensive cattle grazing. Biosyst. Engin. 95: 271-280.

Bardgett, Richard D., David A. Wardle, Gregor W. Yeates. 1998. Linking above-ground and below-ground interactions: How plant responses to foliar herbivory influence soil organisms. Soil Bio. & Biochem. 30: 1867-1878.

Bardgett, R. D., D. A. Wardle. 2010. Ecosystem-level significance of aboveground consumers. (pp 113-167). In: Aboveground-Belowground Linkages: Biotic Interactions, Ecosystem Processes, and Global Change. Oxford University Press. Oxford, U.K.

Berry, J.K. 2013. "GIS evolution and future trends. *In:* Beyond Mapping III. Basis Press, Fort Collins, CO. Available at: [http://www.innovativegis.com/basis/mapanalysis/Default.htm]. [verified: 15 Dec 2016].

Biederbeck V.O., C.A. Campbell, V. Rasiah, R.P. Zentner, G. Wen. 1998 Soil quality attributes as influenced by annual legumes used as green manure. Soil Biol. & Biochem.30:1177-1185.

Blanco-Canqui, H., and R. Lal. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil Till. Res. 95: 240-254.

Boitt, M.K., C.N. Mundia, P. K. E. Pellikka, and J. Kapoi. 2015. Land suitability assessment for effective crop production, a case study of Taita Hills, Kenya. J. Agric. Inform. 6: 23-31.

Calderon, F.J., D.C. Nielsen, V. Acosta-Martinez, M.F. Vigil, and D. Lyon. 2016. Cover crop and irrigation effects on soil microbial communities and enzyme activity in semiarid agroecosystems of the central Great Plains of North America. Pedosphere. 26: 192-205.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179-192.

Carr, P.M., R.L. Anderson, Y.E. Lawley, P.R. Miller, and S.F. Zwinger. 2012. Organic zero-till in the northern US Great Plains Region: Opportunities and obstacles. Renew. Agric. Food Sys. 27:12-20.

Clark, J. T., J.R. Russell, D. L. Karlen, P.L. Singleton, W. D. Busby, and B. C. Peterson. 2004. Soil surface property and soybean yield response to corn stover grazing. Agron. J. 96:1364-1371.

Costa, S.E.V.G.A, E.D. Souza. I. Anghinoni, P.C.F. Carvalho, A.P. Martins, T.R. Kunrath, D. Cecagno, F. Balerini. 2014. Impact of an integrated no-till crop-livestock system on phosphorous distribution, availability and stock. Agric., Ecosyst., & Environ. 190: 43-51.

Dick, R.(ed.). 2011. Methods of Soil Enzymology. SSSA Book Ser. 9. SSSA and ASA. Madison, WI.

Dunbabin, V., A. Diggle, and Z. Rengel. 2003. Is there an optimal root architecture for nitrate capture in leaching environments? Plant, Cell, Environ. 26: 825- 844.

Engel, R.E., P.R. Miller, B.G. McConkey, R. Wallander, and J.A. Holmes. 2017. Soil organic C changes to ten years of increasing cropping system intensity and no-till in a semiarid climate of the northern Great Plains. Soil Sci. Soc. Am. J. 81:404-413.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: The significance of cropping intensification. Soil Sci. Soc. Am. J. 62: 984-991.

Fiskel, J. 2003. Designing resilient, sustainable systems. Environ. Sci. Tech. 37: 5330-5339.

Florence, A. 2016. Cover crop mixture diversity and function. Ph.D. dissertation. University of Nebraska, Lincoln. 141 pp.

Ford, G. L., J.L. Krall. 1979. The history of summer fallow in Montana. Volume 704 Montana Agric. Exper. Bull. Montana State University. Bozeman, MT.

Fornara, D.A., and D. Tilman. 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. J. Ecol. 96: 314–322.

Fraase, A.R., B.W. Neville, D.L. Whitted, P.E. Nyren, G.P. Lardy, and K.K. Sedivec. 2010. Utilizing annual forages in a single and dual cropping system for late-fall and early winter grazing: Impacts on forage production and quality, cow performance, soil health , and economics. pp 1–12. https://www.ag.ndsu.edu/centralGrasslandsREC/cgrec-annual-reports-1/2010-report/Cover_crops_2010.pdf. [Verified: Dec 1, 2016].

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Till. Res. 82: 121-145.

Hatfield, P.G., R.A. Field, J.A. Hopkins, and R. W. Kott. 2000. Palatability of wethers fed an 80% barley diet processed at different ages and of yearling wethers grazed on native range. J. Animal Sci. 78:1779-1785.

Hendrix P.F, D.A. Crossley, Jr., J.M. Blair, and D.C. Coleman. 1990. Soil biota as components of sustainable agroecosystems. (p 637-654). In: Sustainable Agricultural Systems, editors C.A. Edwards, R. Lal, P. Madden, R.H. Miller, and G House. Soil and Water Conservation Society, Ankeny, IA.

Hilimire, K. 2011. Integrated crop/livestock agriculture in the United States: A review. J. Sust. Agric. 35:376-393.

Hopkins, L., 1977. Methods for generating land suitability maps: a comparative evaluation. J. Am. Inst. Plan. 34 19–29.

Hudson, B.D. 1994. Soil organic matter and available water capacity. J. Soil Water Cons. 49: 189-194.

Jones, C.A. and K. Olson-Rutz. 2011. Crop and fertilizer management practices to minimize nitrate leaching. Montana State University Extension MontGuide. Montana State University, Bozeman, MT. http://landresources.montana.edu/soilfertility /PDFbyformat/publicationpdfs/mt201103AG.pdf.

Jones, C., R. Kurnick, P. Miller, K. Olson-Rutz, C. Zabinski. 2015. 2015 Montana cover crop survey results. Montana State University, Bozeman, MT. http://landresources.montana.edu/soilfertility/documents/PDF/reports/2015CCSurveyReport.pdf.

Keeney, D. 1982. Nitrogen – availability indices. (pp. 711–733) In: Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. ed. S. Segou. SSSA, Madison, WI.

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger. 2014. Cover crops in the upper Midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. J. Soil Water Cons. 69: 279-291.

Malczewski, Jacek. 2004. GIS-based land-use suitability analysis: A critical overview. Prog. Plan. 62: 2-65.

Marchao, R. L., T. Becquer, D. Brunet, L. C.Balbino, L. Vilela, and M. Brossard. 2009. Carbon and nitrogen stocks in a Brazilian clayey Oxisol: 13-year effects of integrated crop-livestock management systems. Soil Till. Res. 103: 442-450.

McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24: 560-570.

McVay, K., M. Burrows, F. Menalled, and K. Wanner. 2010. Montana wheat production guide. Montana State University Extension – Publication. Bozeman, MT. 32 pp.

Mendas, A, and A. Delali. 2012. Integration of multicriteria decision analysis in GIS to develop land suitability for agriculture: Application to durum wheat cultivation in the region of Mleta in Algeria. Comp. Electr. Agric. 83, 117–126.

Miller, P.R., W. Lanier, S. Brandt. 2001. Using growing degree days to predict plant stages. Montana State University Extension – Publication. Bozeman, MT.

Miller, P.R., and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the northern Great Plains. Agron. J. 97:189-200.

Miller, P.R., E.J. Lighthiser, C.A. Jones, J.A. Holmes, T.L. Rick, and J.M. Wraith. 2011. Pea green manure management affects organic winter wheat yield and quality in semiarid Montana Can. J. Plant Sci. 91: 497-508.

Miller, P.R., A. Bekkerman, C. A. Jones, M. H. Burgess, J. A. Holmes, and R.E. Engel. 2015. Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. Agron. J. 107: 541-550.

Montana Dept. Commerce. 2017. Census & economic information center – select Montana agricultural commodities dashboard. http://ceic.mt.gov/Economics/AgricultureDashboard.aspx. [Verified: Jan 2, 2017].

Montana State Library Cadastral Parcel Data. 2016. Published land ownership and usage data layer [ArcGIS]. Available at: http://geoinfo.msl.mt.gov/Home/msdi/cadastral. Verified: 11 Nov 2016. Helena, MT.

NASP. 2010. A pivotal time in agriculture. (pp. 43–82). In: Toward Sustainable Agricultural Systems in the 21st Century: The National Academies Press.

O' Dea, J.K. 2011. Greening summer fallow: Agronomic and edaphic implications of legumes in dryland wheat agroecosystems. MS Thesis, Montana State University, Bozeman, MT. 145 pp.

O'Dea, J.K., P.R. Miller and C.A. Jones. 2013. Greening summer fallow with legume green manures: On-farm assessment in north-central Montana. J. Soil Water Conserv. 68:270-282.

Ortiz, R., K. D. Sayre, B. Govaerts, R. Gupta, G.V. Subbaroa, T. Ban, D. Hodson, J.M. Dixon, J. I. Ortiz-Monsaterio, and M. Reynolds. 2008. Climate change: Can wheat beat the heat? Agric., Ecosys., & Environ. 126: 46-58.

Parham, J.A., and Deng, S.P. 2000. Detection, quantification and characterization of β-glucosaminidase activity in soil. Soil Biol. Biochem. 32: 1183–1190.

Parr, J.F., R.I. Papendick, S.B. Hornick, and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. Am. J. Alt. Agric. 7: 5-11.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Ag. 9: 180-186.

Powell, J.M., and M.A. Mohammed-Saleem. 1987. Nitrogen and phosphorus transfers in a crop-livestock system in West Africa. Agric. Syst. 25: 261-277.

Robertson, G.P., and S.M. Swinton. 2005. Reconciling Agricultural Productivity and Environmental Integrity: A Grand Challenge for Agriculture. Front. Ecol. Environ. 3: 38-46

Russelle, M.P., M. H. Entz, A. J. Frazluebbers. 2007. Reconsidering Integrated Crop-Livestock Systems in North America. Agron. J. 99: 325-334.

Sainju, U.M, B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil & Till. Res. 63: 167-179.

Schomberg, H.H., D.W. Reeves, D.S. Fisher, R.L Raper, D.M Endale, M. Jenkins. Evaluating stocker cattle in a Southern Piedmont conservation tillage cotton-cover crop system to increase productivity. In: Proceedings of 30th Southern Agriculture Systems Conference, and 8th Annual Georgia Conservation Production Systems Training Conference. Eds. D.M. Endale 29-31 July 2008. Tifton, Georgia.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66: 1296-1303.

Shaver, T.M., G.A. Peterson, L.A. Sherrod, and L.R. Ahuja. 2003. Cropping intensification in dryland systems improves soil physical properties: Regression relations. Geoderma. 116:149–164.

Sher, H., M. Ansar, F.U. Hassan, G. Shabbir, and M.A. Malik. 2012. Hydrocyanic acid content variation amongst sorghum cultivars grown with varying seed rates and nitrogen levels. Intern. J. Agric. and Biol. 14: 720-726.

Shrestha, B.M., B.G. McConkey, W.N. Smith, R.L. Desjardins, C.A. Campbell, B.B. Grant, and P.R. Miller. 2013. Effects of crop rotation, crop type and tillage on soil organic carbon in a semiarid climate. Can. J. Soil Sci. 93: 134-146.

Six, J., K. Paustian, E. T. Elliott, and C. Combrink. 2000. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated Carbon. Soil Sci. Soc. Am. J. 64:681-689.

Snap, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping systems niches. Am. Soc. Agric. J. 97: 322-323.

Sulc, M. R., and A. J. Franzluebbers. 2014. Exploring integrated crop-livestock systems in different ecoregions of the United States. Euro. J. Agric. 57: 21-30.

Tallman, S.M. 2014. Cover crop mixtures as partial summerfallow replacement in the semi-arid northern Great Plains. MS Thesis, Montana State University, Bozeman, MT. 146 pp.

Tanaka, D.L., and J.K. Aase. 1987. Fallow method influences on soil water and precipitation storage efficiency. Soil Till. Res. 9:307–316.

Tanaka, D.L. 1989. Spring wheat parameters as affected by fallow methods in the Northern Great Plains. Soil Sci. Soc. Am. J. 35: 1518-1524.

Tanaka D.L., A. Bauer, and A.L. Black. 1997.Annual legume cover crops in spring wheat- fallow systems. J. of Prod. Ag.10:251-255.

Tanaka, D.L., D. J. Lyon, P. R. Miller, S. D. Merrill, and B. G. McConkey. 2010. Soil and Water Conservation Advances in the Semiarid Northern Great Plains. In: Soil and Water Conservation Advances in the United States. Eds: T.M. Zobeck, and W.F. Schillinger. SSSA – Spec. Pub. 60. SSSA, Madison, WI. pp. 81-102.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature. 371: 783 – 785.

Tracy, B. F., and Y. Zhang. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Sci. 48: 1211-1218.

USDA, Farm Service Agency. 2017. Conservation reserve program statistics. https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index. Accessed [May 20, 2017]. USDA-FSA, Washington, DC.

USDA, National Agricultural Statistics Service. 2007. Census of agriculture – state data. Washington, DC. http://www.agcensus.usda.gov/ Publications/2007/ Full_Report/ Volume_1,_Chapter_1_State_Level/Montana/st30_1_008_008.pdf. [Verified 22 Dec 2016]. USDA-NASS,.

USDA, National Agricultural Statistics Service Cropland Data Layer. 2016. Published crop-specific data layer [ArcGIS]. Washington, DC. https://nassgeodata.gmu.edu/CropScape/. [Verified: 11 Nov 2016].

Wade, T., L. Kurkalova, and S. Secchi. 2016. Modeling field-level conservation tillage adoption with aggregate choice data. J. Agric. and Res. Eco. 41: 266-285.

Wang, G., and M. Danzl. 2014. Annual forage species production on delayed seeding areas in the Missouri Coteau Region of North Dakota. North Dakota State University Extension, Fargo, ND. pp. 1–3.

Wardle, D.A., K.I. Bonner, and G.M. Barker. 2002. Linkages between plant litter decomposition, litter quality and vegetation responses to herbivores. Funct. Ecol. 16: 585-595.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. Am. J. Altern. Ag. 18: 3-17.

West, A.W., and G.P. Sparling. 1986. Modifications to the substrate-induced respiration method to permit measurement of microbial biomass in soils of differing water contents. J. Microbiol. Meth. 5: 177-189.

Wilson, J.P. 1999. Local, national, and global applications of GIS in agriculture. (pp. 981-998). In: Geographical Information Systems: Volume 2, Management Issues and Applications. Eds. P.A. Longley, D.J. Maguire, M.F. Goodchild, and D.W. Rhind). John Wiley and Sons, New York, NY.

Yousefi, M. R., and A.M. Razdari. 2015. Application of GIS and GPS in precision agriculture (a review). Intern. J. Adv. Biol. and Biomed. Res. 3: 7-9.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, F. Selles, R. Lemke, P.G. Jefferson, and Y. Gan. 2004. Long-term assessment of management of an annual legume green manure crop for fallow replacement in the Brown soil zone. Can. J. Plant Sci. 84: 11–22.

CHAPTER TWO

COVER CROP GRAZING: OPTIMAL SEASONALITY FOR SOIL AND LIVESTOCK BENEFIT

Introduction

Wheat (*Triticum aestivum* L.), the most commonly planted crop in Montana, is often cultivated under summerfallow due to low annual precipitation (250 – 350 mm; Ford and Krall, 1979; Tanaka et al., 2010). For many dryland wheat producers in Montana, water availability is the limiting factor for cash crop production, making summerfallow an attractive management tool. However, the practice of summerfallow leads to increased soil erosion (Tanaka et al., 2010), decreased soil organic matter (Campbell et al., 2000), and lower soil biological activity (Acosta-Martinez, 2007). Although the area under summerfallow has significantly decreased since the 1970's, large parts of Montana's wheat producing regions, namely the "Golden Triangle" (NRCS MLRA 52), remain under summerfallow (Miller et al., 2015). While summerfallow helps recharge valuable soil water, the costs of decreased soil quality and increased erosion indicate a lack of sustainability in the long-term. More research is required to find sustainable alternatives to summerfallow in Montana.

One potential fallow replacement is planting cover crops during the fallow period, which may enhance soil quality and decrease soil erosion. Cover crops can be single species or mixtures of species (i.e. cocktails) that benefit soil properties by enhancing nutrient cycling (Lu et al., 2000), increasing soil organic matter (SOM) and soil structure

(Zentner et al., 2004), increasing bioturbation (Williams and Weil, 2004), decreasing erosion (Tanaka et al., 1997), and suppressing weed growth (Fisk et al., 2000). These characteristics make the addition of cover crops to chemical-fallow (herbicide-based summerfallow) systems an important step in the pursuit of sustainable food production, but the price of cover cropping is soil water use (O’Dea et al., 2013; Miller, 2014). While the economic trade-off with improved soil nutrient cycling is positive in the long run (Zentner et al., 2004; Allen et al., 2011, Miller et al., 2015), the short-term risk remains considerable (O’Dea et al., 2013; Miller et al., 2014). Research is needed to produce economically viable alternatives to current cover cropping systems that offset the marginal costs associated with cover crop incorporation in the short run.

One way to offset the costs of cover cropping may be to hay or graze cover crops which may offer adequate biomass quantity for livestock forage (O’Dea, 2013; Tallman, 2014; Housman, 2016). Utilizing cover crops as livestock forage is one way to create integrated crop-livestock systems (ICLS), which offer a diversified and sustainable means of crop production in many regions (Hilimire, 2011; Sulc and Franzluebbers, 2014). However, little work examining the implications of ICLS – specifically grazing cover crops – has been conducted in Montana.

The addition of livestock to a cropping system can have important implications for soil quality and crop yield, including enhanced nutrient cycling which increases available nitrogen (Tracy and Zhang, 2008; Assmann, 2014), phosphorous (Costa et al., 2014), and labile carbon (Acosta-Martinez et al., 2004; Tracy and Zhang, 2008). However, grazing livestock on cropland could result in increased soil compaction, which may hinder root growth and decrease crop yield (Hamza and Anderson, 2005; Bardgett and Wardle, 2010). Furthermore, over-grazing and subsequent reductions in crop residue can also increase soil surface compaction and decrease water infiltration (Shaver et al., 2002), and may even increase erosion to the extent that protective crop stubbles are compromised (Vigil, 2013). Appropriate livestock management, including close attention to livestock forage consumption and grazing livestock on dry or frozen soil, may mitigate the risk of compaction (Clark et al., 2004; Hamza and Anderson, 2005). It should be noted that even with soil compaction, some studies have found no significant effects on subsequent cash crop yield (Schomberg et al., 2008; Tracy and Zhang, 2008), especially in regions with freeze-thaw cycles like Montana.

While current evidence suggests potential benefits and drawbacks to ICLS (Russelle et al. 2007; Sulc and Tracy 2007), further research at the systems level is needed to fully understand the implications of integration for edaphic and agronomic parameters in dryland systems in Montana. This research aimed to further our understanding of how cover crops perform as livestock forage as well as how grazing a dryland wheat system affects soil nutrient cycling and subsequent wheat yields.

Objectives/Performance Targets

The purpose of this research was to investigate the effects of integrating livestock grazing in dryland wheat-cover crop systems.:

1. Livestock Grazing Objective: To compare cool- and warm-season annual cover crop mixtures for potential forage in dryland wheat-cover crop systems.

2. Edaphic Objective: To investigate how grazing cover crop mixtures affects soil biochemical properties in comparison to both cover crop green manures and chemical-fallow.
3. Agronomic Objective: To assess how changes in soil properties, catalyzed by cover crops and grazing, affect subsequent wheat yields in comparison to chemical-fallow.

Materials and Methods

Site Characterization

The first study site was at the Montana State University – Fort Ellis Research Farm (N 45.667°, W 110.978°) located near Bozeman, MT. The site was planted in barley during the 2014 growing season and has been under no-till management since 2012. The predominant soil type at the Fort Ellis Research Farm is Blackmore silt loam and the mean annual precipitation is approximately 500 mm. The second study site, established in 2016, was located on a farm in the northern Gallatin Valley, MT (NGV). The NGV site was sown to winter wheat during the 2015 season and hayed alfalfa for several years before that. This NGV experiences less annual precipitation (~360 mm) with a predominant soil type of Amsterdam silt loam (Tables 1 and 2). Cover crop treatments were sown at these sites in 2015 and 2016, respectively, and followed by spring wheat response crop sin 2016 and 2017.

Study Design

The study was a randomized complete block design consisting of six cover crop/termination treatments (main plot = 15.2 x 7.6 m) with a split plot arrangement for N fertility rates and four replications. Each cover crop mixture consisted of cereal, legume, and brassica crops. Cereal species were oat (*Avena sativa L.* cv. Oatana) in the cool-season mixture and sorghum (*Sorghum bicolor L. vns*- 2015) and prosomillet (*Panicum milliaceum L. vns* - 2016) in the warm-season mixture. Legume species used included forage pea (*Pisum sativum L.* cv. Arvika) in the cool-season mixture and soybean (*Glycine max L. vns*) in the warm-season mixture. Radish (*Raphanus sativus L.vns*) was the brassica used in both the cool- and warm-season mixes as its growth pattern is day length-sensitive and varies relative to planting date. Radish bolts if planted prior to mid-June and otherwise remains vegetative and forms a large tap root (USDA-NRCS, 2009). Cover crops species were seeded together (row spacing = 30 cm) to a depth of 2.5 cm with a low-disturbance no-till disk seeder. Seeding rates were calculated by dividing a recommended monoculture rate proportionally by the number of species in the mixture. Each mixture was seeded at a target rate of 120 m^{-2} with individual cover crop species added to a mixture at a target seed rate of 40 m^{-2}. Cover crop termination coincided with first-bloom (>50% of plants with one open flower) of pea in the cool-season mixtures (McCauley et al., 2012; Table 3). Termination of warm-season cover crop mixtures was determined by the accumulation of growing degree days (GDD; T_{base} = 0°C) of the cool-season mixture (i.e. both mixtures' GDD were matched as closely as possible).

Treatments and cover crop mixes for Fort Ellis and NGV are listed in Table 4. Chemical fallow (‘Fallow’), served as a control treatment absent vegetation during the summerfallow period. In cool-season grazing (‘Cool Graze’) and warm-season grazing (‘Warm Graze’), lambs graze cover crops via mob grazing (i.e. 430 – 520 lambs ha^{-1} d^{-1}) during a 24-hr interval with a target removal of 50% of cover crop biomass. In addition, after grazing, the Cool Graze treatment was sprayed approximately two weeks after grazing to terminate cover crops and preserve soil moisture. The Warm Graze and warm-season haying (‘Warm Hay’) were not sprayed after grazing/swathing, as the first frost in the Bozeman area typically occurs mid-September and terminates re-growth of warm-season cover crop foliage; however, 2015 and 2016 experienced exceptionally late first fall frosts (Table 3). Radish is frost tolerant and can withstand temperatures as low as -4 °C, indicating its termination may not occur until well after the Autumnal equinox, so that warm-season treatments may not be fully terminated until early fall (NRCS, 2009). Cool-season spraying (‘Cool Spray’) and warm-season spraying (‘Warm Spray’) were terminated with a glyphosate (N-(phosphonomethylglycine)) mixture and left as a green manure (Table 3). The Warm Hay treatment was swathed and removed cover crops to a 10-cm cutting height, and then killed by frost. However, at the NGV site, due to low biomass growth, Warm Hay was swathed and the biomass was left on the plots to simulate mowing – instead of haying – which was not a viable practice there.

In Year-2, all main plots at Fort Ellis were seeded in spring wheat (cv. Duclair) with a low-disturbance no-till drill to a depth of 2.5 cm, perpendicular to Year-1 cover crop seeding. Nitrogen fertilizer treatments subplots were banded at >5 cm below and to the side of the seed at three rates: 0, 67.5, and 135 kg N ha^{-1} in randomized subplots

Cover Crop Sampling

Cover crop population stand counts were conducted 4 wk after planting in four 1-m strips per plot totaling ~1 m^2 area. Above-ground cover crop biomass was sampled ~24 hr prior to termination by cutting plants to the soil surface. Grazed and swathed plots were resampled similarly ~48 hr after termination to measure residual biomass. All samples were dried at 50 °C prior to weighing. For warm-season cover crop treatments, enlarged radish roots below the soil surface were included in biomass measurements. After weighing, cover crop samples were ground and analyzed for C and N using a LECO combustion analyzer (LECO Corp., St. Joseph, Michigan). Radish roots from the warm-season treatments were not included in C and N analysis. Cover crop forage quality samples were taken from all grazed and swathed treatments pre- and post-termination. Samples were sent to Midwest Laboratories (Omaha, NE) and analyzed for crude protein, acid-detergent fiber, neutral-detergent fiber, and total digestible nutrients via NIR spectroscopy. These data were then used to calculate forage relative feed values (RFV) for each treatment.

Soil Sampling and Laboratory Procedures

Six measurements were taken with a hand-held static cone penetrometer (Durham Geo-Enterprises Inc.- Nova Metrix, Wakefield, MA) from each treatment within a week prior to seeding in 2015 and after seeding in 2016 at relatively uniform soil water content (soil water also measured). Samples were oven-dried at 50 °C and sieved through a 5-mm sieve. Additionally, soil bulk density was measured by extracting 2.5 cm-diameter cores to a 0.9 m depth, in 0.3 m increments, prior to seeding in both years, and dividing soil weight by soil volume. Site bulk densities, by depth, were determined by averaging all values for each block and used to calculate Equivalent Depth (mm) of soil water to a depth of 0.9 m (Or and Wraith, 1999). Soil water was measured again prior to planting cover crops or wheat. In cover crop years, soil water was additionally measured after cool- and warm-season cover crop termination, respectively.

Soil nitrate was measured using the same cores as soil water. Samples were oven-dried at 50 °C and sieved through a 5-mm sieve. After sieving, 5 g of soil was added to 25 mL of 1 M KCL, shaken for 30 min, filtered through a Whatman 5 filter, and then analyzed on a Lachat flow injection analyzer (Lachat Instr., Loveland, Colorado).

Soil P was measured by collecting six 2.5 cm-diameter soil cores to a depth of 15 cm in each plot and processing samples by adapting methods from Olsen and Sommers (1982). Samples were dried at 50 °C and sieved (5-mm). After sieving, 1.25 g of soil was added to 25 mL of 0.5 M $NaHCO_3$ (pH 8.5), shaken for 30 min, and then filtered through a Whatman 5 glass fiber filter. Then, 5 mL of soil solution was combined with H_2SO_4 as described in Kuo (1996) and analyzed by spectroscopy at 880 nm.

Potentially mineralizable nitrogen (PMN) was measured by collecting six soil cores (2.5 cm dia x 15 cm d) from each plot with soil probe was sterilized with flamed isopropyl alcohol. Cores were composited and stored at 40 °C for less than 6 wk before analyzing. PMN is calculated as the difference in plant available N at time zero and after incubation for 14 d at 30 ^{o}C (Keeney 1982). Time-zero plant available N (NH_4^+ and NO_3^-) was measured using 5-g dry-equivalent, field-moist soil subsamples (moist samples ~ 6 g) and the same method noted previously for soil nitrate extraction above. To calculate plant available N after incubation, three 5-g dry-equivalent, field-moist soil subsamples (moist samples ~ 6 g) from each plot were added to 12.5 mL of double-deionized water and held under a flow of N_2 gas for five seconds in order to create a nitrogen atmosphere. Next, 12.5 mL of 2 M KCl was added to each sample and incubated in a hot water bath at 30 °C for 14 d. After incubation, samples were filtered through a Whatman 5 filter and analyzed on a Lachat flow injection analyzer. The three incubated subsamples from each plot were averaged prior to statistical analysis. PMN was reported as the amount of NH_4 (kg NH_4 ha^{-1}) after incubation minus the amount measured prior to incubation.

Microbial biomass was calculated from the same composite samples collected for PMN using the Soil Induced Respiration method modified from West and Sparling (1986). A 5-g field-moist soil subsample was added to 10 mL of yeast solution and shaken horizontally at 20 °C for 4 hr. Headspace CO_2 concentrations, caused by microbial respiration, were measured after 10 min of shaking (Time 0), after 2 hr of shaking (Time 2), and after 4 hr of shaking (Time 4). Headspace CO_2 concentrations were measured using gas chromatography (Varian Inc., Palo Alto, CA).

Soil enzyme activity was measured from the same soil core composite samples as PMN and microbial biomass, using methods adapted from Parham and Deng (2000) and Dick (2011). Specific enzymes targeted were: β-glucosidase (EC 3.2.1.21; cleaves cellobiose from cellulose), β-glucosaminidase (EC 3.1.2.52; cleaves N-acetyl glucosamine from chitin), and acid and alkaline phosphatase (EC 3.1.3.1, EC 3.1.3.2; cleaves phosphates from organic phosphorus compounds). A 1 g field-moist soil was inoculated in duplicate with a p-nitrophenol (pNP)-labelled substrate for each enzyme substrate, incubated for 1 hr at 37 °C, and then analyzed for pNP using a spectrophotometer (Parham and Deng, 2000).

Wheat Sampling

At Fort Ellis, in 2016, Spring wheat biomass samples were taken in two 1-m strips from each fertilization subplot at anthesis. Plants were cut at the soil surface, dried at 50°C, and weighed to estimate total above ground biomass. A plot combine (Wintersteiger, Salt Lake City, UT) was used to harvest a 1.8-m swath of wheat from each treatment plot and N fertilization subplot. A NIR transmittance machine (Infratec GmbH, Dresden, Germany) was used to analyze wheat for protein and moisture content.

Statistical Analyses

All statistical analyses were performed with R statistical software (The R Foundation for Statistical Computing, Vienna, Austria; version 3.2.5). Data were examined for normality and homogeneity of variance using residual and Q-Q plots. Linear models using treatment and block (rep) as independent variables and analyzed with ANOVA were used in all parameter analyses except for wheat parameters. For wheat parameters, a linear model was built with cover crop treatment (previous year), block, and fertility subplot as independent variables and analyzed with ANOVA. Statistical differences were determined using Fisher’s Protected Least Significant

Difference (LSD) Test with no p-adjustment and $\alpha = 0.05$ (package: *agricolea*). Pre-planned orthogonal contrasts were used to compare combinations of cover crop and fallow treatments.

Results and Discussion

Cover Crops as Livestock Forage

The first objective of this study was to compare cool- and warm-season annual cover crop mixtures for potential forage in dryland wheat-cover crop systems. In the northern Great Plains (NGP), both forage quality and quantity affect the monetary value of hay and pasture. Biomass at termination ranged from 1.0 Mg ha^{-1} (Warm Graze) to 4.6 Mg ha^{-1} (Cool Graze; $p = 0.16$; Fort Ellis). Taking into account that the average field in Montana yielded 4.6 Mg ha^{-1} of hay for all hay types and 3.6 Mg ha^{-1} for non-alfalfa hay between 2013 and 2016 (MDOC, 2017), the biomass production at Fort Ellis was comparable, but overall yields were low at NGV – especially for the warm-season treatments (Table 5). Cool-season biomass was 8% greater than warm-season biomass ($p = 0.03$) in 2015. At Fort Ellis, this is likely due to the fact that the cool-season treatments received 91 mm of precipitation between seeding and termination while the warm-season treatments received 47 mm of precipitation between seeding and termination and only 5 mm precipitation during the last 13 d of growth (data from on-site weather station). In 2016, cool-season biomass was ~126% greater than warm-season biomass ($p < 0.01$). While the 2016 cool-season treatments received 96 mm of precipitation between seeding and termination, the warm-season treatments received only 16 mm between seeding and termination (WRCC, 2016). June 2015 and June 2016 were the driest June’s on record since 2003 at the NGV and since 1985 at Fort Ellis, respectively (WRCC, 2016). These irregularly dry June's and their effect on cover crop biomass production do not accurately reflect biomass production potential in years which receive June precipitation closer to the LTA.

These results imply that cover crops mixtures, especially spring-sown mixtures, in areas of the NGP with higher annual rainfall (>350 mm), may attain similar biomass levels to other hay fields in Montana (WRCC, 2016; MDOC, 2017) for grazing. However, in drier areas of the NGP (< 350 mm annual precipitation), cover crops may not produce comparable amounts of forage compared to other forage and hay production lands (WRCC, 2016; MDOC, 2017). Furthermore, given the cover crop biomass production noted in this study, years with May-dominated precipitation patterns may not be conducive to high levels of warm-season cover crop biomass production. It should also be noted that these results may be confounded by variations in soil fertility between sites (see "Edaphic Implications" section) as well as decreased soil temperatures due to increased stubble height at the NGV site (Cutforth et al., 2002). While cover crops are a useful tool for encouraging species diversity on the landscape scale by engaging the warm-season plant growth period, warm-season mixtures may not produce adequate forage quantity for grazing in years with insufficient June-July precipitation. One solution is to plant warm-season cover crop mixtures earlier in the year (mid-to-late May) to increase the likelihood of sufficient precipitation for biomass optimization (USDA-NRCS, 2016). However, early season temperatures may limit establishment and growth of warm-season mixtures earlier in the season (Helms et al., 1997; See Ch.3 of this thesis for more information).

Pre-termination cover crop biomass differed among species at Fort Ellis where sorghum had the greatest biomass (2,014 kg ha^{-1}) and soybean had the least biomass (1,048 kg ha^{-1}; p <0.01; Table 6). Interestingly, sorghum produced 91% and 92% more biomass than radish (warm-season) and soybean, respectively, indicating high variability among some species in warm-season cover crop biomass production. Sorghum, under certain conditions, may be a valuable cover crop due to its ability to yield high quantities of biomass under drought conditions (Table 8; Fracasso et al., 2016). Post-termination (i.e. post-grazing) cover crop biomass also differed among species in 2015 where oat had the greatest biomass residue with 581 kg ha^{-1} and soybean had the least residual biomass with 236 kg ha^{-1}. In both cool- and warm-season treatments, legumes (pea and soybean) had the least amount of post-termination biomass indicating high palatability to livestock, while fibrous rooted cover crops (oat and sorghum) had the greatest amount of post-termination biomass. These results were expected as livestock often consume the most palatable and easily digested forages prior to consuming coarser, less palatable forages when given the opportunity (Bedell, 1967).

In 2016 at NGV, radish (cool-season) yielded the highest pre-termination biomass with 1086 kg ha^{-1} while millet yielded the lowest biomass with 344 kg ha^{-1} (p <0.01), the opposite pattern of what occurred at Fort Ellis. These results were surprising as millet is often considered a highly drought tolerant crop (Serba and Yadav, 2016), yet millet biomass was likely stunted by limited growing season precipitation. Post-termination (i.e.

post-grazing) cover crop species biomass did not differ (*p* = 0.08), likely due to limited forage production and relatively heavy grazing by sheep (6 animals per plot for ~22 hours). Further research should measure the performance of individual cover crop species grown in mixtures under varying environmental conditions. Such research may yield information regarding cover crop mixture performance as forage under extreme environmental conditions like drought.

In 2015 (Fort Ellis), the Warm Hay treatment had a neutral detergent fiber (NDF) value of 561 g kg^{-1} while the Cool Graze treatment was 526 g kg^{-1}, and the Warm Graze treatment was 488 526 g kg^{-1} (*p* = 0.01; Table 6). Acid detergent fiber (ADF) was highest in the Cool Graze treatment (426 g kg^{-1}) followed by the Warm Graze (370 g kg^{-1}) and Warm Hay treatments (370 g kg^{-1}; *p* = 0.02). Forages produced in the Warm Graze and Warm Hay treatments were both more digestible (ADF) than the Cool Graze treatment, while intake potential (NDF) was lowest in the Warm Hay treatment and highest in the Warm Graze treatment. These differences are likely due to variability in plant maturity among treatments caused by abnormally an abnormally dry June. The Cool Graze treatment received more precipitation over the growing season and was terminated at a later growth stage than both the Warm Graze and Warm Spray treatments.

Crude protein (CP) was highest in the Warm Graze treatment (229 g kg^{-1}), followed by the Warm Hay treatment (185 g kg^{-1}) and then the Cool Graze treatment (158 g kg^{-1}; *p* <0.01). This order persisted among treatments with regard to total digestible nutrients (TDN) where both the Warm Graze and Warm Hay treatments had a value of 604 g kg^{-1} and the Cool Graze treatment had a value of 540 g kg^{-1} (*p* <0.01).

These results are, again, likely due to differences in plant maturity between treatment types (i.e. cool- and warm-season). While plant growth was standardized by GDD (i.e. the warm-season treatments were grown for a similar number of GDD as the cool-season treatments), differences in precipitation and plant growth requirements (i.e. warm-season plants require warmer basal growth temperatures than cool-season) likely led to differences in plant maturity. Overall, the Warm Graze treatment had the highest RFV (115) and was statistically different from other treatments (*p* =0.02), while the Cool Graze (99) and Warm Hay (100) treatments were not statistically different from one another.

Patterns in forage quality were similar in 2016 (NGV) where ADF was highest in the Cool Graze treatment (351 g kg^{-1}) followed by the Warm Hay treatment (303 g kg^{-1}) and then the Warm Graze Treatment (274 g kg^{-1}; *p* = 0.02; Table 8). Interestingly, NDF among treatments was not statically different. CP was highest in the Warm Graze (224 g kg^{-1}) followed by the Warm Hay treatment (212 g kg^{-1}), and then the Cool Graze treatment (155; *p* <0.01), while TDN was highest in the Warm Graze treatment (711 g kg^{-1}) followed by the Warm Hay treatment (680 g kg^{-1}) and then the Cool Graze treatment (625 g kg^{-1}; *p* = 0.01). RFV was not statistically different among treatments in 2016 (*p* = 0.24); however, CP, ADF, and TDN all indicate that warm-season treatments were higher in quality than cool-season treatments. Like the 2015 growing season at Fort Ellis, the 2016 growing season in NGV encompassed an incredibly dry June (Table 1) which greatly reduced growth in the warm-season treatments. This inhibition of growth led to a higher quality forage (Lloveras, 1990), but did so at the cost of biomass production.

In reality, forage quality was likely higher in the grazed treatments than noted as biomass and forage sampling included basal portion portions of plants which, in most cases, would be left ungrazed by livestock (Collins, 1988). It should also be noted that, in Montana, forage quantity is typically more valuable than quality as little of Montana's livestock production is focused on beef and therefore does not usually require high quality forage (Lalman, 2004; Kott, 2007). This means that the economic value of cover crops may offset the short-term costs of cover cropping as biomass production may be adequate to warrant use as livestock forage (Table 5) – especially as CRP ha decline and reduce emergency forage reserves in the NGP (USDA-FSA, 2017)

Edaphic Implications

The second objective of this study was to investigate how grazing cover crop mixtures affects soil biochemical properties in comparison to both swathing and spraying out cover crops as a green manure. A major point of concern when grazing cropland is the potential for soil compaction (Hamza and Anderson, 2005; Bardgett and Wardle, 2010). Compaction differed among proceeding cover crop treatments with the greatest resistance in the Cool Graze treatment and the lowest resistance in the Fallow treatment at the 7.5 – 15 cm and 15 – 22.5 cm depths (p <0.01; Table 9).

It should be noted that static cone penetrometer resistance measurements are highly variable with regard to soil moisture and soil penetration speed (Vaz et al., 2001). Further analysis of soil bulk density data prior to seeding spring wheat at Fort Ellis in 2016 (Table 10) showed no sign of compaction at any depth, including 0 – 30 cm. Contrast comparisons in Table 9 also indicate that most of the variation among treatments at the 7.5 – 15 cm and 15 – 22.5 cm depths are attributable to differences between cool- and warm-season treatments, not spray or graze treatments. Therefore, it is unlikely that biologically important compaction occurred as a result of livestock grazing in this study. It should also be noted that sheep only grazed plots for ~24 hr (6 lambs plot^{-1}, or ~500 lambs ha^{-1}) and that may not be reflective of less intense field- and herd-scale cover crop grazing in the NGP.

At both site-years, the Fallow treatment, measured after cool-season cover crop termination, had an average of 8.5 – 9.7 mm more total soil water than all other treatments ($p < 0.01$), while Fallow treatments measured after warm-season cover crop termination had an average of 6.7 – 7.9 mm more soil water than all other treatments ($p < 0.01$; Table 11). In 2015, (Fort Ellis) warm-season treatments had an average of 3.8 mm more total soil water than cool-season treatments after termination; in 2016 (NGV), warm-season treatments had an average of 0.8 mm more soil water than cool-season treatments after termination. Differences between cool- and warm-season cover crop treatments were likely attributable to differences in pre-termination cover crop biomass (Table 5) as cool-season treatments significantly outgrew warm-season treatments in both site-years ($p = 0.03$). Soil water depletion by cover crops is a major concern for many Montana producers (Jones et al., 2015) and an unavoidable consequence in dryland systems, regardless of cover crop species or mixtures (Nielsen et al., 2005; Nielsen et al., 2015). However, long-term analysis has shown that the gains in soil quality may eventually offset the negative implications of short-term water use by legume cover crops (Miller et al., 2015).

Interestingly, no differences in soil water were noted among treatments prior to spring wheat seeding following spring recharge, indicating attenuation of differences at Fort Ellis in 2016 (Table 13). However, the Fallow treatment had 4 mm greater water than the average of all cover crop treatments ($p = 0.02$) in the 0-0.3 m depth. These results agree with those of Miller and Holmes (2005) who recorded overwinter soil water recharge in a variety of cropping systems in Bozeman, MT, and found that most systems had comparable soil water to crop-fallow systems. This means that, in parts of the NGP where the annual precipitation amount and over-winter pattern is comparable to the Bozeman area (500 mm), soil water depletion by cover crops is not a troublesome issue. However, it should be noted that the Bozeman area is anomalous as most of the region receives between 260 mm and 400 mm of precipitation annually and has experiences relatively high winter moisture (Tanaka et al., 2010).

Following cover crop termination in 2015 (Fort Ellis), fallow treatments had 30 kg ha^{-1} greater total soil NO_3-N than all other treatments averaged. Warm-season treatments had 5 kg ha^{-1} greater soil NO_3-N than cool-season treatments at the 0-0.3 m depth ($p = 0.01$; Table 13). Similar trends occurred in 2016 at the NGV site where fallow treatments had 24.2 kg ha-1 total soil NO_3-N than all other treatments averaged. Warm-season treatments had 4 kg ha^{-1} soil NO_3-N at the 0-0.03 m. This is likely due to the dry conditions which stunted warm-season cover crop biomass and, presumably, root growth (not measured), thus leaving the 0.61-0.9 m depth of the soil unmined by warm-season roots. Cool-season treatments averaged 9 and 63% greater cover crop biomass compared to warm-season treatments in 2015 and 2016, respectively, which implies that more soil N was taken up by cool-season treatments and used for plant growth.

Prior to spring wheat seeding at Fort Ellis (2016), soil NO_3-N was not statistically different (but trended closely) at the 0-0.3 m depth (p = 0.06) and differed statistically among treatments at the 0.31-0.6 m (p <0.01) depth where the Fallow treatment had the greatest amount of Soil NO_3-N (39 kg ha^{-1}) and the Warm Graze treatment had the smallest amount of soil NO_3-N (14 kg ha^{-1}; Table 12). At the 0.61-0.9 m (p = 0.02) depth, the same pattern emerged where the Fallow treatment had 28 kg ha^{-1} NO_3-N and Warm Graze had 12 kg ha^{-1} NO_3-N. The Fallow treatment had an average of 43 kg ha^{-1} greater NO_3-N than the average of all other cover cropping treatments.

Prior to spring wheat planting in 2016 at Fort Ellis, fallow treatments had 43 kg ha^{-1} more total soil NO_3-N than all other treatments averaged. Interestingly, in contrast with post-termination NO_3-N, soil cool-season treatments had 9 kg ha^{-1} and 7 kg ha^{-1} more NO_3-N than warm-season treatments at the 0-0.3 m (p = 0.03) and 0.31-0.6m (p <0.01) depths, respectively. Changes in soil NO_3-N from 2015 to 2016 at Fort Ellis are likely the result of differences in biomass and cover crop decomposition time. Cool-season treatments had 4 wk longer to decompose and return N to the soil compared to warm-season treatments. Other studies (Biederbeck et al., 1996; Miller et al., 2006; van Kessel and Hartney, 2000) have noted similar short-term losses of soil NO_3-N following cover cropping as a result of N immobilization in plant residues, while long-term effects of cover cropping on soil NO_3-N show a net increase in some instances (Sainju et al., 2002; Jones et al., 2015b), but require further study in order to understand how the long-term break-down of cover crop litter affects soil NO_3-N.

Potentially mineralizable nitrogen (PMN) did not differ ($p = 0.07$) among treatments prior to spring wheat seeding at Fort Ellis in 2016 (Table 14). However, when comparing spray- and graze-terminated treatments favored spray-terminated treatments, PMN was over 60% higher in soils of spray-terminated treatments and grazed treatments had 22% more PMN than the swathed treatment (Warm Hay) prior to spring wheat seeding at Fort Ellis ($p = 0.01$). The differences between spray and graze are most likely a result of biomass-N removal from treatments, but may also be because grazing enhances the rate of plant material decomposition, since animal waste is already at an advanced state of decomposition relative to other litter of the same age (Wardle and Bardgett, 2004). Animal waste is highly labile and easily assimilated into the below-ground food web (Wardle et al., 2002; Ruess and Ferris, 2004). Long-term study of PMN dynamics in grazed cover cropping systems may shed more light on the effects of grazing on PMN and other nutrient cycles.

After one year of cover crops and prior to spring wheat planting in 2016 at Fort Ellis, Olsen-P levels did not differ among treatments ($p = 0.24$; Table 15). However, contrasts showed that the Fallow treatment had an average of 14% less soil Olsen-P than did all other treatments ($p = 0.03$) in a relatively well-endowed site for soil P – a result of the lack of plant biomass in the Fallow treatment. While livestock deposition of P-rich waste is thought to be one of the positive outcomes of grazing on cropland, this study showed little impact on soil Olsen-P from grazing. These results agree with Hatfield et al.

(2007) who noted that soil P concentrations were not different among sheep-grazed and ungrazed treatments after 2 y in Montana. Elsewhere, Costa et al. (2014) noted increases in soil P over 6 y in both grazed and ungrazed systems in Brazil, while Sainju et al. (2011) recorded decreases in Soil P in grazed spring wheat-fallow systems in Montana after 5 y of rotations. Without subsequent crop year data, it is difficult to make judgements about how soil P differed among cover crop treatments in this study. Ogejo et al. (2010) reported that a 29-kg sheep consumed 28 g P within a day and only returned ~7% (1.9 g P) to the soil through feces and urine, indicating that P can be lost from a cropping system via animal tissue. Further long-term analysis of soil Olsen-P levels in grazed versus ungrazed cover cropping systems would provide valuable information regarding soil Olsen-P dynamics in such systems.

Soil microbial biomass measured prior to spring wheat seeding at Fort Ellis (2016) showed no differences among treatments (*p* = 0.97) or groups of treatments (Table 16). A lack of treatment effect on soil microbial biomass may be the result of a short cover crop growing season and a lack of subsequent rotation years. Other studies have shown positive correlation between soil microbial biomass and cover cropping (Acosta-Martinez et al., 2011; Biederbeck et al., 2005; O'Dea, 2011; Housman, 2016); however, these studies were conducted for a duration of four years or more. Soil microbial biomass is highly variable with regard to environmental conditions like soil moisture and temperature (Lundgren and Soderstrom, 1983). Further, long-term study of the effects of ICLS may present a clearer conclusion regarding the implications of animal and cover crop integration in dryland wheat production and subsequent effects on microbial populations.

In terms of soil enzyme activity prior to spring wheat planting at Fort Ellis, Fallow treatments had 35%, 23%, and 36% less acid phosphatase ($p < 0.01$), alkaline phosphatase ($p = 0.04$), and β-glucosidase ($p = 0.05$; Table 17) activity then all other treatments, respectively. This effect is likely due to the absence of plant growth in 2015 in the Fallow treatment and subsequent lack of soil inputs (i.e. cover crop litter) which increase soil enzyme substrate input. A similar effect was noted in Acosta-Martinez et al. (2011), in which enzyme activity was strongly correlated with winter cover crop presence, regardless of grazing, in a 5-y study in Texas. Biederbeck et al. (2005) also noted a similar effect when comparing legume-wheat rotations to fallow-wheat rotations in Swift Current, Saskatchewan, after 6 y of rotations in which fallow-wheat rotations were significantly lower in dehydrogenase, acid phosphatase, and arylsulfatase than all other treatments.

Interestingly, acid phosphatase levels were also 45% higher in grazed treatments when compared to all other treatments ($p < 0.01$), indicating that grazing cover crops may enhance soil nutrient cycling. While treatments did not statistically differ in terms of Olsen-P, both acid and alkaline phosphatase were higher in cover cropped treatments than Fallow treatment. These results are in agreement, in part, with Housman (2016), who found 1.3 times greater acid phosphatase activity in cover cropped treatments compared to fallow treatments at a field site adjacent to the Fort Ellis study. While these results are likely due to the presence of both cover crops and grazing (high P, labile animal waste deposition) it was surprising that only 24 hr of mob-grazing by sheep, with trivial amounts of P deposition in feces and urine (~ 1 kg^{-1ha}), could cause an effect on soil 9-10 mo later. Further research demonstrating the long-term effects of cover cropping and grazing versus fallowing on soil enzyme activity may provide producers with more data regarding the implications of cover cropping for soil quality.

Agronomic Implications

The third objective of this study was to assess how changes in soil properties, catalyzed by grazing and cover cropping, affect subsequent wheat yields. At Fort Ellis, spring wheat yields did not differ between 2015 cover crop treatments ($p = 0.32$; Table 18). This was not surprising as wheat yield is closely correlated with available soil water (Peterson et al. 1996; Schillinger et al., 2012) and soil water prior to spring wheat planting at Fort Ellis did not differ among treatments. Several studies in the NGP and Montana (O'Dea, 2011; Tallman 2014; Housman, 2016) have noted statistical differences in stored soil water when comparing fallow treatments to cover cropped treatments; however, given the relatively high annual precipitation at Fort Ellis (500 mm) when compared to other parts of the NGP, it is not surprising that soil water was recharged over the course of a single winter.

Although cover crop treatments did not affect subsequent wheat yields, they influenced subsequent spring wheat grain protein where the Fallow treatment had the highest value (137 g kg^{-1}) and the Cool Graze treatment had the lowest value (132 kg ha^{-1}; $p = 0.04$). Spring wheat grain protein was 3 g kg^{-1} greater after Fallow compared with all other treatments ($p = 0.01$), while sprayed cover crop treatments had 2 g kg^{-1} greater grain protein than the grazed cover crop treatments ($p = 0.03$). This variation is due, in part, to the fact that Fallow treatments averaged 43 kg NO_3-N ha^{-1} greater than all other plots prior to spring wheat seeding (Table 12). Other studies in Montana have noted a similar deficit in soil NO_3-N following cover crops when compared to fallow (O'Dea, 2011; Housman, 2016).

It is likely that some biomass-N was removed from the grazed treatments in the form of livestock tissue. While pre-spring wheat planting soil NO_3-N values (Table 12) do not indicate a statistical difference between grazed and sprayed treatments, Table 14 shows that sprayed treatments had over 60% more PMN than grazed treatments and the grazed treatments had 22% more PMN than the swathed treatment (Warm Hay) prior to spring wheat seeding at Fort Ellis. These results imply that removal of cover crop biomass from plots – via grazing or swathing – leads to a reduction of soil N which may have important implications for wheat grain protein.

Unsurprisingly, spring wheat yields differed at the fertilization subplot level and ranged from 3.28 Mg ha^{-1} in the 0 kg N ha^{-1} subplot to 4.06 Mg ha^{-1} in the 135 kg N ha^{-1} subplot ($p < 0.01$; Table 18). Wheat grain protein also differed among fertilization subplots ranging from 129 g kg^{-1} in the 0 kg N ha^{-1} to 139 g kg^{-1} in the 135 kg N ha^{-1} subplot ($p < 0.01$).

Conclusions

Cover cropped treatments depleted soil water reserves slightly (~4 mm) in comparison to Fallow, but did not differ among cover crop treatments. Depletion of soil water led to a 0.22 Mg ha^{-1} decrease in spring wheat yield ($p = 0.06$) in cover crop treatments compared with Fallow after one cover crop – spring wheat rotation at Fort Ellis. Cover crop treatments also depleted soil Nitrate-N (41 kg ha^{-1}; $p < 0.01$) which likely led to decreased spring wheat protein levels (3 g kg^{-1}; $p < 0.01$) in comparison to Fallow. However, cover cropped treatments increased soil phosphate (16 kg ha^{-1}; $p =$ 0.03), acid (31%; $p < 0.01$) and alkaline (19%; $p = 0.04$) phosphatase enzyme activity, and β-glucosidase enzyme activity (26%; $p = 0.05$) in comparison to Fallow treatments. These results show that cover crops may have a negative effect on subsequent cash crop yields over the short-term, but have a potentially positive effect on soil quality. However, it should be noted that these results may be, in part, due to the brevity of this study which was conducted through a full cover crop-spring wheat rotation at one of the two sites (other site completed after this M.S. obligation). Soil quality changes slowly and short-term studies often fail to capture the long-term implications of diversified cropping rotations. Long-term analysis of cover cropping implications for soil quality and cash crop yields in dryland systems across multiple sites in Montana may tell a different story with regard to the benefits and draw backs of cover cropping.

While no formal economic analysis was conducted in this study, utilizing cover crops as livestock forage may be a viable way to offset the negative short-term effects of cover cropping in dryland what systems in Montana. Cover crop treatments produced both high- and medium-quality forage in both years at both sites, while cover crop biomass production, specifically in the cool-season mixtures, was comparable to other types of hay and forage produced in Montana. Furthermore, soil compaction in grazed cover crop treatments was not different from sprayed treatments implying that soil compaction may not be a significant drawback of grazing on cropland in Montana where seasonal freeze-thaw cycles likely help soils resist compaction from short duration livestock use.

Grazed cover crop treatments showed a negative effect on PMN levels compared to non-grazed cover crop treatments ($p = 0.01$) indicating that grazing may have important implications for nutrient cycling in dryland systems. However, soil microbial biomass and three-out-of-four soil enzymes did not statistically differ between grazed and non-grazed cover crop treatments. This may, again, have to do with the short duration of the study and it is likely that grazing cover crops for multiple years would produce different results, especially in regions of MT with higher precipitation and greater biomass production.

Further studies of the effects of cover cropping and grazing cover crops in dryland wheat systems in Montana should: 1) be conducted for longer durations; 2) encompass multiple study sites across the major wheat producing regions of Montana; and, 3) include an economic analysis assessing the market value of cover crop forage production. Including these analyses in future research would inform our understanding of the potential of incorporating cover crops and ICLS to build diverse, sustainable agricultural systems in Montana.

Table 1.1 Monthly precipitation and cover crop GDD (Tbase = 0 °C) at Fort Ellis and NGV, MT. Growing season is Apr–July. GDD calculated from day after seeding to day of termination for each cover crop mixture. Long-term average (LTA) calculated from 1981-2010, Western Regional Climate Center. WRCC station number and distance to field site are listed below site name.

	Fort Ellis (241044, 5.5 km)			NGV (240622, 14.5 km)	
	2015	2016	LTA	2016	LTA
Annual Precipitation (mm)	450	472	501	336	357
Annual Temperature (°C)	8.2	7.8	7.1	6.9	6.0
Growing Season Rainfall (mm)	214	166	254	155	193
Cover Crop Mixture	Cool	Warm		Cool	Warm
GDD (°C)	902	944		862	961

Table 1.2. Pre-planting soil characterization* of Fort Ellis and NGV, MT.

	Fort Ellis (2015)	NGV (2016)
Location	45.667°, -110.978°	45.904°, -111.154°
Elevation (m)	1493	1430
Soil Texture	Silt loam	Silt loam
pH	6.5	5.9
Soil Organic Matter (%)	5.3	2.6
Nitrate (mg kg^{-1})	9.1	4.8
Olsen P (mg kg^{-1})	56	39
Sample Date	24 Apr	6 May
Previous crop	Spring barley	Winter wheat

*All soil samples were composited from 6 cores per treatment plot to a depth of 15 cm and analyzed by AgVise Laboratories, Northwood, ND.

Table 1.3. Dates for agronomic management for cover crop mixtures and spring wheat at Fort Ellis and NGV, MT.

Event	2015	2016	2016
	---------Fort Ellis-------		--NGV--
Soil sample date	Apr 24	Apr 13	May 6
Cool-season cover crop seeding date	Apr 29	--	May 5
Cool-season cover crop stand counts	May 28	--	June 1
Cool-season cover crop pre-termination biomass	June30	--	July 4
Cool-season cover crop termination[†]	Jun 29	--	July 5
Cool-season cover crop post-termination biomass	July 2	--	July 6
Cover crop supplemental spraying (grazed plots)[†]	Aug 3	--	Aug 11
Soil sample date (NO_3 and H_2O only)	July 10	--	July 12
Warm-season cover crop seeding date	June 15	--	June 20
Warm-season cover crop stand counts	July 7	--	July 17
Warm-season cover crop pre-termination biomass	Aug 3	--	Aug 10
Warm-season cover crop termination[¨]	Aug 4	--	Aug 10
Warm-season cover crop post-termination biomass	Aug 5	--	Aug 11
Soil sample date (NO_3 and H_2O only)	Aug 17	--	Aug 18
Spring wheat seeding date	--	Apr 12	--
Spring wheat herbicide application[$]			
Spring wheat stand counts	--	May 10	--
Spring wheat biomass at antithesis	--	Jul 6	--
Spring wheat harvest date	--	Aug 17	--
First frost date (0 °C)*	Oct 3	Oct 6	Oct 6
Warm-season radish termination date (-4 °C)*	Nov 6	Oct 11	Oct 11

*****Data from Western Regional Climate center station (241044).

[†] 2.24 kg ha^{-1} glyphosate + 44 ml 10 g^{-1} AMS + 379 ml 10 g^{-1} MSP + 1449 ml ha^{-1} Sharpen® (N '-[2 -chloro-4-fluoro-5-(3-methyl-2, 6-dioxo-4-(trifluoromethyl)-3, 6-dihyd ro-1 (2 H)-pyrimidinyl)benzoyi]-N-isopropyi-N-methylsulfamide).

[¨] 1 kg ha^{-1} glyphosate + 44 ml 10 g^{-1} AMS + 30 ml L^{-1} Hel-Fire ® (Alkyl amine ethoxylate, monocarbamide dihydrogen sulfate, and 1,2,3-trihydroxypropane).

[$] 2 kg ha^{-1} glyphosate + 30 ml L^{-1} Hel-Fire ®

Table 1.4. Study treatments, termination methods and cover crop mixtures for year-1 at Fort Ellis and year-2 at NGV, MT.

Treatment	Termination Method	Cover Crop Mixture
1) Chemical-Fallow (Fallow)	None	None
2) Cool-season – graze (Cool Graze)	grazed by lambs and sprayed with Glyphosate	radish, pea and oat
3) Cool-season – spray out (Cool Spray)	sprayed with glyphosate	radish, pea and oat
4) Warm-season – graze (Warm Graze)	grazed by lambs and frost kill	radish, soybean and sorghum/millet*
5) Warm-season – spray out (Warm Spray)	Sprayed with Glyphosate and frost kill	radish, soybean and sorghum/ millet*
6) Warm-season – swath (Warm Hay)**	swathed and frost kill	radish, soybean and sorghum/ millet*

*Millet was substituted for sorghum in the warm-season mixture in year-2 as sorghum can produce toxic levels of prussic acid (hydrocyanic acid) and poison livestock (Sher et al., 2012).

** In year-2, due to low biomass growth, treatment 6 was swathed and the biomass was left on the plots to simulate mowing.

Table 1.5. Cover crop treatment biomass yield and quality at Ft. Ellis (2015) and NGV (2016), MT.

Treatment	Pre-termination Biomass		Post-termination Biomass		Pre-termination C:N*	
	2015	2016	2015	2016	2015	2016
P-values	*0.16*	***<0.01***	***<0.01***	*0.43*	***<0.01***	***<0.01***
	------ Mg ha^{-1} ------		-------- Mg ha^{-1} ------			
Cool Graze	4.65	2.59	1.41	0.22	19.4	17.8
Cool Spray	4.33	2.32	N/A	N/A	19.1	17.4
Warm Graze	4.04	1.10	1.43	0.16	15.0	12.0
Warm Spray	4.22	1.02	N/A	N/A	15.1	12.3
Warm Hay	4.09	1.14	0.28	0.27	14.9	12.8
LSD$_{0.05}$	NS	2.36	0.41	NS	1.80	2.24
Contrasts	-------------------------------- *P-values* --------------------------					
Cool v. Warm	***0.03***	***<0.01***	*N/A*	*N/A*	***0.04***	***<0.01***
Spray v. Graze	*0.70*	*0.20*	*N/A*	*N/A*	*N/A*	*N/A*

CG = Cool Graze, and WG = Warm Graze

*All cover crop species combined per plot.

† Results come from an omnibus ANOVA.

Table 1.6. Cover crop biomass means by species pre- and post-termination* in 2015 at Fort Ellis, Montana.

Species	Pre-Termination	Post-Termination
	------------------------ kg ha^{-1}	----------------------
Oat	1259	581
Pea	1454	330
Radish (cool)	1778	501
Radish (warm)	1049	244
Sorghum	2014	376
Soybean	1048	236
p-value	*<0.01*	*<0.01*
LSD$_{0.05}$	94	45

*Ungrazed treatments (CS and WS) not measured post-termination as biomass was not removed from these plots.

Table 1.7. Cover crop biomass means by species pre- and post-termination* in 2016 at NGV, Montana.

Species	Pre-Termination	Post-Termination
	------------------------ kg ha^{-1}	----------------------
Oat	854	61
Pea	1053	11
Radish (cool)	1086	195
Radish (warm)	456	108
Millet	344	74
Soybean	522	78

p-value	*<0.01*	*.08*
$\mathrm{LSD}_{0.05}$	76	N/A

*Ungrazed treatments (CS and WS) not measured post-termination as biomass was not removed from these plots.

Table 1.8. Treatment *P* values and means (g kg^{-1}) of cover crop mixtures from grazed and hayed plots at Fort Ellis (2015) and NGV (2016), MT. Dry matter (DM), crude protein (CP), acid-detergent fiber (ADF), neutral-detergent fiber (NDF), total digestible nutrients (TDN), and Relative Feed Value (RFV).

Treatment	DM	CP	ADF	NDF	TDN	RFV	DM	CP	ADF	NDF	TDN	RFV
p-value	*0.63*	*0.02*	*0.02*	*0.01*	*0.02*	*0.02*	*0.26*	*<0.01*	*0.02*	*0.41*	*0.02*	*0.24*
	----------------------- 2015 -----------------------						----------------------- 2016 -----------------------					
CG	907	158	426	526	540	99	901	155	351	475	625	121
WG	908	229	370	488	604	115	889	224	274	475	711	149
WH	914	185	370	561	604	100	899	212	303	430	680	130
$LSD_{0.05}$	NS	41	37	39	42	11	NS	28	49	NS	54	NS

CG = Cool Graze, WG = Warm Graze, and WH = Warm Hay

RFV Index = DDM x DMI / 1.29, where:

DDM = Digestible Dry Matter = 88.9 – (0.779 x %ADF) on a dry matter basis

DMI = Dry Matter Intake = 120 / %NDF on a dry matter basis

Table 1.9. Soil penetration resistance measured 13 Apr 2016 prior to wheat planting, following 2015 cover crop treatments, Fort Ellis, MT

	Depth (cm)			
Treatment	0 - 7.5	7.5 - 15	15 - 22.5	22.5 - 30
p-values	*0.15*	***<0.01***	***<0.01***	*0.26*
	-----------------------------kg cm^{-1}-------------------------			
Fallow	7.2	8.2	7.9	8.0
Cool Graze	7.0	10.6	10.9	9.3
Cool Spray	8.3	10.0	9.5	9.4
Warm Graze	6.3	8.9	9.1	9.1
Warm Spray	6.3	9.4	8.9	8.1
Warm Hay	7.5	8.6	7.8	8.3
LSD$_{0.05}$	NS	1.1	1.5	NS
Contrast	----------------------- *p*-values---------------------			
Fallow v. All	*0.33*	***<0.01***	***0.03***	*0.17*
Cool v. Warm	*0.10*	***<0.01***	***<0.01***	*0.09*
Spray v. Graze	*0.28*	*0.94*	*0.13*	*0.41*

Table 1.10. Soil bulk density measured 13 Apr 2016 prior to wheat planting, and following 2015 cover crop treatments, Fort Ellis, MT.

	Depth (m)		
Treatment	0 - 0.3	0.3 - 0.61	0.61 - 0.91
p-values	*0.51*	*0.99*	*0.44*
	----------------- kg cm^3 -----------------		
Fallow	1.31	1.37	1.32
Cool Graze	1.35	1.41	1.33
Cool Spray	1.29	1.42	1.22
Warm Graze	1.34	1.34	1.32
Warm Spray	1.34	1.49	1.37
Warm Hay	1.38	1.47	1.26
LSD$_{treat}$	NS	NS	NS
Contrasts	---------------- *p*-values---------------		
Fallow v. All	*0.13*	*0.72*	*0.37*
Cool v. Warm	*0.34*	*0.86*	*0.66*
Spray v. Graze	*0.40*	*0.86*	*0.14*

Table 1.11. Soil water (mm water equivalence) measured after cover crop termination, at Fort Ellis, MT, 2015, and NGV, MT, 2016.

	Fort Ellis 2015				NGV 2016			
Treatment	0 to 0.3 m	0.3 to 0.61 m	0.61 to 0.91 m	Total	0 to 0.3 m	0.3 to 0.61 m	0.61 to 0.91 m	Total
p-value	***<0.01***	***<0.01***	***<0.01***		***<0.01***	***<0.01***	***<0.01***	
	------------------------------------- Soil Water mm^{-1} -------------------------------------							
Fallow (Cool)	9.0	9.1	8.0	26	8.3	6.5	4.9	20
Fallow (Warm)	9.9	9.9	8.4	28	7.0	5.8	5.0	18
Cool Graze	5.6	6.0	6.5	18	6.2	3.9	4.0	14
Cool Spray	5.4	5.6	5.9	17	6.2	3.8	3.9	14
Warm Graze	6.1	7.7	7.6	21	4.7	4.8	4.5	14
Warm Spray	7.4	6.7	7.1	21	4.9	4.7	4.5	14
Warm Hay	7.7	7.2	7.5	22	5.3	5.0	4.7	15
$LSD_{0.05}$	1.3	1.1	0.7		0.7	0.7	0.6	
Contrasts	------------------------------------- *p* -values -------------------------------------							
Fallow v. All	***<0.01***	***<0.01***	***<0.01***		***<0.01***	***<0.01***	***<0.01***	
Cool v. Warm	***<0.01***	***<0.01***	***<0.01***		***<0.01***	***<0.01***	***<0.01***	
Spray v. Graze	*0.2*	*0.6*	*0.4*		*0.67*	*0.59*	*0.81*	

Table 1.12. Soil water (mm water equivalence) and nitrate (kg ha^{-1}), measured on 12 Apr 2016, prior to planting wheat and following 2015 cover crop treatments, Fort Ellis, MT.

	Soil Water			Soil NO_3-N		
Treatment	0 to 0.3 m	0.31 to 0.6 m	0.61 to 0.9 m	0 to 0.3 m	0.31 to 0.6 m	0.61 to 0.9 m
p-values	0.09	*0.54*	*0.82*	*0.06*	***<0.01***	***0.02***
	----------------Soil Water mm^{-1} ------------			------------- Soil NO_3-N kg ha^{-1} -----------		
Fallow	94	87	80	30	39	28
Cool Graze	87	85	78	25	24	18
Cool Spray	90	84	78	24	22	16
Warm Graze	90	86	77	18	14	12
Warm Spray	91	84	80	13	16	21
Warm Hay	91	83	80	16	17	15
LSD$_{0.05}$	NS	NS	NS	NS	3.6	8.6
Contrasts	--- *p-values*--					
Fallow v. All	***0.02***	*0.17*	*0.57*	***0.02***	***<0.01***	***<0.01***
Cool v. Warm	*0.13*	*0.93*	*0.67*	***0.03***	***<0.01***	0.50
Spray v. Graze	*0.19*	*0.36*	*0.45*	*0.40*	*0.87*	*0.87*

*Results come from an omnibus ANOVA.

Table 1.13. Soil Nitrate-N (NO_3-N) measured after cover crop termination, at Fort Ellis, MT, 10 Jul 2015, and NGV, MT, 12 Jul 2016.

	Fort Ellis 2015				NGV 2016			
Treatment	0 to 0.3 m	0.31 to 0.6 m	0.61 to 0.9 m	Total	0 to 0.3 m	0.31 to 0.6 m	0.61 to 0.9 m	Total
p-value	***<0.01***	***<0.01***	*0.60*		***<0.01***	***<0.01***	***<0.01***	
	-- kg ha^{-1} --							
Fallow (Cool)	31	12	10	53	24	7	11	42
Fallow (Warm)	23	13	12	48	30	12	12	54
Cool Graze	8	3	6	17	7	3	18	28
Cool Spray	6	2	6	14	10	3	5	18
Warm Graze	13	2	10	25	12	3	6	21
Warm Spray	17	4	10	31	14	5	8	27
Warm Hay	7	3	6	16	12	5	8	25
LSD$_{0.05}$	10	4	NS		9	4	11	
Contrasts	-- *p* -values --							
Fallow v. All	***<0.01***	***<0.01***	*0.64*		***<0.01***	*0.19*	*0.67*	
Cool v. Warm	***0.01***	*0.41*	*0.33*		*0.08*	*0.07*	*0.24*	
Spray v. Graze	***<0.01***	***<0.01***	*0.22*		***<0.01***	***<0.01***	*0.50*	

Table 1.14. Soil PMN (kg NH_4 ha^{-1}; standard error) measured 13 Apr 2016 prior to wheat planting, Fort Ellis, MT. An omnibus ANVOA showed no treatment effect (p = 0.07).

Treatment	Fallow	Cool Graze	Cool Spray	Warm Graze	Warm Spray	Warm Hay
PMN (kg NH_4 ha^{-1})	28.6 (2.70)	26.5 (3.92)	42.9 (4.70)	24.6 (4.16)	40.7 (4.00)	20.8 (3.52)

Contrasts	Fallow v. All	Cool v. Warm	Spray v. Graze	CG v. WG	WG v. WH
p-values	*0.68*	*0.25*	***0.01***	*0.50*	*0.13*

Table 1.15. Pre-planting soil phosphate (ppm; standard error) measured 13 Apr 2016 prior to wheat seeding and following cover crops, Fort Ellis, MT. An omnibus ANOVA showed no treatment effect (*p* = 0.24).

Treatment	Fallow	Cool Graze	Cool Spray	Warm Graze	Warm Spray	Warm Hay
	54.0 (2.48)	60.7 (2.74)	62.1 (3.89)	63.8 (4.16)	59.8 (2.62)	59.8 (1.30)
Contrasts	Fallow v. All	Cool v. Warm	Spray v. Graze	CG v. WG	WG v. WH	
p-values	***0.03***	*0.87*	*0.66*	*0.24*	*0.88*	

Table 1.16. Pre-spring wheat seeding and following cover crops soil microbial respiration rate (μl CO_2 g^{-1} soil h^{-1}) measured on 13 Apr 2016, Fort Ellis, MT (*p* = 0.97).

Treatment	Fallow	Cool Graze	Cool Spray	Warm Graze	Warm Spray	Warm Hay
	140 (3.08)	138 (1.75)	144 (2.00)	142 (1.76)	143 (1.71)	144 (1.36)
Contrast	Fallow v. All	Cool v. Warm	Spray v. Graze			
p-values	*0.74*	*0.75*	*0.55*			

Table 1.17. Soil enzyme activity, measured 13 Apr 2016, prior to wheat planting and following cover crops, Fort Ellis, MT. Mean treatment values of soil enzyme activity represent mg of p-nitrophenol (PN) produced per kg soil per hour.

Treatment	β-Glucosaminidase	Acid Phosphatase	Alkaline Phosphatase	β-Glucosidase
p-values	*0.21*	***<0.01***	*0.32*	*0.11*
	---------------------------- mg PN kg^{-1} soil h^{-1} --------------------------			
Fallow	154 (6.52)	215 (6.21)	224 (7.10)	139 (5.64)
Cool Graze	204 (6.18)	377 (2.05)	291 (4.37)	209 (6.37)
Cool Spray	180 (4.54)	287 (6.87)	266 (4.91)	155 (5.52)
Warm Graze	223 (7.53)	363 (9.38)	283 (5.95)	193 (6.85)
Warm Spray	174 (4.58)	287 (8.18)	262 (7.85)	218 (3.12)
Warm Hay	164 (4.85)	235 (14.7)	279 (3.74)	168 (6.85)
$LSD_{0.05}$	NS	84.3	NS	NS
Contrasts	--------------------------------- *p*-values -----------------------------			
Fallow v. All	*0.14*	***<0.01***	***0.04***	***0.05***
Cool v. Warm	*0.79*	*0.17*	*0.85*	*0.57*
Spray v. Graze	*0.09*	***<0.01***	*0.29*	*0.51*

Table 1.18. Means for cover crop treatment effects on subsequent spring wheat at three N fertilizer rates on spring wheat at Fort Ellis, MT 2016.

Source of variation*	Wheat Yield	Wheat Seed Protein
	------------- *p*-values ------------	
Treatment	*0.32*	***0.04***
Block	***<0.01***	***<0.01***
Fertilizer	***<0.01***	***<0.01***
Treatment x Fertilizer	*0.69*	*0.67*
Treatment	---- Mg ha^{-1} ----	----- g kg^{-1} ----
Fallow	3.87	137
Cool Graze	3.72	132
Cool Spray	3.70	135
Warm Graze	3.73	133
Warm Spray	3.57	135
Warm Hay	3.68	133
LSD$_{0.05}$	NS	4
Fertilizer Rate		
0 kg N ha^{-1}	3.3	129
68 kg N ha^{-1}	3.8	134
135 kg N ha^{-1}	4.1	139
LSD$_{0.05}$	0.2	3
Contrasts	----------- *p*-values ----------	
Fallow v. All	*0.06*	***0.01***
Cool v. Warm	*0.51*	*0.99*
Spray v. Graze	*0.32*	***0.03***

*Results come from omnibus ANOVA

References

Acosta-Martinez, V., T.M. Zobeck, and V. Allen. 2004. Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci. Soc. Am. J. 68: 1875-1884.

Acosta-Martinez, V., M.M. Mikha, and M.F. Vigil. 2007. Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat-fallow for the Central Great Plains. App. Soil Eco. 37:41-52.

Acosta-Martinez, V., R. Lascano, F. Calderon, J.D. Booker, T.M. Zobeck, and D.R. Upchurch. 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Bio. Fert. Soils 47: 655-667.

Assmann, T.S, M. A. de Bortolli, A.L. Assmann, A. B. Soares, C. S. Rocha Pitta, A.J. Franzluebbers, C. L. Glienke, J.M Assmann. 2014. Does cattle grazing of duel purpose wheat accelerate the rate of stubble decomposition and nutrients released? Agric., Ecosyst., & Envi. 190: 37-42.

Bardgett, R. D., D. A. Wardle. 2010. Ecosystem-level significance of aboveground consumers. (pp 113-167). In: Aboveground-Belowground Linkages: Biotic Interactions, Ecosystem Processes, and Global Change. Oxford University Press. Oxford, U.K.

Bedell, T.E. 1967. Estimated digestibility of diets of cattle and sheep grazing two pasture mixtures. Pro. West. Sect. Amer. Soc. Anim. Sci. 18: 225-230.

Biederbeck V.O., O.T. Bouman, C.A. Campbell, L.D. Bailey, and G.E. Winkleman. 1996. Nitrogen benefits from four green-manure legumes in dryland cropping systems. Can. J. Plant Sci. 76: 307-315.

Biederbeck, V.O., R.P. Zentner and C.A. Campbell. 2005. Soil microbial populations and activities as influenced by legume green fallow in a semiarid climate. Soil Biol. and Biochem. 37: 1775-1784.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179-192.

Collins, M. 1988. Composition and fiber digestion in morphological components in alfalfa-timothy sward. Anim. Feed Sci. Tech. 19:135-143.

Cutforth, H.W., B.G. McConkey, D. Ulrich, P.R. Miller, and S.V. Angadi. 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian prairie. Can.J. Plant Sci. 82: 681-686.

Dick, R.(ed.). 2011. Methods of Soil Enzymology. SSSA Book Ser. 9. SSSA and ASA. Madison, WI.

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Hardwood, J.M. Squire, and C.C Sheaffer. 2000. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93: 319-325.

Fracasso, A., L.M. Trindade, S. Amaducci. 2016. Drought stress tolerance strategies revealed by RNA-Seq in two sorghum genotypes with contrasting WUE. BMC Plant Biol. 16: 1-18.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Till. Res. 82: 121-145.

Hatfield, P.G., R.A. Field, J.A. Hopkins, and R. W. Kott. 2000. Palatability of wethers fed an 80% barley diet processed at different ages and of yearling wethers grazed on native range. J. Animal Sci. 78:1779-1785.

Hatfield, P.G., H.B. Goosey, T.M. Spezzano, S.L. Blodgett, A.W. Lenssen, and R.W. Kott. 2007. Incorporating sheep into dryland grain production systems: III. Impact on changes in soil bulk density and soil nutrient profiles. Small Rumin. Res. 67: 222-232.

Helms, T.C., E.L. Deckard, and P.A. Gregoire. 1997. Corn, sunflower, and soybean emergence influenced by soil temperature and soil water content. Agron. J. 89:59-63.

Housman, M.L. 2016. Multi-species cover crops in the northern Great Plains: An ecological perspective on biodiversity and soil health. MS Thesis. Montana State University, Bozeman, MT. 160 pp.

Jones, C., R. Kurnick, P. Miller, K. Olson-Rutz, C. Zabinski. 2015a. 2015 Montana cover crop survey results. Montana State University, Bozeman, MT. http://landresources.montana.edu/soilfertility/documents/PDF/reports/2015CCSurveyReport.pdf.

Jones, C., P. Miller, M. Burgess, S. Tallman, M. Housman, J. O’Dea, A. Bekkerman, and C. Zabinski. 2015b. Cover cropping in the semi-arid west: Effects of termination timing, species, and mixtures on nitrogen uptake, yield, soil quality, and economic return. Proc. Western Nutrient Manag. Conf. 5-6 Mar 2015. Reno, NV. 11:39-45. https://www.ipni.net/ipniweb/conference/wnmc.nsf/e0f085ed5f091b1b852579000057902e/4be3031d1d87927a85257e37004fa7a8/$FILE/00%20WNMC15%20Title%20Page%20&%20Table%20of%20Contents.pdf

Keeney, D. 1982. Nitrogen – availability indices. (pp. 711–733) In: Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. ed. S. Segou. SSSA, Madison, WI.

Kott, R.W. 2007. Montana farm and flock sheep production handbook. Montana State University Extension Publication. Bozeman, MT. [http://animalrangeextension.montana.edu/sheep/handbook-TOC.html].

Kou, S. 1996. Phosphorous. p. 869-915. In: Methods of Soil Analysis, Part 3. Chemical Methods. Eds D.L. Sparks. SSSA Book Ser. 5. SSSA and ASA. Madison, WI.

Lalman, D. 2004. Nutrient requirements of beef cattle. Oklahoma State University Extension Publication. Stillwater, Ok. pp. 24

Lloveras, J. 1990. Dry matter yield and nutritive value of four summer annual crops in north-west Spain (Galicia). Grass For. Sci. 45: 243-248.

Lu, Y.C., K.B. Watkins, J.R Teasdale, and A.A. Abdul-Baki. 2000. Cover crops in sustainable food production. Food Rev. Intern. 16: 121-157.

Lundgren, B. and B. Soderstrom. 1983. Bacterial numbers in a pine forest soil in relation to environmental factors. Soil Biol. Biochem. 15: 625-630.

McCauley, A., C. Jones, P. Miller, M. Burgess, and C. Zabinski. 2012. Nitrogen fixation by pea and lentil green manures in a semi-arid cropping system: Effect of planting and termination time. Nutr. Cycl. Agroecosyst. 92: 305-314.

Miller, P.R., and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the northern Great Plains. Agron. J. 97:189-200.

Miller, P.R., A. Bekkerman, C. A. Jones, M. H. Burgess, J. A. Holmes, and R.E. Engel. 2015. Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. Agron. J. 107: 541-550.

Montana Dept. Commerce. 2017. Census & economic information center – select Montana agricultural commodities dashboard. http://ceic.mt.gov/Economics/AgricultureDashboard.aspx. [Verified: Jan 2, 2017].

Nielsen, D.C., D.J. Lyon, R.K. Higgins, G.W. Hergert, and J.D. Holman. 2015. Cover crop effect on subsequent wheat yield in the central Great Plains. Agron. J. 108: 243-256.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland dropping systems in the Great Plains. Agron. J. 97: 364-372.

O' Dea, J.K. 2011. Greening summer fallow: Agronomic and edaphic implications of legumes in dryland wheat agroecosystems. MS Thesis, Montana State University, Bozeman, MT. 145 pp.

Ogejo, J.A., S. Wildeus, P. Knight, and R.B. Wilke. 2010. Estimating goat and sheep manure production and their nutrient contribution in the Chesapeake Bay watershed. Appl. Eng. Agric. 26: 1061-1065.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorous. (pp 403-430). In: Methods of Soil Analysis, Part 2, 2nd Ed. Eds: A.L. Page. Agron. Mongr. No. 9 ASA and SSA. Madison, WI.

Or, D., and J.M. Wraith. 1999. Soil water content and water potential relationships. (pp A53-A85). In: Handbook of Soil Science. Eds. M. Summer. CRC Press, Boca Raton, FL.

Parham, J.A., and Deng, S.P. 2000. Detection, quantification and characterization of β-glucosaminidase activity in soil. Soil Biol. Biochem. 32: 1183–1190.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Ag. 9: 180-186.

Ruess, L., and H. Ferris. 2004. Decomposition pathways and successional changes. Nematology Monographs and Perspectives. 2: 547-556.

Sainju, U.M, B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil & Till. Res. 63: 167-179.

Sainju, U.M., A.W. Lessen, H.B. Goosey, E. Snyder, and P.G. Hatfield. 2011. Sheep grazing in a wheat-fallow system affects dryland soil properties and grain yield. Soil Sci. Soc. Am J. 75: 1789-1798.

Serba, D.D. and R.S. Yadav. 2016. Genomic tools in pearl millet breeding for drought tolerance: Status and prospects. Front Plant Sci.7. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5118443/.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66: 1296-1303.

Schillinger, W.F., S.E. Schofstoll, and J. R. Alldredge. 2012. Predicting wheat grain yields based on available water. Washington State University Extension Publication. Pullman, MT. pp. 7. http://cru.cahe.wsu.edu/CEPublications/EM049E/EM049E.pdf.

Tallman, S.M. 2014. Cover crop mixtures as partial summerfallow replacement in the semi-arid northern Great Plains. MS Thesis, Montana State University, Bozeman, MT. 146 pp.

Tanaka, D.L., A. Bauer, and A.L. Black. 1997. Annual legume manures and conservation tillage for grain sorghum production on prairie soil. Soil Sci. Soc. Am. J. 58: 1518-1524.

USDA Farm Service Agency. 2016. Crop Acreage Data. https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index. [Verified: 2 Jan 2017].

USDA-NRCS. 2009. Radishes: A new cover crop option. Crops & Soils: 14-17. ASA, Madison, WI. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022940.pdf.

USDA-NRCS. 2016. Warm season cover crops and planting specifications. Plant Materials Technical Note (No: TX-PM-16-01). Washington, D.C. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/etpmctn12917.pdf.

van Kessel, C., and C. Hartley. 2000. Agricultural management of grain legumes: Has it led to an increase in nitrogen fixation? Field Crops Res. 65: 165-181.

Vaz, C.M.P., L.H. Bassoi, J. W. Hopmans. 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer -TDR probe. Soil Till. Res. 60: 35-42.

Wardle, D.A., K.I. Bonner, and G.M. Barker. 2002. Linkages between plant litter decomposition, litter quality and vegetation responses to herbivores. Funct. Ecol. 16: 585-595.

Wardle, D. A., R. D. Bardgett. 2004. Human-induced changes in large herbivorous mammal density: The consequences for decomposers. Front. Ecol. Environ. 2: 145-153.

West, A.W., and G.P. Sparling. 1986. Modifications to the substrate-induced respiration method to permit measurement of microbial biomass in soils of differing water contents. J. Microbiol. Meth. 5: 177-189.

Western Regional Climate Center. 2016. Historical climate data. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt1050. [Verified: 20 Dec 2016].

Vigil, M.F. 2013. Standing crop residues and wind erosion. Southeast Area Extension Circular Farm and Ranch Newsletter. 1(3): 1-11.

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68: 1403-1409.

CHAPTER THREE

GIS LAND SUITABILITY ANALYSIS FOR WARM-SEASON COVER CROPPING AND INTEGRATED CROP-LIVESTOCK SYSTEMS ADOPTION: A CASE STUDY OF FOUR MONTANA COUNTIES

Introduction

Modern cropping systems in the northern Great Plains and Montana are often highly specialized and focus on the production of one or two major cereal crops (NASP, 2010; Tanaka et al., 2010). Wheat (*Triticum aestivum* L.) is the most commonly planted crop in Montana and is often cultivated under dryland conditions (Ford and Krall, 1979; Tanaka et al., 2010). However, many dryland wheat systems in Montana rely on both summerfallow for soil water recharge and external inputs like fertilizers and pesticides for increased yields; practices which may not be sustainable in the long run. The practice of summerfallow leads to increased soil erosion (Tanaka et al., 2010), decreased soil organic matter (Campbell et al., 2000), and lower soil biological activity (Acosta-Martinez, 2007). Reliance of external inputs, including fertilizers and pesticides, can lead to a host of environmental consequences including increased energy use, greenhouse gas production, and impairment of water quality (Russelle et al., 2007; Sulc and Franzluebbers, 2014).

Two relatively simple sustainable agronomic practices that may increase long-term sustainability of dryland wheat systems in the Montana are: 1) utilizing warm-season cover crops as fallow replacement; and 2) building integrated crop-livestock systems (ICLS).

Cover crops can be single species or mixtures of species that alter soil properties by enhancing nutrient cycling (Lu et al., 2000), increasing soil organic matter and soil structure (Zentner et al., 2004), increasing bioturbation (Williams and Weil, 2004), decreasing erosion (Tanaka et al., 1997), and suppressing weed growth (Fisk et al., 2000). Furthermore, the addition of warm-season crops to cool-season dominated cropping systems offers enhanced diversity to cropping systems which may subsequently enhance systems resilience and robustness (Snapp et al., 2005; Anderson, 2008; Florence, 2016). Capitalizing on warm-season cash crops is not a reliable agronomic strategy along the northern Rocky Mountain front due to a spring-centric rainfall pattern. Most often there is adequate plant biomass yield that does not translate to grain yield due to insufficient late season rainfall (Miller and Holmes, 2005). However, cover crops are not grown for a marketable cash crop, rather they are often left on the soil as a green or green manure as a plant biomass input to soil. Alternatively, warm-season cover crops could be used as livestock forage which would help offset some of the costs associated with cover cropping, and still provide net positive plant biomass inputs.

Building ICLS involves re-coupling crop and livestock systems which may reduce the need for external inputs (i.e. fertilizers, herbicides, etc.) as livestock deposit N- (Bardgett and Wardle, 2010; Assmann et al., 2014) and P-rich excretions on the landscape (Costa et al.; 2014). While some nutrients, including N and P, are removed from grazed systems in the form of animal tissue (Hatfield et al., 2000), several studies have shown an overall improvement of soil quality following crop-livestock integration (Acosta-Martinez et al., 2004; Tracy and Zhang, 2008; Assmann, 2014). While the presence of livestock grazing on cropland may enhance nutrient cycling and benefit cash crops (Acosta-Martinez et al., 2004), further research is needed to fully understand the impacts of grazing on cropland and soil nutrient cycle dynamics (Russelle et al., 2007), especially in semiarid regions. Overall, integrating crops and livestock increases cropping systems complexity and ultimately enhances sustainability of crop and livestock production (Sulc and Franzluebbers, 2014).

In Montana, aptness for warm-season cover crop growth and ICLS adoption is unstudied. Put simply, there is little knowledge about where in Montana the climates and geographies of crop and livestock production are suitable for warm-season cover cropping and potentially coincident ICLS adoption. A first step in addressing the existing knowledge gap is to examine the spatial relationships among climate, livestock, and wheat production in Montana. Assessing suitability as well as distances between crop and livestock operations may offer insight for producers and land managers regarding: 1) where warm-season cover crop growth and adoption is potentially viable, and 2) where, from a spatial perspective, conditions exist that would support coupling of livestock and crop production.

Geographic Information Systems (GIS) technology may offer an efficient means of identifying opportunities for planning warm-season cover crop and ICLS adoption in Montana. GIS land suitability analysis (LSA) is a common approach used by land managers across multiple disciplines to identify optimal location(s) for particular land uses. LSA, in a broad sense, examines spatial relationships among multiple data sets to search for or predict land-use potential of an area based on pre-determined criteria for a particular activity (Hopkins, 1977; Malczewski 2004). LSA is increasingly being used in agricultural land-use planning practices including land suitability for specific crop production (Akinci et al., 2013; Kkadivko et al., 2014; Boitt et al. 2015) and grazing potential (Barbari et al., 2006; Amiri et al., 2012). However, no published research has utilized LSA to identify regions with high potential for warm-season cover crop growth or crop-livestock integration among ranchers and farmers in the northern Great Plains, specifically, Montana.

Readily available public data can be used in an LSA to map land suitability for the adoption of both warm-season cover cropping and ICLS. This research sought to identify areas within four study counties in Montana that may be suitable for warm-season cover crop production and ICLS adoption based on a GIS analysis of data encompassing: 1) agronomic factors i.e. commodities produced; 2) environmental factors i.e. climate data; and, 3) logistical factors i.e. distances between relevant crop and livestock operations.

Methods

Study Areas

The study areas included four exemplary counties in Montana including: Fallon, Fergus, Hill, and Stillwater (Figure 1). These counties were selected because: 1) in all four counties, wheat and livestock production are the predominant land use; and, 2) the counties extend across temperature and rainfall gradients in Montana (ACSL, 2016; USDA-NASS, 2017). The average annual precipitation in the study areas ranges from 256 to 1,404 mm with greater precipitation occurring in high elevation areas (ACSL, 2016). Elevation in the study areas ranges from 712 to 3526 m; however, most land above 2280 m was excluded from analysis due to lack of suitability for crop production. The predominant crop in the study areas, as well as in Montana in general, is wheat (USDA-NASS, 2017).

Laboratory Analyses

All analyses were conducted using Arcmap 10.1.3 GIS Software (2015; Esri, Redlands, CA). All data used were publicly available datasets distributed by various institutions (Table 1). The final products of these analyses are displayed in map form for ease of use by local producers, government institutions, and other land managers.

Warm-Season Cover Crop Land Suitability

Land suitability for warm-season cover crop growth was determined by combining the following environmental and agronomic data layers: 1) 30-yr mean precipitation (1981-2010) for June, July, and August (ACSL, 2016); 2) 30-yr mean June temperature (1981-2010; ACSL, 2016); and 3) the Cropland Data Layer (CDL) showing land planted in all varieties of wheat (i.e. wheat production) anytime from 2012 to 2016 (USDA-NASS, 2017).

Each layer was first converted to raster and then, as necessary, resampled using the Nearest Neighbor method to a 30-m spatial resolution using the Resample Tool (Data

Management) to enhance processing speed and accuracy. Then, the Reclassify Tool (Spatial Analyst) was used to assign score class values (0-3) to each respective variable creating a simple suitability index for each individual parameter. Variable score classes are listed in Table 2 where a reclassified variable score (index) of "0" is considered least suitable and a score of "3" is considered most suitable. Reclassification of variables into score classes allowed for faster processing in Arcmap and a cleaner map in terms of final suitability score (discussed further below).

Precipitation score classes were chosen under the assumption that warm-season cover crops produce approximately 25 kg of biomass per hectare for every 1 mm of precipitation during the growing season (Lenssen and Cash, 2011). Given this assumption, for every 40 mm of soil moisture and precipitation, 1 tonne ha^{-1} of warm-season cover crop biomass is produced. So, precipitation score classes were set in increments of 40 mm of available water for plant growth and (i.e. stored soil water and precipitation) ranging from < 40 mm (score of '0') to > 120 mm (score of '3'; Table 2) Two variations of available water for plant growth were run in this model – one with no change to the precipitation raster cell values (i.e. original data) and one that accounted for an additional 50 mm of stored soil water. The Plus Tool (Spatial Analyst) was used to add 50 mm to each raster cell value of the original precipitation raster. While 50 mm is a conservative credit, it reflects a common amount of soil water used by cover crops at various locations in Montana (Tallman, 2014; Housman, 2016).

Temperature score classes were determined based on the assumption that soil temperature at a 0-30-cm depth can range from 1.5°C to over 6°C greater than ambient air temperature at certain times during the day (Toy et al., 1978; Dwyer et al., 1990; Barman et al., 2017). . So, for every 1°C in air temperature, soil temperature was assumed to be approximately 4°C warmer. Many warm-season crops require a minimum soil temperature of ~12.5°C to germinate (Hsu et al., 1985; Langell et al., 1998; Gerik et al., 2003). Under these assumptions, at 12.79°C average ambient air temperature, soil temperature would be high enough (16.79°C) to support warm-season plant germination. Therefore, 12.79°C air temperature was set as a minimum mean June temperature for warm-season germination and growth. Using the Reclassify Tool (Spatial Analyst), raster cells with a temperature value </= to 12.79°C received a score of '0', while cells with a value of 12.79 – 14.44°C received a score of '1', cells with a value of 14.45 – 17.22°C received a score of '2', and cells with a value >17.23 received a score of '3'. Temperature score classes were set to reflect the increased likelihood of warm-season germination and enhanced growth based on the findings of Helms et al. (1997) in which a strong linear trend between warm-season crop germination and soil temperature increases is noted (Table 2).

While many agronomic LSAs incorporate a suite of soil parameters when determining suitability for crop growth (Boitt et al., 2015; El Baroudy, 2016; Tiemen et al., 2016), this model used wheat production as a proxy for appropriate soil conditions under the assumption that cover crops soil requirements closely match those of cash crops pending appropriate management. Wheat production was determined by selecting 30 by 30 m pixels of land on which wheat (all varieties) was grown at least once from 2012 to 2016 (CDL). The Majority Filter Tool (Spatial Analyst) was run on the CDL three times to remove anomalous and likely misidentified pixels of wheat production. The Majority Filter Tool replaces cells in a raster based on the majority values of the four contiguous neighboring cells (ESRI, 2016). Next, the “Select by attributes” (Data Management) was used to select contiguous wheat pixels larger than 1 ha to further filter anomalous wheat production pixels. The resulting layer showed land planted in all varieties of wheat from 2012 to 2016. Land (pixels) where wheat production occurred at least once from 2012 to 2016 was assigned a value of “3”, while all other land (pixels) received a value of “0” (i.e. where wheat was not planted).

After reclassifying variables with a score between 0 and 3, Raster Calculator (Spatial Analyst) was used to weight and combine each variable with a resulting model of:

Eq. 1 Suitability = Temperature[¨] * 0.25 + Precipitation[†] * 0.25 + Wheat Production[β] * 0.5

[¨] 30 yr (1981-2010) mean June temperature.

[†] 30 yr (1981-2010) mean precipitation for the months of Jun, Jul, and Aug combined. Additional 50 mm of precipitation added to one iteration of the model to account for stored soil moisture.

[β] Land planted in all varieties of wheat from 2012 to 2016; CDL wheat spatially joined with MCDL ownership parcels.

where temperature and precipitation are weighted equally as both temperature and precipitation must reach particular thresholds to promote warm-season germination and biomass production. Wheat Production was weighted the heaviest in Eq.1 as this variable both excludes land without wheat production from the analysis and accounts for appropriate soil conditions. For each study area, the resulting raster dataset was symbolized to show pixels with warm-season cover crop suitability scores of: less than 1.75 (Low Suitability), 1.76 to 2.25 (Medium Suitability), and greater than 2.25 (High Suitability). The lowest possible score in Eq. 1 was 0, while the highest possible score was 3. The number of hectares of land that fell within each score class were recorded for both iterations of the model. The final maps show land suitability for warm-season cover crop adoption in the four study counties at a resolution of 30 x 30 m.

Integrated Crop-Livestock Land Suitability

Land Suitability for ICLS adoption was determined using Montana Cadastral Data Layer (MCDL; State of MT, 2016) and the CDL showing land planted in all varieties of wheat planted from 2012 to 2016 (USDA-NASS, 2017). Overall, few georeferenced grazing or livestock datasets are available in Montana. Several datasets exist which can be used to infer the presence of grazing (i.e. land classification data, cadastral data, etc.); however, extensive research uncovered no publicly available GIS data that indicate where, definitively, livestock grazing occurs on the landscape. The MCDL, however, does include a great deal of information regarding the land uses associated with any given parcel, including the number of hectares used for livestock grazing (“grazing hectares”). These values can be used to estimate the amount of specific types of land use in a given parcel. For these reasons, it was determined that the MCDL was the best publicly available grazing data. However, it should be noted that the ‘grazing hectares’ classification is not self-reported by land owner, but actually calculated via GIS and minimal ground-truthing by the Montana Department of Revenue (MDR, 2016). In order to account for inaccuracies in the MCDL, a cadastral parcel was considered a “grazing parcel” (i.e. livestock present) if 90% or greater of the total parcel area (hectares) was categorized as ‘grazing hectares’ in the MCDL dataset. Parcels that contained less than 90% ‘grazing hectares’ were excluded from further analysis.

Minimum grazing parcel size was set at 64.8 ha following the findings of Sanderson et al. (2015), which noted that 1 ha of mixed-grass prairie, the predominant grazing land type in the northern Great Plains, can support 1.5 AUM. Therefore, it was assumed that a 64.8 ha parcel of mixed-grass prairie grazing land could support 98 AUM of livestock. The minimum grazing parcel size was set at 64.8 ha/98 AUM to exclude smaller livestock operations that lack enough animals to effectively graze commercial-sized wheat fields while including all operations of 64.8 ha or greater size. Although AUM supported was the predominant factor in deciding minimum grazing parcel size, the Public Land Survey System’s township and section sizes were also considered. A minimum grazing parcel size of 64.8 ha/98 AUM is a quarter of a section under the Public Land Survey System and is therefore reflective of a common agricultural parcel size. All MCDL parcels that were at least 90% ‘grazing hectares and a minimum of 64.8 ha in size were considered “Grazing Land”.

Wheat production was determined by first converting the CDL from raster to vector (Conversion Tool – Conversion) and then spatially joining (Spatial Join Tool – Spatial Analyst) the ‘cleaned’ CDL polygon (see methods for cleaning noted in “Warm-

Season Cover Crop Suitability” section) with the MCDL vector layer. All MCDL parcels that spatially intersected CDL wheat production were considered “Wheat Production” parcels.

Finally, Near Analysis (Proximity) was used on the Wheat Production layer to calculate geodesic (i.e. crow-flies measurement that accounts for the curvature of the Earth) distances between Wheat Production parcels and the nearest Grazing Land parcels (Eq. 2).

Eq. 2 ICLS = Distance between Wheat Production[¨] and nearest Grazing Land[†]

[¨] Land planted in all varieties of wheat from 2012 to 2016; CDL wheat spatially joined with MCDL ownership parcels.

[†] MCDL parcels with minimum of 90% of total acres considered ‘grazing’; Minimum parcels size of 64.8 ha.

Each Wheat Production parcel was then symbolized based on distance to the nearest Grazing land parcel using intervals of: less than 1 km, 1.000001 km to 5 km, 5.000001 km to 10 km, and greater than 10 km. The final maps show ICLS adoption suitability based on distances between Wheat Production and Grazing Land. The number of hectares considered Grazing Land were recorded as well as the number of hectares of land planted in all varieties of wheat at least once from 2012 to 2016 (i.e. Wheat Production) for each county.

Warm-Season Cover Crop as Forage in an ICLS Suitability

Land suitability for warm-season cover crop use as forage in an ICLS was determined by first converting the MCDL to a raster and then spatially joining (Spatial Join Tool – Spatial Analyst) land considered High Suitability for warm-season cover crop growth with the MCDL. Next, the Near Tool (Proximity) was used to calculate distances from land ownership parcels that intersected with the High Suitability land for warm-season cover crop growth to the nearest Grazing Land (see "Integrated Crop Livestock Land Suitability" section for methodology; Eq. 3). The Near Tool creates in the High Suitability Parcels attribute table a separate 'near distance' field that stores the distance to the nearest Grazing Land parcel.

Eq. 3 WS-ICLS = High Suitability Parcels[¨] + Grazing Land[†]

[¨] Land considered highly suitable for warm-season cover crops (see "Warm-Season Cover Crop Land Suitability" section for methodology) spatially joined with MCDL ownership parcels.

[†] MCDL parcels with minimum of 90% of total acres considered 'grazing'; Minimum parcels size of 64.8 ha.

The final maps are symbolized based on this near distance value to show distances between (i) cadastral parcels that intersect with High Suitability land for warm-season cover crop growth, and (ii) cadastral parcels considered Grazing Land. These maps show areas where it may be feasible to graze warm-season cover crops based on biogeophysical attributes and the distances between crop and livestock operations.

Results and Discussion

Warm-Season Cover Crop Land Suitability

In the first iteration of the warm-season cover crop land suitability model, which does not account for stored soil water, 0 ha were found to be in the High Suitability score class for warm-season cover crop growth (Table 3). Hill Co. (Fig 6) had the greatest number of hectares in the Medium Suitability score class (60%) followed by Fergus Co. (20%; Fig 4), then Fallon Co. (17%; Fig 2), and finally Stillwater Co. (12%; Fig 8). In Fallon Co., Fergus Co., and Stillwater Co., over 80% of all ha fell within the Low Suitability score class, respectively. These results demonstrate land suitability for warm-season cover crop growth without accounting for any soil moisture. However, this iteration of the warm-season cover crop suitability model likely does not reflect actual field conditions as most wheat production land in Montana provides crops with stored soil water (Tallman, 2014; Housman, 2016). Yet, it is useful in demonstrating both isolated effects of growing season precipitation as well as the possible implications of decreased soil moisture in drought years.

In the second iteration of the warm-season model, which accounts for 50 mm of stored soil water, Fergus Co. (Fig 5) had the greatest number of High Suitability ha with 225,432 ha. Fallon Co. (Fig 3) followed with 12,730 ha, then Stillwater Co. (Fig 9) with 2,461 ha, and finally Hill Co. (Fig 7) with 558 ha of High Suitability Land (Table 4).

Interestingly, 20% of Fergus Co.'s total area fell within the High Suitability score class while only 2% of Fallon Co.'s total area and less than 0.5% of Stillwater Co. and Hill Co. fell within the same score class, respectively.

In both Fergus and Fallon Co.'s, areas of High Suitability were spatially clustered. In Fergus Co., High Suitability areas are influenced by increased elevation near the Moccasin, Judith, and Big Snowy mountains ranges, respectively, which create 'sweet spots' of temperature and precipitation. The increased elevation leads to increased summer precipitation without a large drop (< 1°C) in mean June temperature. Closer to the mountains, mean June temperature decreases by at least 2°C and therefore decreases overall suitability score of those areas. In Fallon Co., the areas of High Suitability are most influenced by higher temperatures found in or around the lower elevation areas (associated with the Yellowstone River Drainage) in the northwestern portion of the county.

While all four study counties have large portions of area that fell within the Medium Suitability classification when accounting for stored soil water and growing season precipitation, Fergus and Fallon Counties appear to be the most suitable for warm-season cover crop growth. Further research efforts should focus on plot- and field-scale experiments examining how warm-season cover crops perform in the High Suitability areas of Fergus Co. and Fallon Co. as well as the Medium Suitability areas of all four study counties. Establishing study sites in both High Suitability and Medium Suitability areas of the study counties will help future researchers test the accuracy and applicability of this LSA model as well as improve future modeling efforts.

Integrated Crop-Livestock Systems Suitability

The total area of land planted in all varieties of wheat from 2012 to 2016 was 803,769 ha in all study counties. The general relationship between Wheat Production and Grazing Land is summarized by the ratio between Grazing Land ha and Wheat Production ha (G:W; Table 5). Fergus Co. (Fig 11) had a G:W ratio of 1.13 indicating that the county has similar number of ha of both Wheat Production and Grazing Land. Interestingly, wheat production tended to be the dominant land use in the western half of Fergus Co., while livestock production (i.e. grazing) was the dominant land use in the eastern half of the county. This trend is likely due to the fact that over 70% of wheat planted in Fergus Co. is winter wheat (USDA-NASS, 2016) which requires cooler summer temperatures for optimal growth and yield (McVay et al., 2010). However, large portions of eastern Fergus Co. receive less growing season precipitation and are 1°C to 2°C warmer than the Western half of the county. This trend is most apparent in the Northeastern portion of Fergus Co., several km away from the mountains and their climactic influence. Although Wheat Production and Grazing Land are somewhat spatially segregated in Fergus Co., a majority of Wheat Production parcels are less than 5 km from the nearest Grazing Land, indicating relatively high suitability for ICLS adoption.

Both Fallon Co. (Fig 10) and Stillwater Co. (Fig 13) had a G:W around 2 indicating that both counties are dominated by Grazing Land relative to Wheat Production. However, Fallon Co. had no Wheat Production parcels greater than 5 km from Grazing Land, indicating high suitability for ICLS adoption in terms of distance between the two land uses. Wheat Production and Grazing Land is somewhat segregated in Stillwater Co. where most Wheat Production occurs in the northern third of the county while Grazing Land is the dominant land use in the south. Although the largest contiguous areas of Wheat Production and Grazing Land are somewhat segregated in Stillwater Co., smaller patches of Wheat Production were found in the southern portion of the county while a moderate amount of Grazing Land was found in the northern third of the county. Overall, both Fallon Co. and Stillwater Co. have areas that are suitable for ICLS adoption.

Hill Co. (Fig 12) was the least suitable county for ICLS adoption with a G:W of 0.15 and a landscape dominated by Wheat Production with Grazing Land confined to the foothill of the Bearpaw Mountains (southeast corner of county), drainages (i.e. Sage Creek, Redrock Coulee, Milk River, etc.) and the northeast corner of the county. A large portion wheat production in western Hill Co. is greater than 10 km from the nearest Grazing Land. Efforts to integrate crop and livestock operations in Hill Co. may be frustrated by the high number of ha under Wheat Production and low number of Grazing Land ha as well as the spatial relationship between the two land uses.

It should be noted that maps showing ICLS Suitability in all four counties show MCDL parcels where wheat is under cultivation but do not show where, inside of each parcel, cultivation is taking place (i.e. these maps do not reflect the discrete spatial location of wheat on the landscape but rather the distances between boundaries of parcels where wheat is being grown). Therefore, precise spatial summary statistics analyzing distances between actual Wheat and Grazing Land could not be calculated using these data. Instead, the distance values are generalized to parcel boundaries and not to the actual discrete location of wheat cultivation. However, these results (presented in map form) do help inform land managers about land suitability for ICLS adoption by showing generalized spatial relationships between Wheat Production and Grazing Land.

A second issue with this LSA model stems from a lack of discrete, accurate grazing and livestock data. These results are based on the MCDL grazing data which may contain misidentified grazing parcels given the methodology used to classify grazing land (MDR, 2016) and should therefore be considered with caution. Further research should seek to: 1) build accurate datasets pertaining to livestock presence and grazing on the landscape; 2) understand the level of interest among producers in building ICLS; and, 3) further understand the economic and agronomic implications of creating ICLS in Montana and the northern Great Plains.

Warm-Season Cover Crops as Forage in an ICLS Suitability

Both Fallon Co. (Fig 14) and Fergus Co. (Fig 15) had the greatest number of High Suitability warm-season cover crop acres (Table 4) and therefore have the greatest number of High Suitability Wheat Production cadastral parcels in close proximity to Grazing Land. Approximately 94% of High Suitability Wheat Production parcels were less than 1 km from Grazing Land in Fallon Co. indicating high potential for use of warm-season cover crops as forage in an ICLS in the northwestern portion of the county. In Fergus Co., approximately 64% of High Suitability wheat parcels were less than 1 km from Grazing Land. Both Fallon and Fergus Co.'s have regions that are suitable for use of warm-season cover crops as forage in and ICLS.

In Hill Co. (Fig 16), approximately 62% of High Suitability Wheat Production cadastral parcels were found to be less than 1 km from Grazing Land. However, because the warm-season cover crop suitability layer was spatially joined to the MCDL (described in detail in “Integrated Crop-Livestock System Suitability” section), this map is deceiving as it appears to greatly inflate the area of High Suitability for cover crop growth. While this problem of apparent spatial inflation occurs in all warm-season use as cover crops as forage maps due to the spatial join, it is most inflated in Hill Co. as larger cadastral parcels containing few pixels of wheat were common in this county. In total, Hill Co. was only found to have 558 ha of Wheat Production in an area of High Suitability for warm-season cover crop growth (Fig 7). Therefore, Hill Co. is likely a poor candidate county for utilizing warm-season cover crops as forage in an ICLS.

In Stillwater Co. (Fig 17), 76% of High Suitability Wheat Production cadastral parcels were found to be less than 1 km from Grazing Land. However, the same issue noted in Hill Co. (Fig 16) was detected in Stillwater Co. in which the spatial join between the warm-season cover crop suitability layer and MCDL inflated the visual representation of High Suitability Wheat Production area. A majority of the High Suitability Wheat Production areas less than 1 km from Grazing Land appear to be clustered in the foothills of the Beartooth Mountains (southwest portion of the county). However, the same issue occurred here as noted in Hill Co. Combining the Wheat Production layer with MCDL parcels highlights parcels, but does not necessarily show where, within the parcels, wheat production occurs. This can greatly inflate the apparent ha of wheat production when looking at the maps of Hill and Stillwater Co.’s. In reality, Stillwater Co. was found to have only 2,461 ha of High Suitability warm-season cover crop land and is therefore a poor candidate county for utilization of warm-season cover crops as forage in an ICLS.

Overall, warm-season cover crops may serve as an appropriate forage source in an ICLS in Fallon Co. and Fergus Co., but not in Hill Co. or Stillwater Co. Further research efforts should focus on plot- and field-scale warm-season cover crop trials in order to understand how warm-season cover crops perform as forages in these regions. Such study would also inform further research efforts about the efficacy of this model and help build increasingly useful models in future agriculturally themed LSAs.

Conclusion

This research identified areas suitable for: 1) warm-season cover crop growth; 2) integrated crop-livestock systems adoption; and 3) integrated crop-livestock systems which utilize warm-season cover crops as a forage source. The results of this research are presented in the form of maps for ease of use by both producers and other land managers. All data used in this project are public and can be easily accessed and used by any interested party. While these maps and their underlying models are relatively simple, this research is meant to show possible work flows for identifying land suitability for adoption of specific agronomic practices, an approach which may enhance long-term sustainability in Montana cropping systems.

While this research shows that there is great potential within the study counties and likely large portions of Montana and the northern Great Plains for the adoption of these agronomic practices, GIS-based LSAs do have limitations. The power of this research is constrained by the availability of accurate public data. Future research in this area should seek to add to the available data used to create land suitability models including better grazing and livestock data at the landscape scale as well as address producer interest in and perceived barriers to adoption of these practices.

Table 2.1. GIS datasets used to map land suitability for warm-season cover crop and integrated crop-livestock systems adoption in four Montana study counties.

Layer Name	Layer Source	Layer Type	Layer Description	Resolution
Cropland Data Layer	USDA - NASS	Raster	Shows all land planted in crops or used for livestock grazing in MT for last 5 years.	30m
30 yr (1981-2010) mean precipitation (Jun, Jul, Aug)	University of Idaho	Raster	Shows 30-year annual mean precipitation for the months of Jun, Jul, and Aug for all of MT.	4km
MT Cadastral Data	State of Montana Montana State Library	Vector	Shows land ownership and use in MT.	N/A
30 yr (1981-2010) mean temperature (June)	Montana Climate Office	Raster	Shows 30-year average monthly temperature for the month of June.	800m
Digital Orthoimagery/ NAIP imagery	National States Geographic Information Council Montana State Library	Raster	Shows aerial images of MT adjusted to compensate for distortions from camera tilt geographic relief.	5m

Table 2.2. Scoring criteria for warm-season cover crop suitability score classes in four study counties of Montana.

	----------Variable----------		
Score	Temperature (°C)	Precipitation (mm)	Wheat Production
0	0 - 12.78	0 - 40	No
1	12.79 - 14.44	41 - 80	N/A
2	14.45 - 17.22	81 - 120	N/A
3	> 17.23	> 120	Yes

Note: Wheat production was a binomial variable with either presence or absence. Therefore, absence was scored as “0” and presence was scored as “3”.

Table 2.3. Number of hectares in each score class for warm-season cover crop adoption suitability without accounting for stored soil water in four study counties of Montana.

	Score Class*			
County	Less than 1.75	1.76-2.25	Greater than 2.25	Total
	---------- Hectares ----------			
Fallon	345,016	71,575	0	416,591
Fergus	900,775	219,146	0	1,119,921
Hill	303,494	447,549	0	751,043
Stillwater	408,705	54,841	0	463,546

* Low Suitability = < 1.75 (Less than 58% of criteria met); Medium Suitability = 1.76 – 2.25 (at least 59% of criteria met); High Suitability = > 2.25 (at least 75% of criteria met)

Table 2.4. Number of hectares in each score class for warm-season cover crop adoption suitability assuming 50 mm of stored soil water in four study counties of Montana.

	Score Class*			
County	Less than 1.75	1.76-2.25	Greater than 2.25	Total
	---------- Hectares ----------			
Fallon	345,009	58,844	12,730	416,583
Fergus	893,519	913	225,432	1,119,864
Hill	303,423	447,045	558	751,026
Stillwater	408,025	53,056	2,461	463,542

* Low Suitability = < 1.75 (Less than 58% of criteria met); Medium Suitability = 1.76 – 2.25 (at least 59% of criteria met); High Suitability = > 2.25 (at least 75% of criteria met)

Table 2.5. Number of hectares of Grazing Land and Wheat Production† in four study in Montana.

County	Grazing Land	Wheat Production	G:W*
	-----------------Hectares-----------------		
Fallon	170,360	71,922	2.37
Fergus	255,494	226,783	1.13
Hill	67,654	449,133	0.15
Stillwater	122,014	55,870	2.18

† Land planted at least once in all varieties of wheat from 2012 to 2016.
*Ratio shows Grazing Land ha to Wheat Production ha.

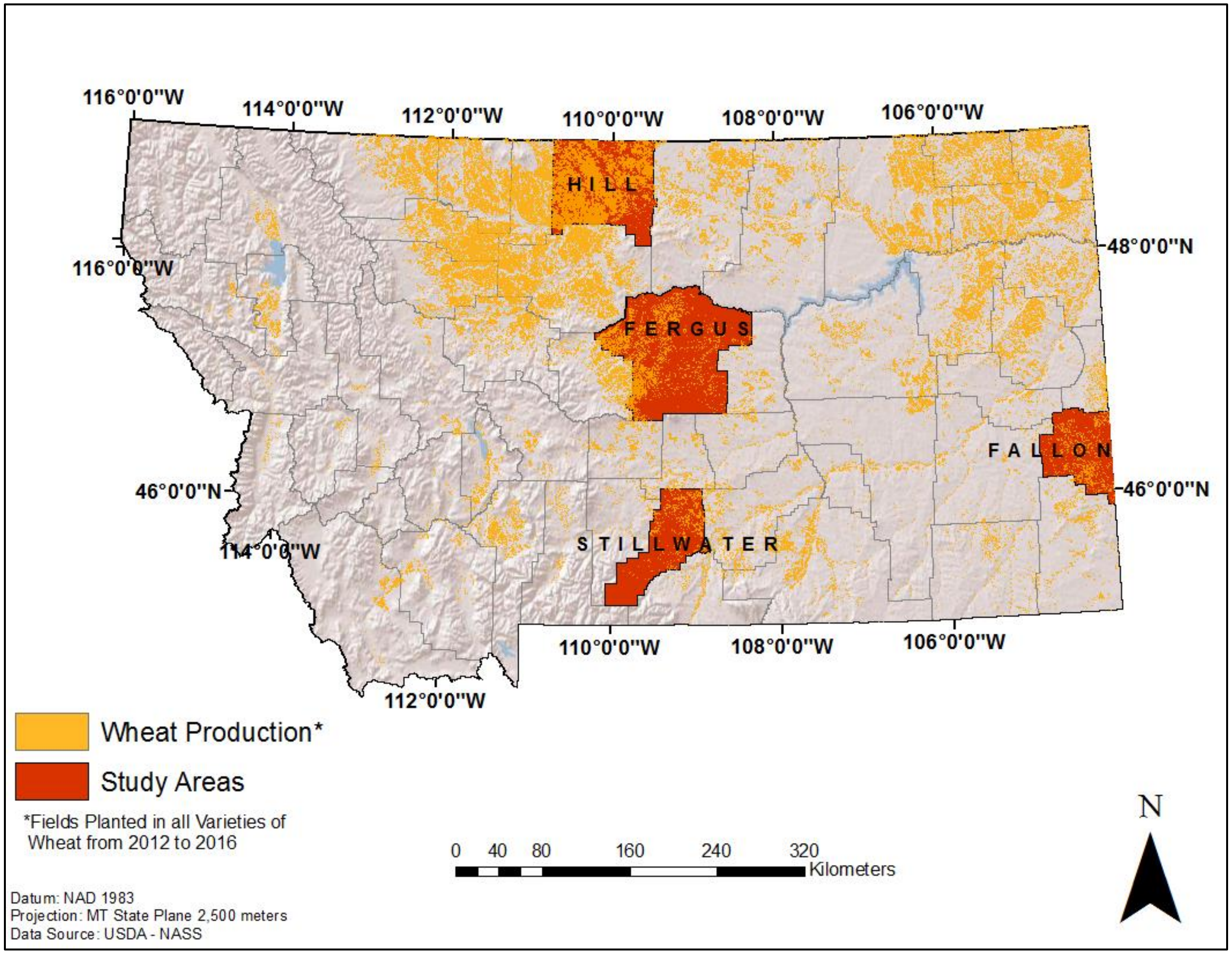


Figure 2.1. Study areas for land suitability for warm-season cover cropping and integrated crop-livestock systems adoption in Montana.

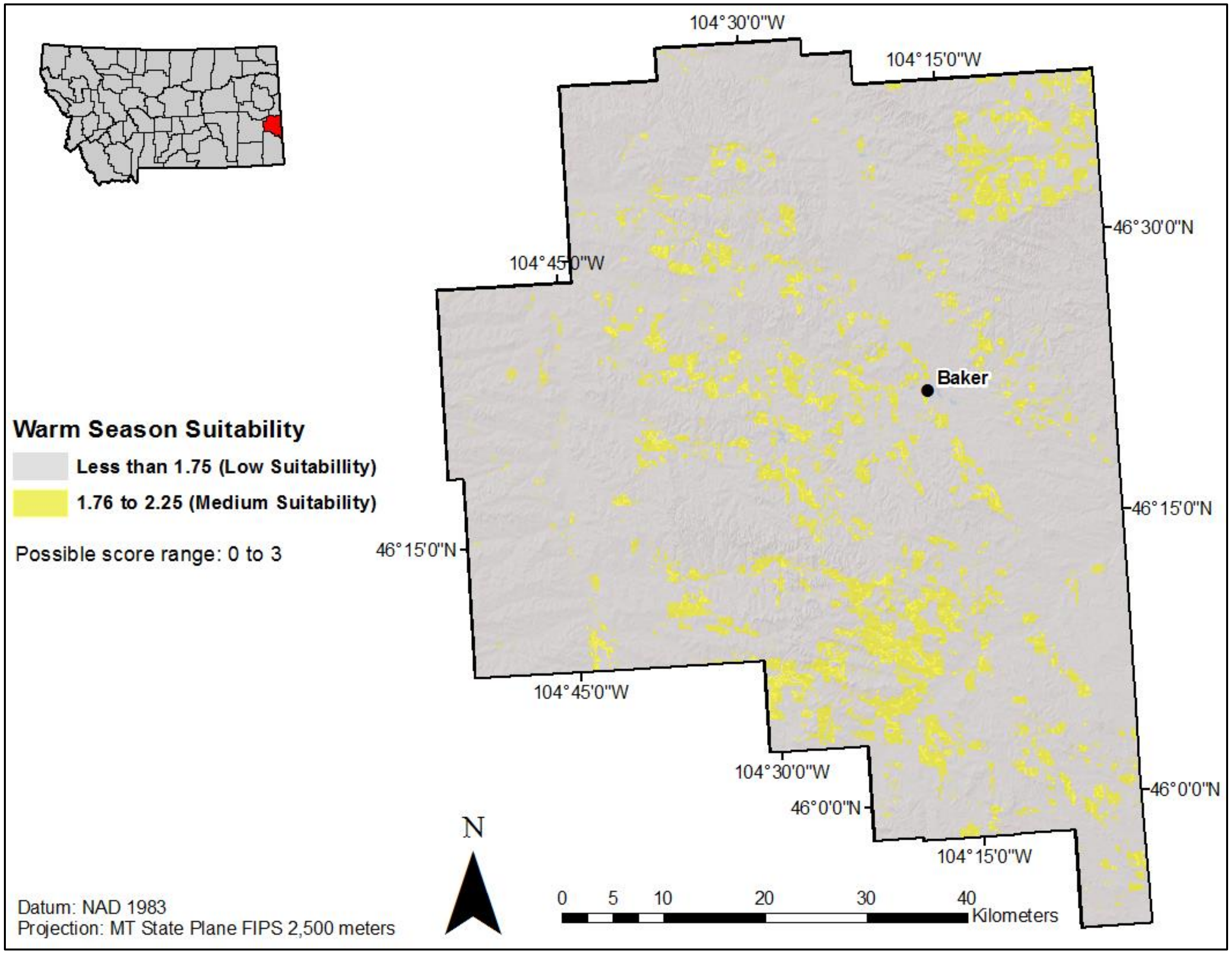


Figure 2.2. Land suitability for warm-season cover crop growth without accounting for stored soil water – Fallon Co., MT. Note: No hectares scored above 2.25 (i.e. High Suitability).

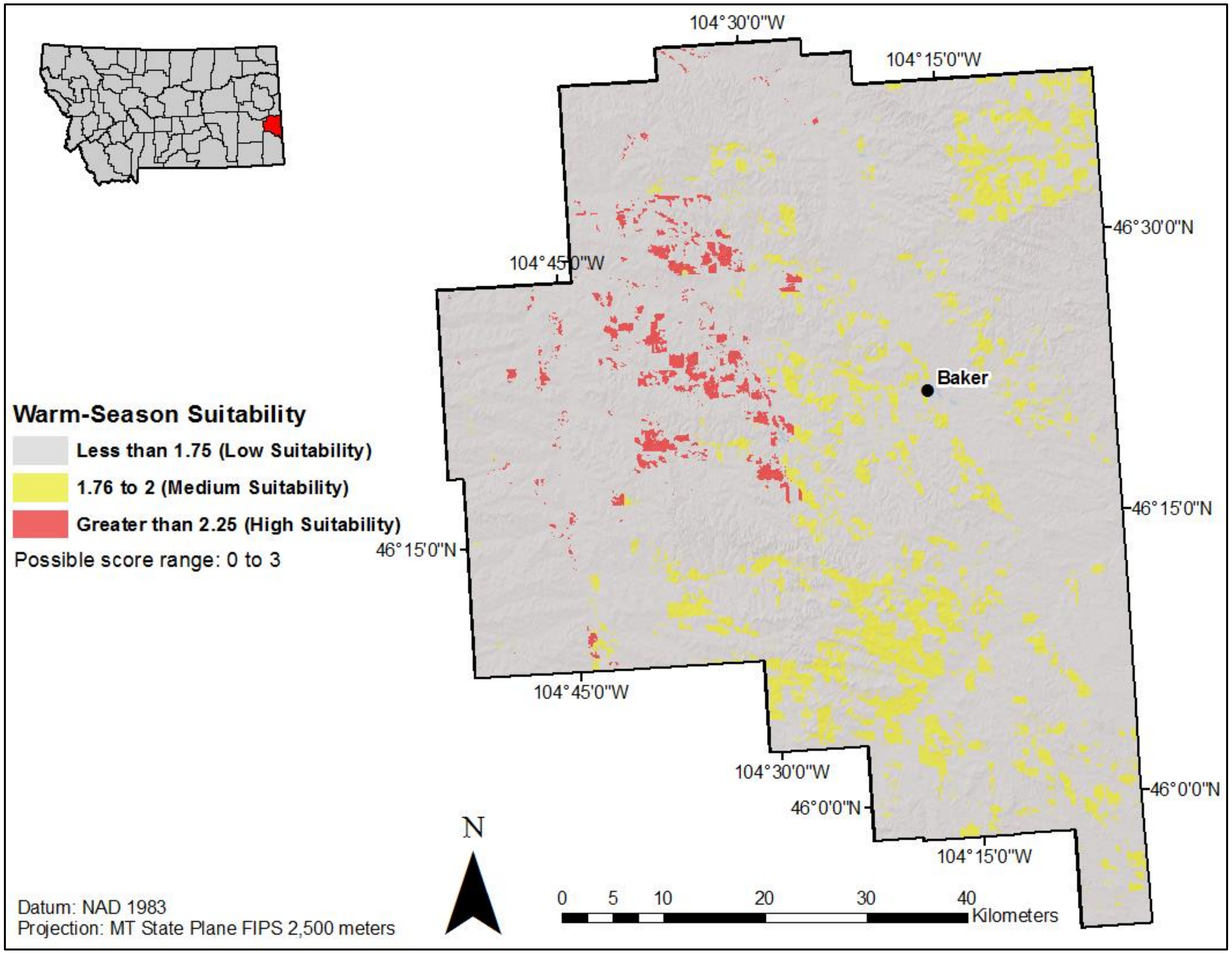


Figure 2.3. Land suitability for warm-season cover crop growth accounting for 50 mm of stored soil water – Fallon Co., MT.

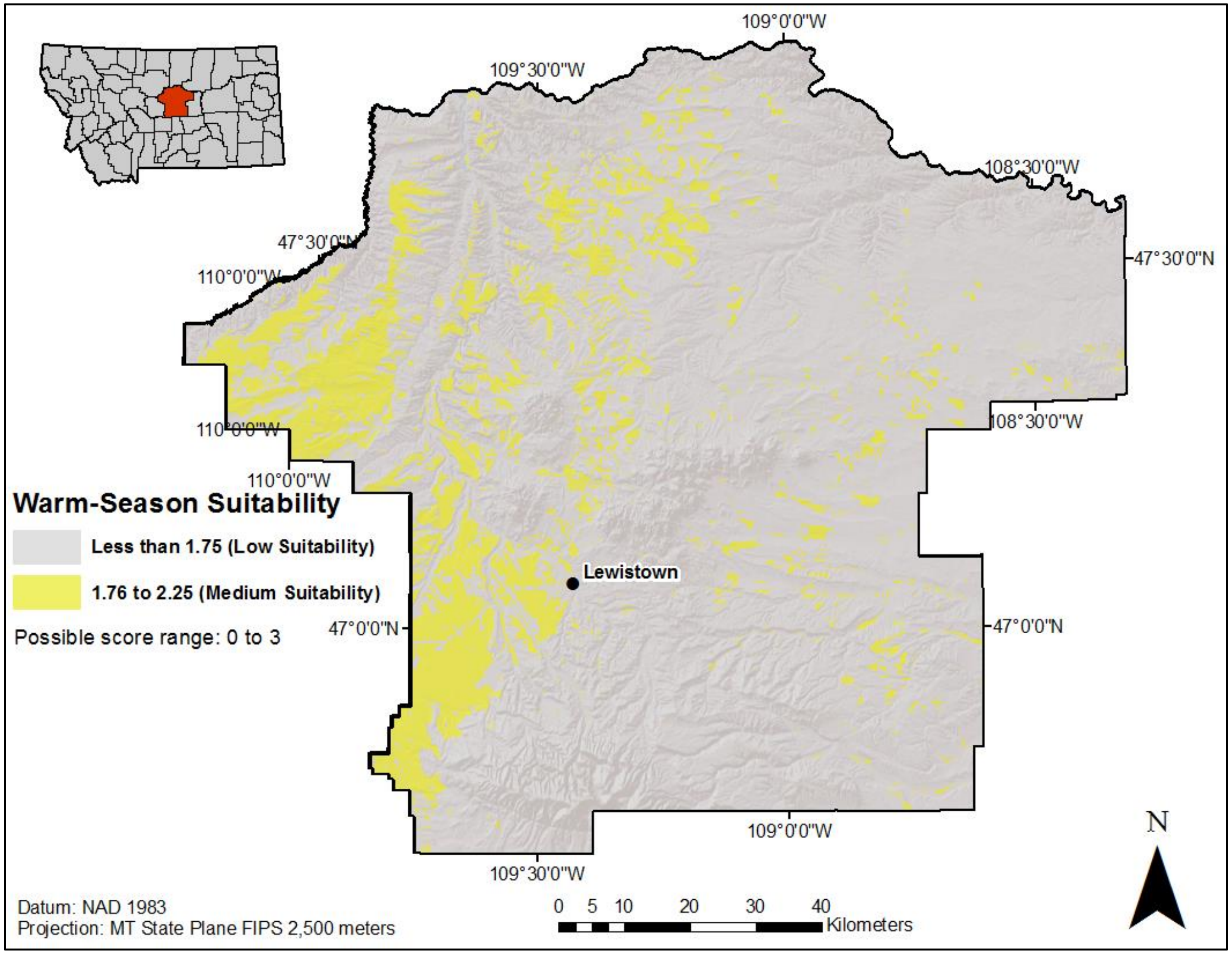


Figure 2.4. Land suitability for warm-season cover crop growth without accounting for stored soil water – Fergus Co., MT. Note: No hectares scored above 2.25 (i.e. High Suitability).

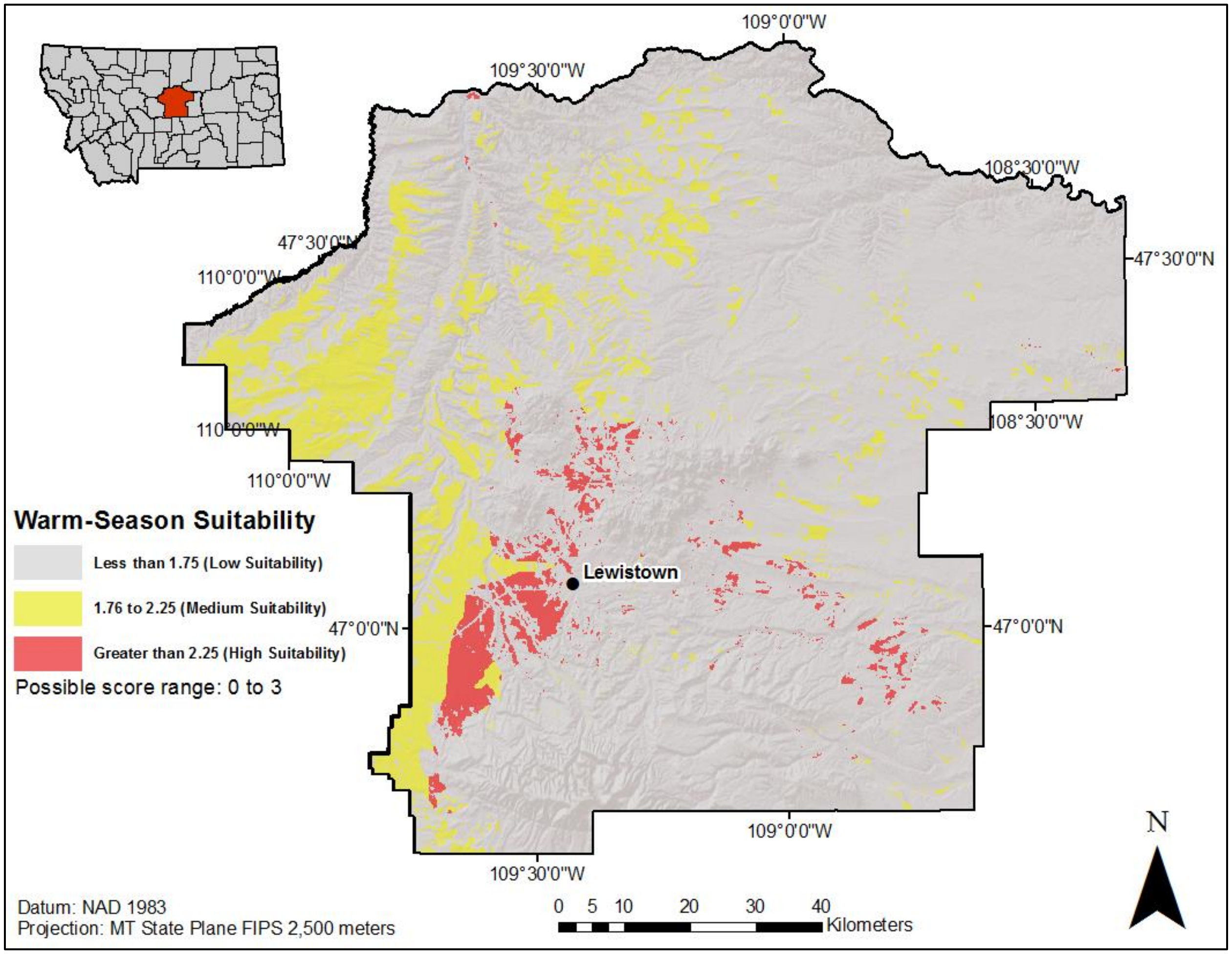


Figure 2.5. Land suitability for warm-season cover crop growth accounting for 50 mm of stored soil water – Fergus Co., MT

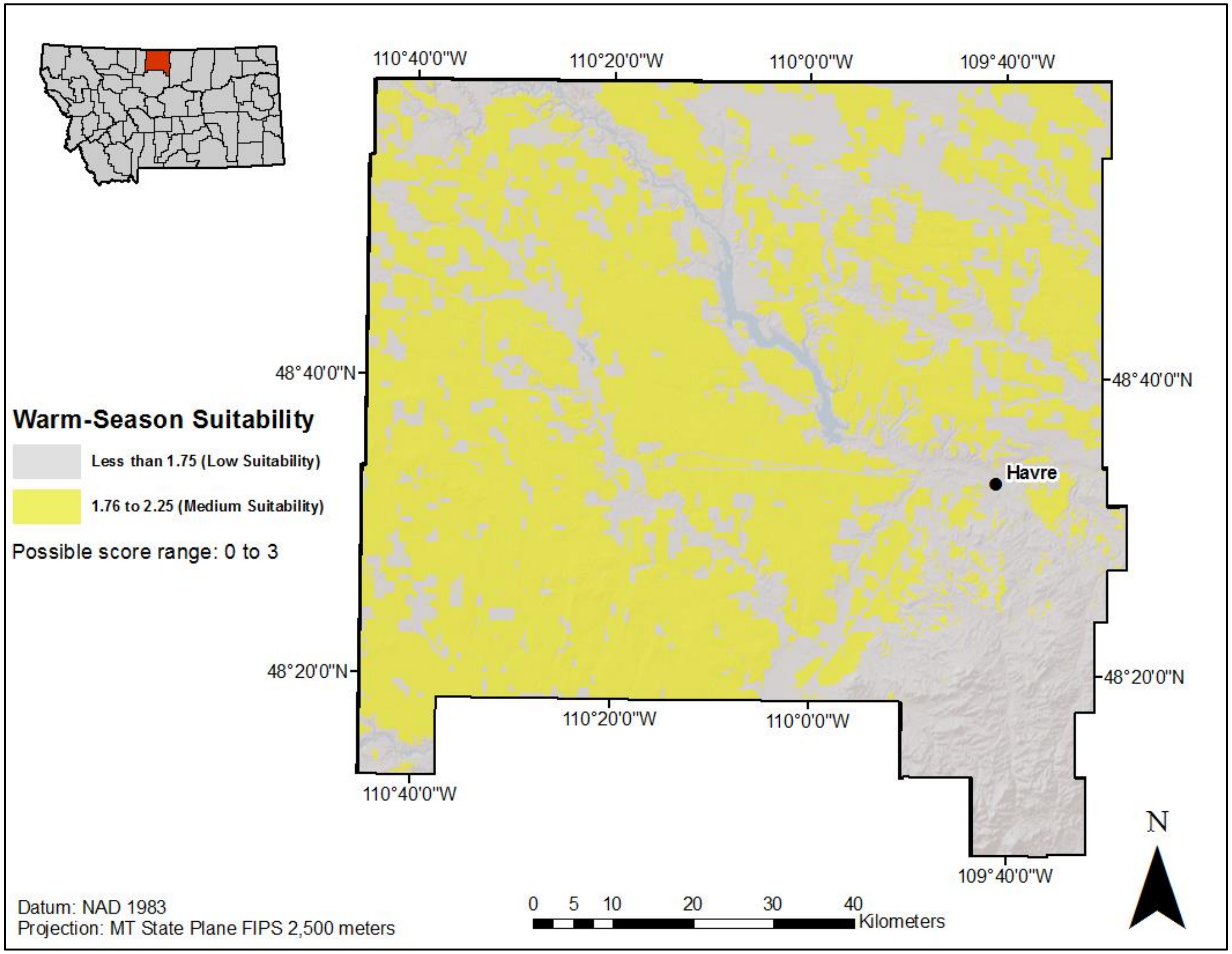


Figure 2.6. Land suitability for warm-season cover crop growth without accounting for stored soil water – Hill Co., MT. Note: No hectares scored above 2.25 (i.e. High Suitability).

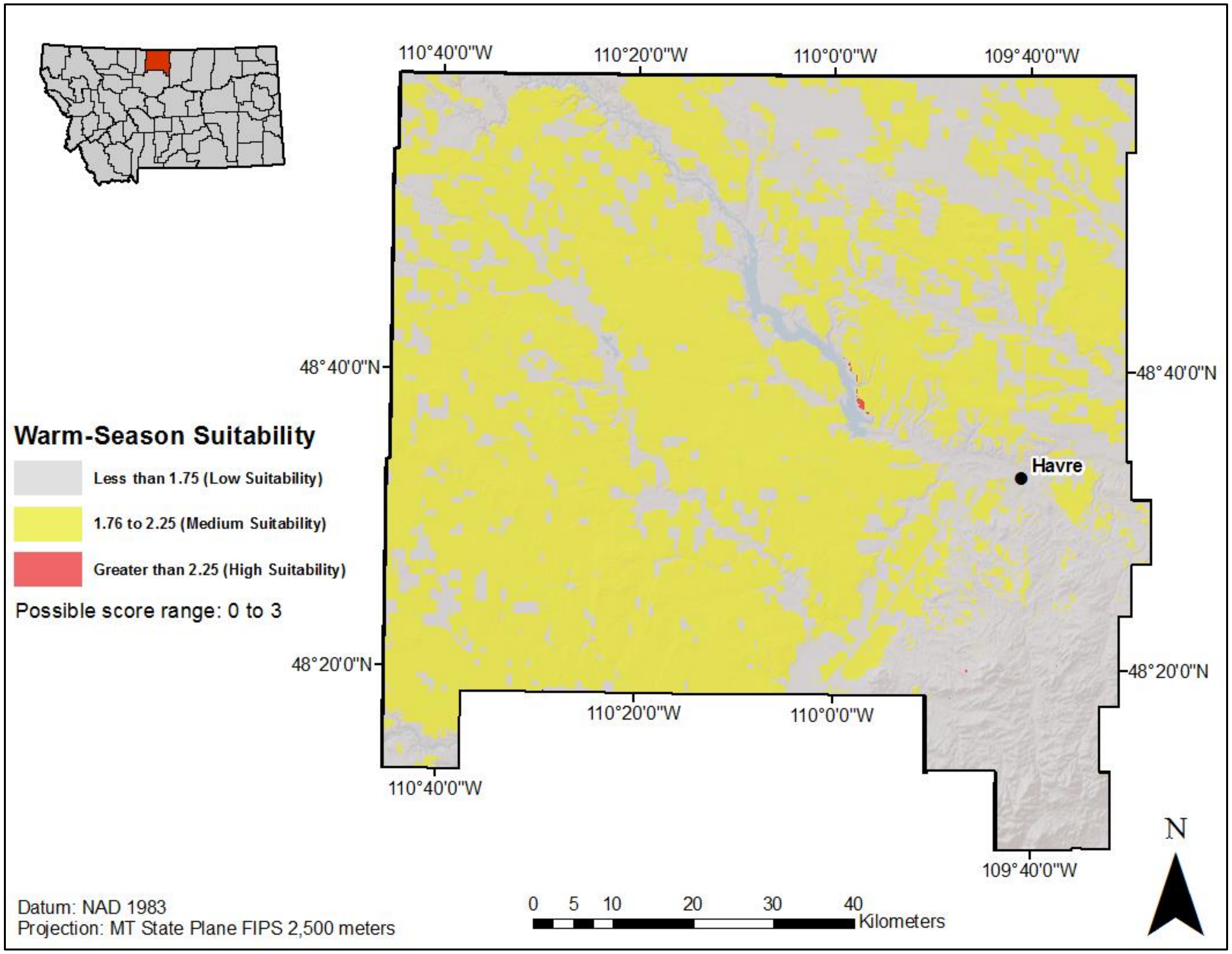


Figure 2.7. Land suitability for warm-season cover crop growth accounting for 50 mm of stored soil water – Hill Co., MT.

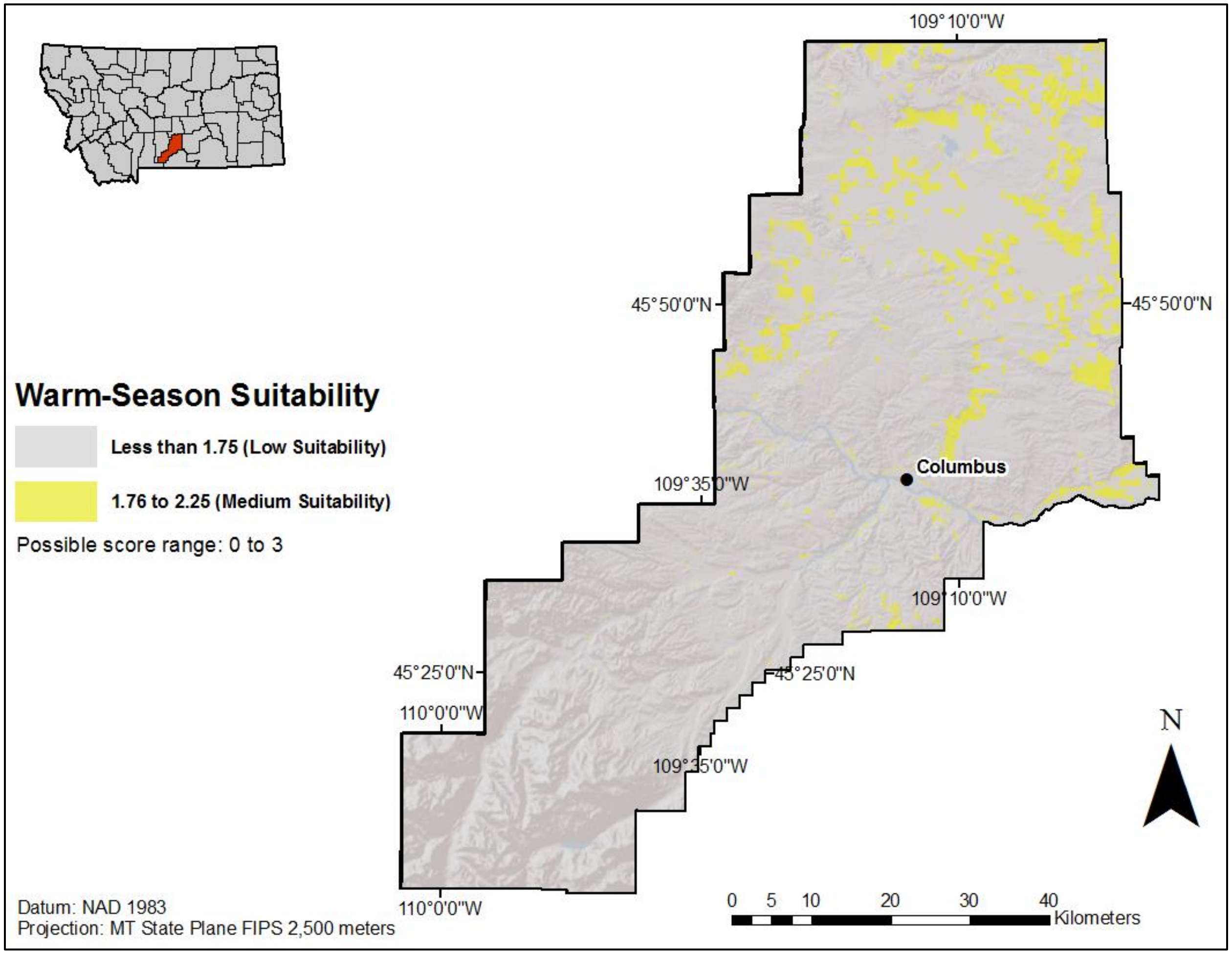


Figure 2.8. Land suitability for warm-season cover crop growth without accounting for stored soil water – Stillwater Co., MT. Note: No hectares scored above 2.25 (i.e. High Suitability).

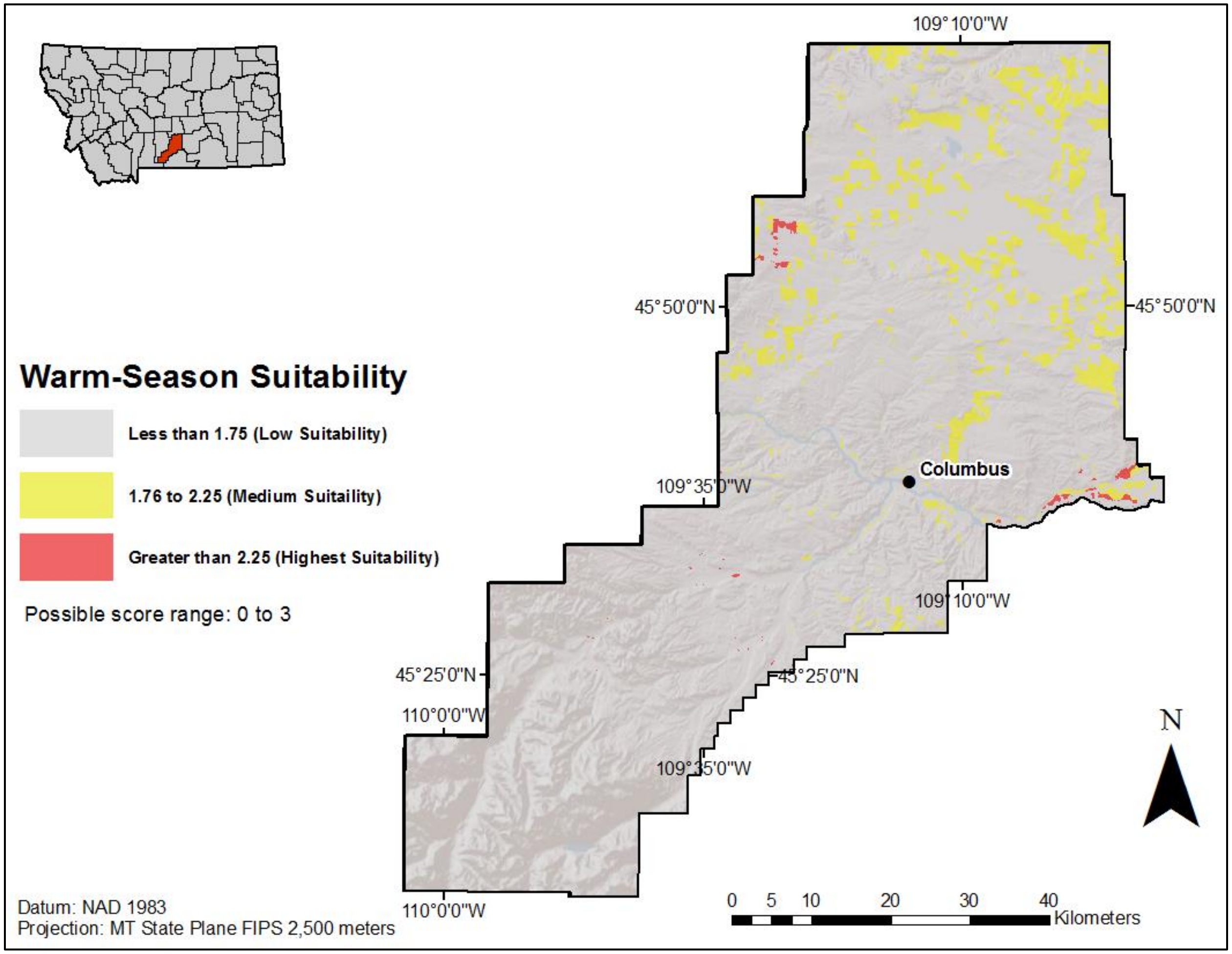
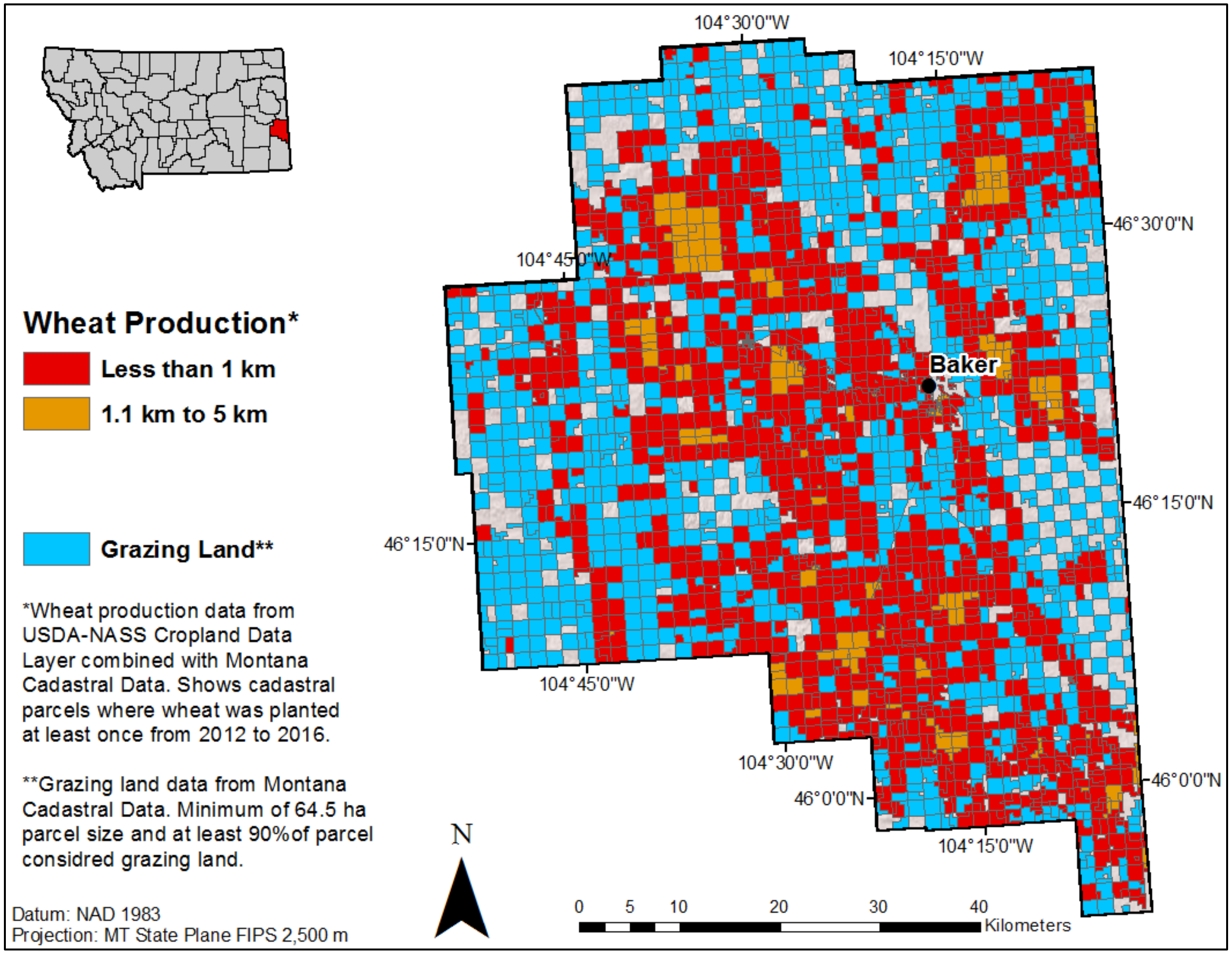


Figure 2.9. Land suitability for warm-season cover crop growth accounting for 50 mm of stored soil water – Stillwater Co., MT.



*Wheat production data from USDA-NASS Cropland Data Layer combined with Montana Cadastral Data. Shows cadastral parcels where wheat was planted at least once from 2012 to 2016.

**Grazing land data from Montana Cadastral Data. Minimum of 64.5 ha parcel size and at least 90%of parcel considred grazing land.

Datum: NAD 1983
Projection: MT State Plane FIPS 2,500 m

Figure 2.10. Land suitability for integrated crop-livestock systems, based on distances between Wheat Production and Grazing Land – Fallon Co., MT. Note: No parcels containing Wheat Production were found to be greater than 5 km from Grazing Land.

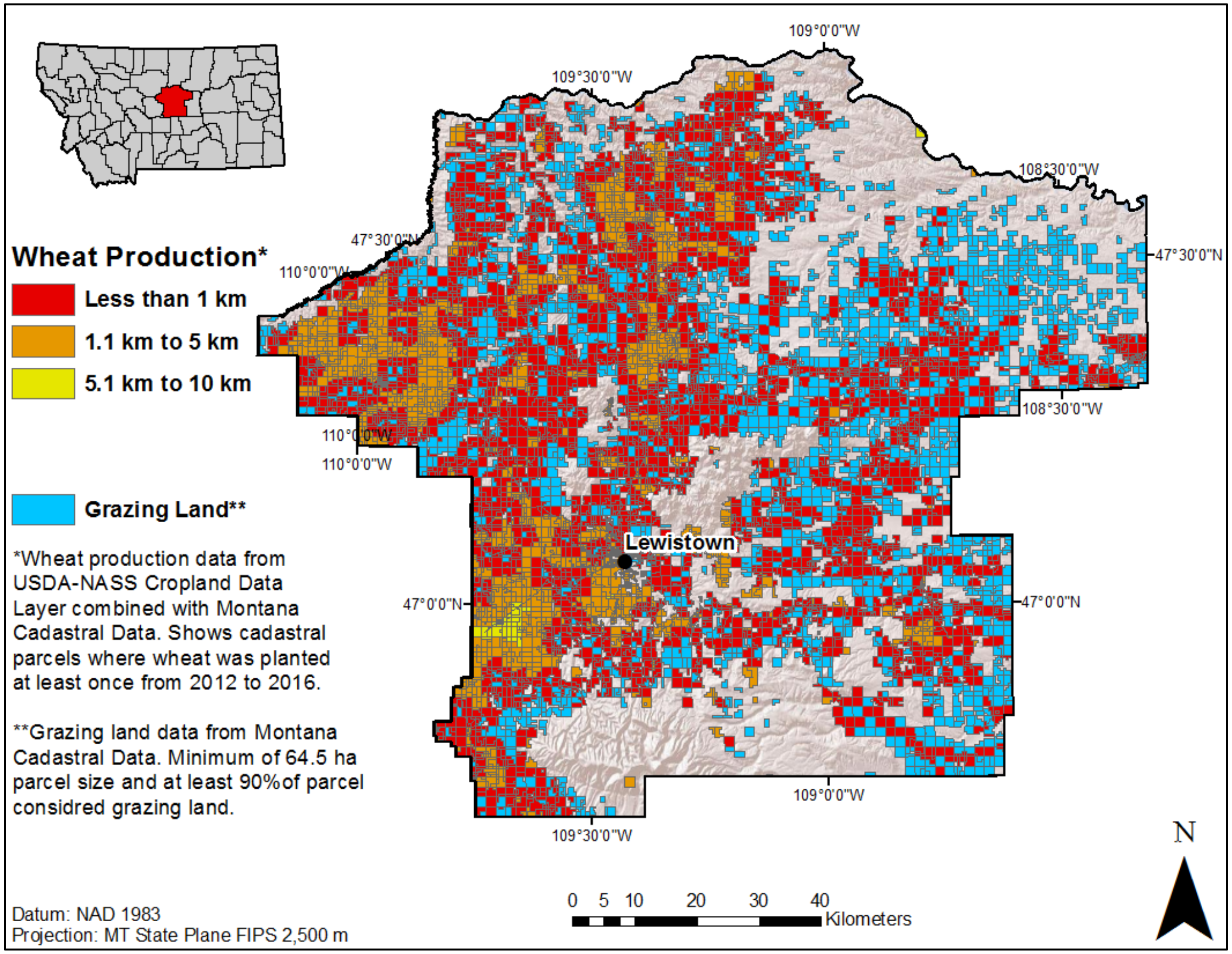


Figure 2.11. Land suitability for integrated crop-livestock systems, based on distances between Wheat Production and Grazing Land – Fergus Co., MT.

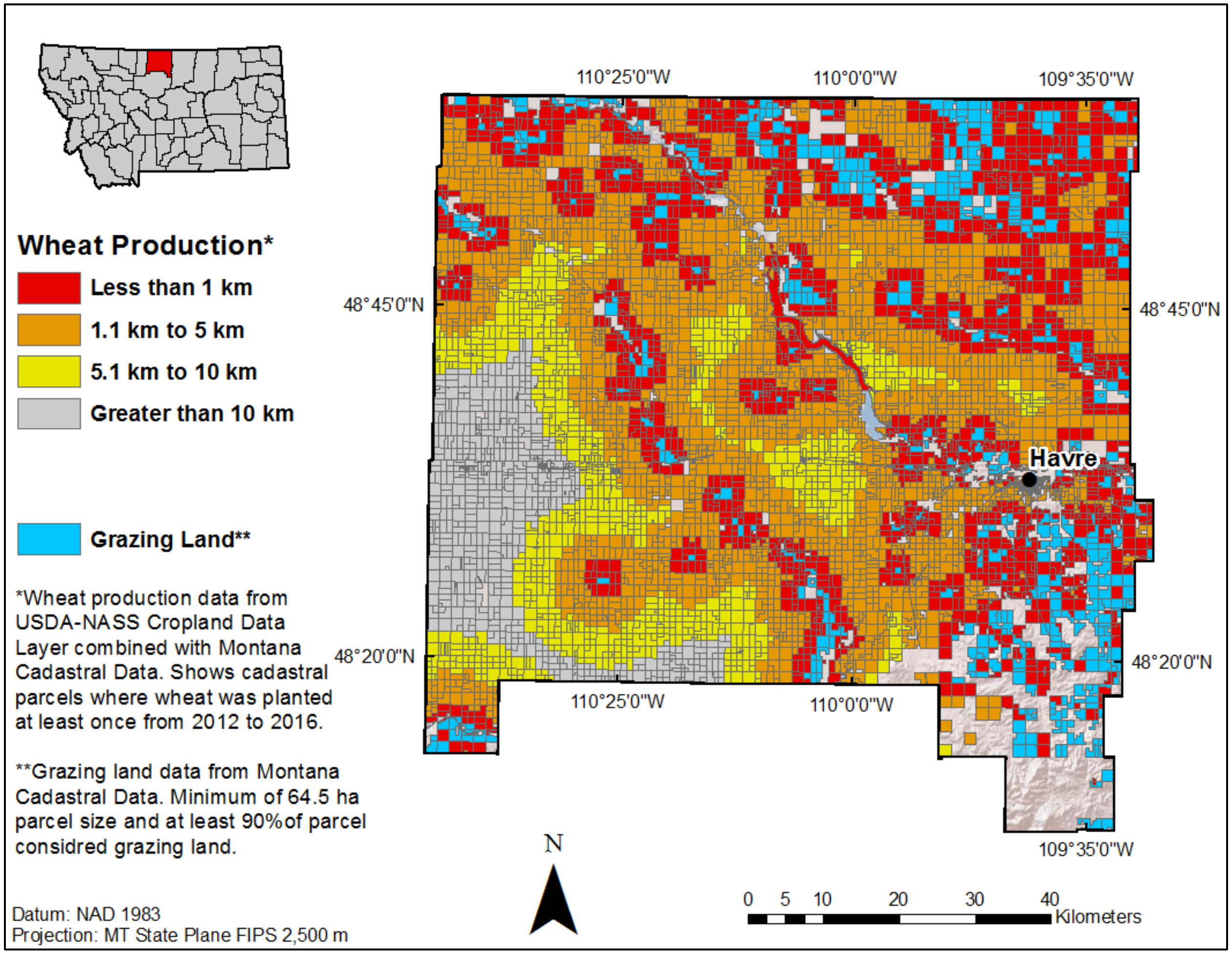
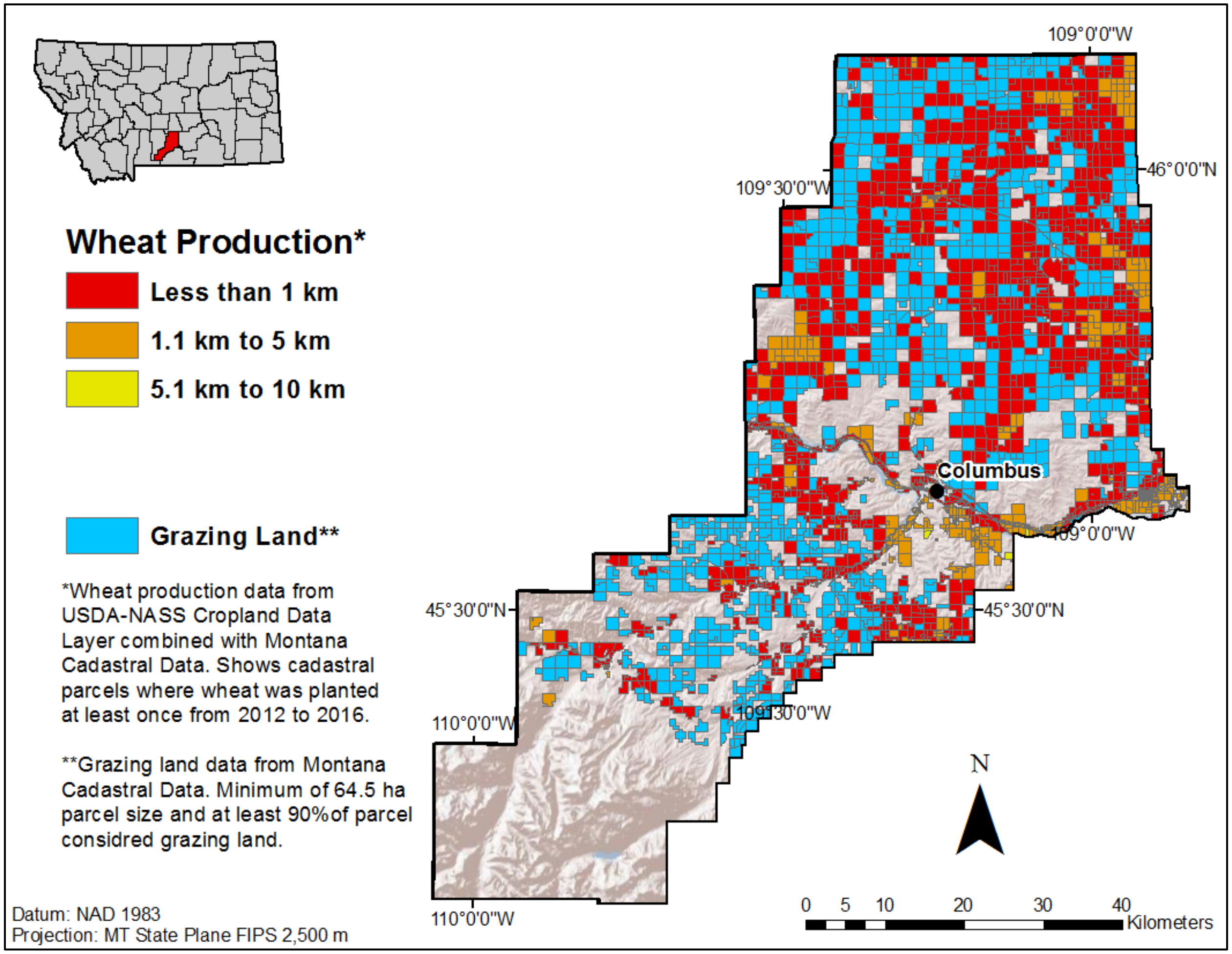


Figure 2.12. Land suitability for integrated crop-livestock systems, based on distances between Wheat Production and Grazing Land – Hill Co., MT.



*Wheat production data from USDA-NASS Cropland Data Layer combined with Montana Cadastral Data. Shows cadastral parcels where wheat was planted at least once from 2012 to 2016.

**Grazing land data from Montana Cadastral Data. Minimum of 64.5 ha parcel size and at least 90%of parcel considred grazing land.

Datum: NAD 1983
Projection: MT State Plane FIPS 2,500 m

Figure 2.13. Land suitability for integrated crop-livestock systems, based on distances between Wheat Production and Grazing Land – Stillwater Co., MT. Note: No parcels containing Wheat Production were found to be greater than 10 km from Grazing Land.

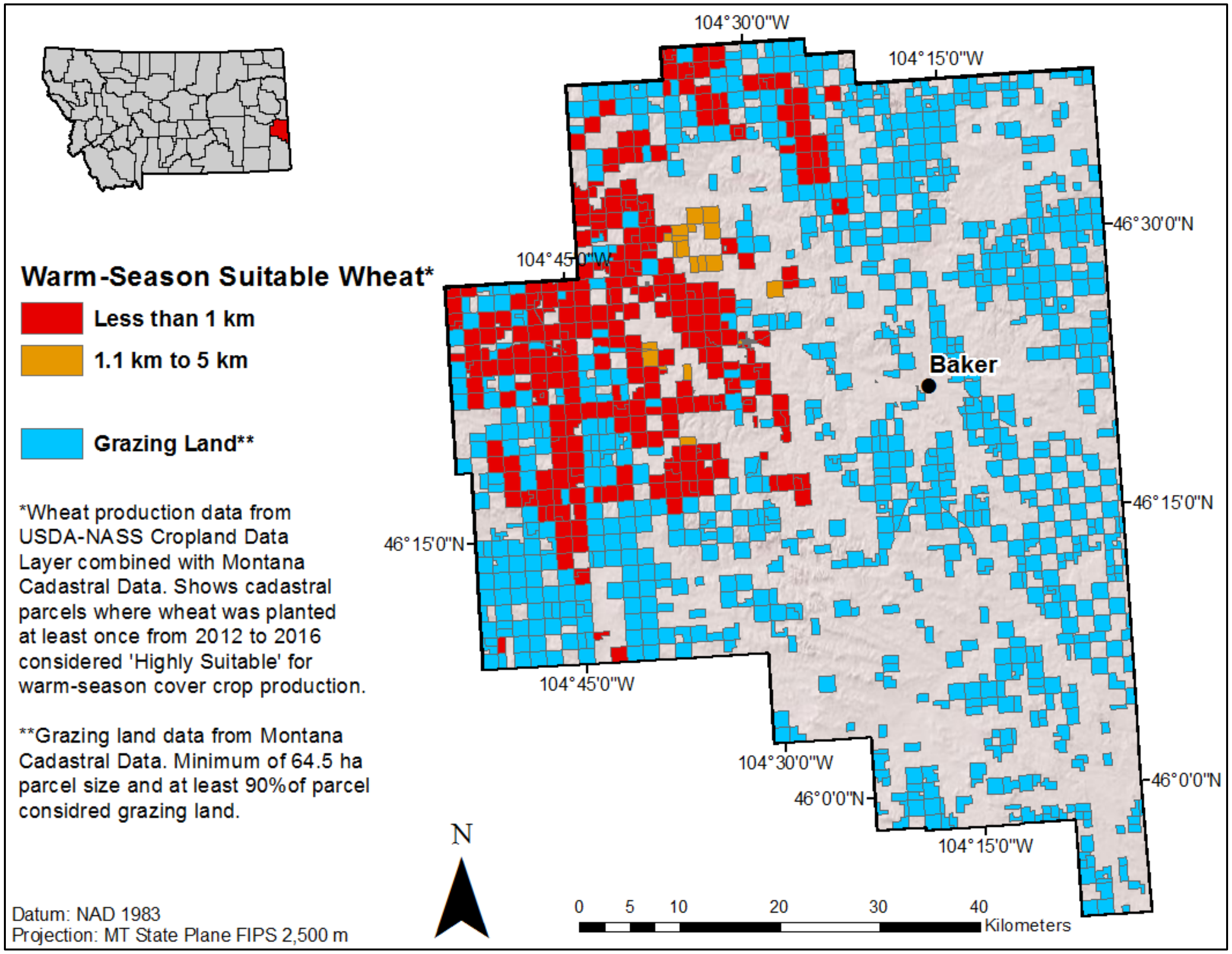
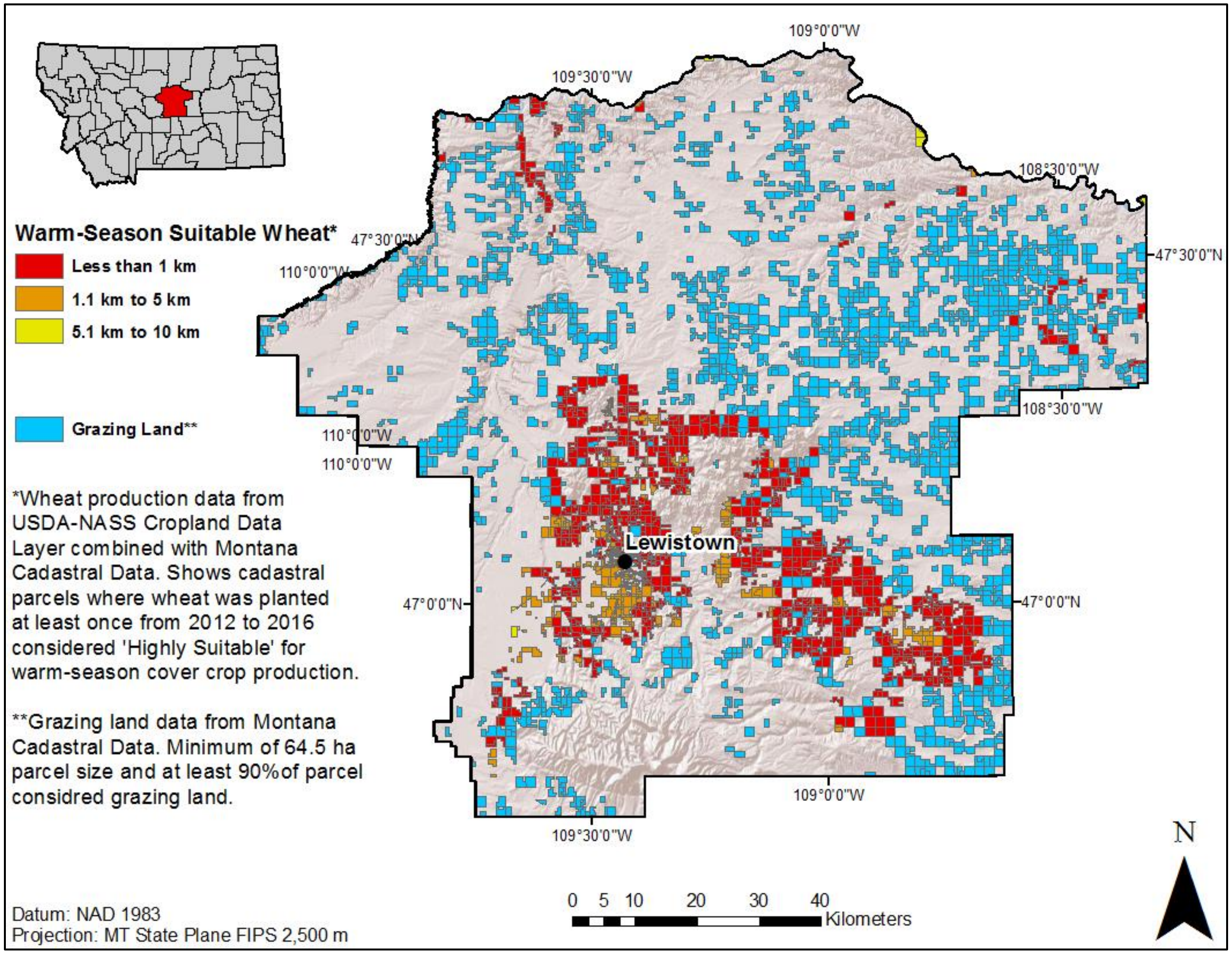


Figure 2.14. Land suitability for warm-season cover crop use as forage in an ICLS, based on distances between Wheat Production land highly suitable for warm-season cover crop growth and Grazing Land – Fallon Co., MT. Note: No parcels containing warm-season high suitability hectares were found to be greater than 5 km from Grazing Land.

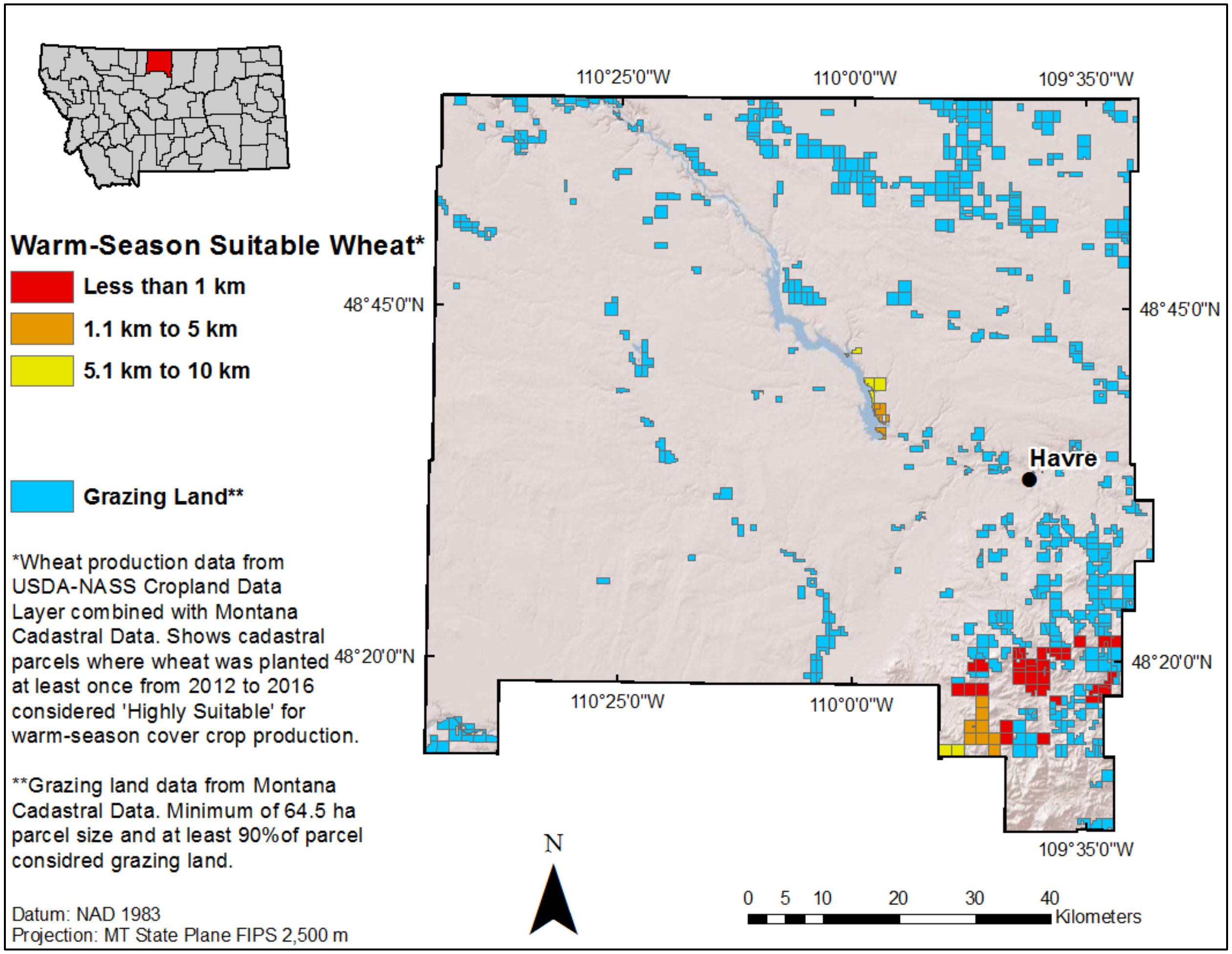


*Wheat production data from USDA-NASS Cropland Data Layer combined with Montana Cadastral Data. Shows cadastral parcels where wheat was planted at least once from 2012 to 2016 considered 'Highly Suitable' for warm-season cover crop production.

**Grazing land data from Montana Cadastral Data. Minimum of 64.5 ha parcel size and at least 90%of parcel considred grazing land.

Datum: NAD 1983
Projection: MT State Plane FIPS 2,500 m

Figure 2.15. Land suitability for warm-season cover crop use as forage in an ICLS, based on distances between Wheat Production land highly suitable for warm-season cover crop growth and Grazing Land – Fergus Co., MT. Note: No parcels containing warm-season high suitability hectares were found to be greater than 10 km from Grazing Land.



*Wheat production data from USDA-NASS Cropland Data Layer combined with Montana Cadastral Data. Shows cadastral parcels where wheat was planted at least once from 2012 to 2016 considered 'Highly Suitable' for warm-season cover crop production.

**Grazing land data from Montana Cadastral Data. Minimum of 64.5 ha parcel size and at least 90%of parcel considred grazing land.

Figure 2.16. Land suitability for warm-season cover crop use as forage in an ICLS, based on distances between Wheat Production land highly suitable for warm-season cover crop growth and Grazing Land – Hill Co., MT. Note: No parcels containing warm-season high suitability hectares were found to be greater than 10 km from Grazing Land.

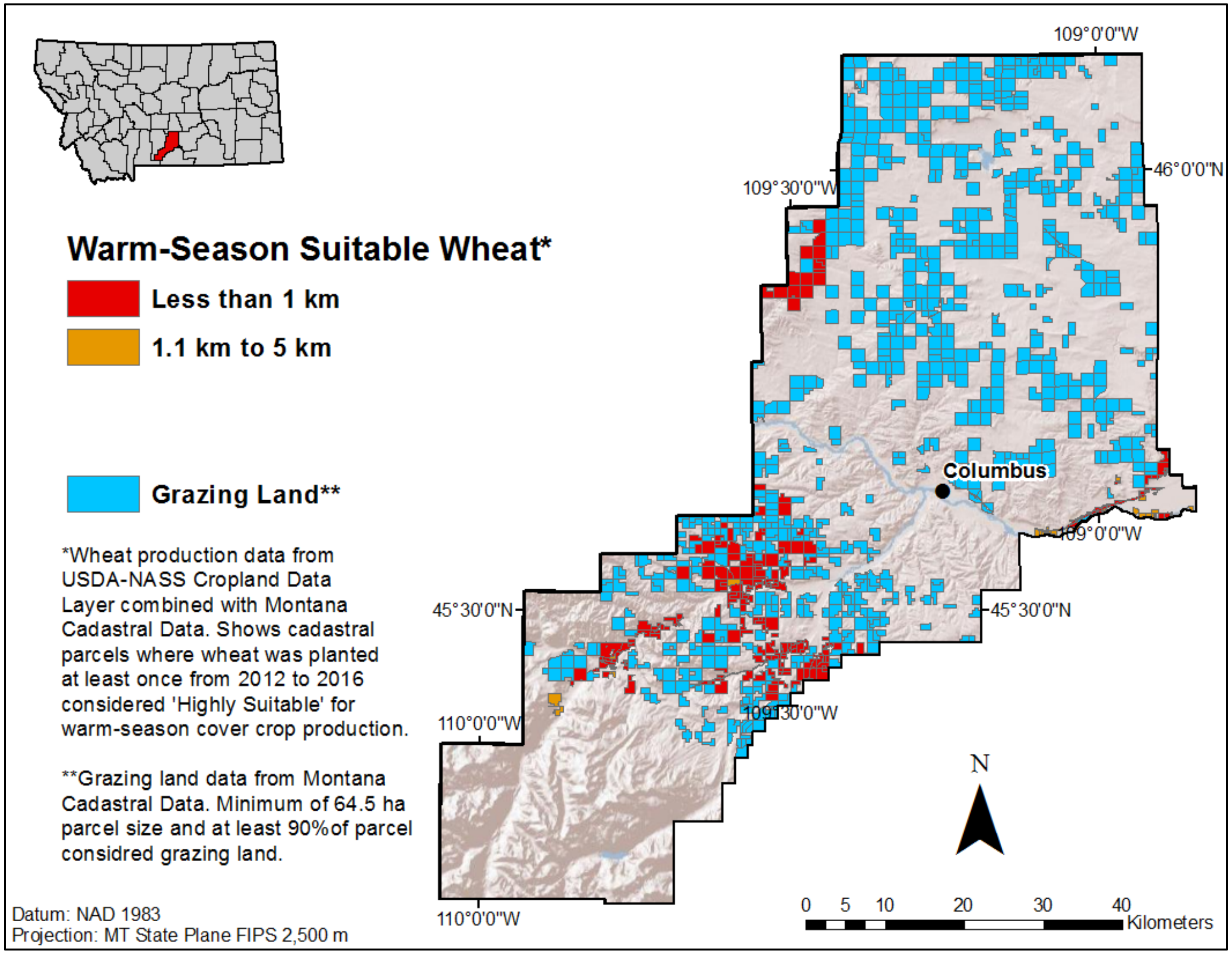


Figure 2.17. Land suitability for warm-season cover crop use as forage in an ICLS, based on distances between Wheat Production land highly suitable for warm-season cover crop growth and Grazing Land – Stillwater Co., MT. Note: No parcels containing warm-season high suitability hectares were found to be greater than 5 km from Grazing Land.

References

Acosta-Martinez, V., T.M. Zobeck, and V. Allen. 2004. Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci. Soc. Am. J. 68: 1875-1884.

Acosta-Martinez, V., M.M. Mikha, and M.F. Vigil. 2007. Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat-fallow for the Central Great Plains. App. Soil Eco. 37:41-52.

Akinci, H., A.Y. Ozalp, and B. Turgut. 2013. Agricultural land use suitability analysis using GIS and AHP technique. Comp. Elec. Agric. 97: 71-82.

Amiri, F., A.R.B.M. Shariff, and T. Tabatabaie. 2012. Monitoring land suitability for mixed livestock grazing using Geographic Information Systems (GIS). (pp.241-266). *In:* Application of Geographic Information Systems. ed: B.M Alam. InTech Publishing, Rijeka, Croatia.

Anderson, R.L. 2008. Diversity and no-till: Keys for pest management in the U.S. Great Plains. Weed Sci. 56: 141-145.

Applied Climate Science Lab at the University of Idaho. 2016. Gridded surface meteorological data. University of Idaho, Moscow, ID. http://climate.northwestknowledge.net/METDATA/. [Verified: 21 Mar 2017].

Assmann, T.S, M. A. de Bortolli, A.L. Assmann, A. B. Soares, C. S. Rocha Pitta, A.J. Franzluebbers, C. L. Glienke, J.M Assmann. 2014. Does cattle grazing of duel purpose wheat accelerate the rate of stubble decomposition and nutrients released? Agric., Ecosyst., & Envi. 190: 37-42.

Barbari, M., L. Conti, B.K. Koostra, G. Masi, F. Sorbetti Guerri, S.R. Workman. 2006. The use of Global Positioning and Geographical Information Systems in the management of extensive cattle grazing. Biosyst. Engin. 95: 271-280.

Bardgett, R. D., D. A. Wardle. 2010. Ecosystem-level significance of aboveground consumers. (pp 113-167). In: Aboveground-Belowground Linkages: Biotic Interactions, Ecosystem Processes, and Global Change. Oxford University Press. Oxford, U.K.

Boitt, M.K., C.N. Mundia, P. K. E. Pellikka, and J. Kapoi. 2015. Land suitability assessment for effective crop production, a case study of Taita Hills, Kenya. J. Agric. Inform. 6: 23-31.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80: 179-192.

Dwyer, L.M., H.N. Heyhoe, and J.L.B. Culley. 1990. Prediction of soil temperature from air temperature for estimating corn emergence. Can. J. Plant Sci. 70: 619-628.

El Baroudy, A.A. 2016. Mapping and evaluating land suitability using a GIS-based model. 2016. Catena. 140: 96-104.

ESRI. 2016. "Tools – Majority Filter" webpage. Available at: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/majority-filter.htm. Verified: 2 Apr 2016. Redlands, CA.

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Hardwood, J.M. Squire, and C.C Sheaffer. 2000. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93: 319-325.

Florence, A. 2016. Cover crop mixture diversity and function. Ph.D. dissertation. University of Nebraska, Lincoln. 141 pp.

Ford, G. L., J.L. Krall. 1979. The history of summer fallow in Montana. Volume 704 Montana Agric. Exper. Bull. Montana State University. Bozeman, MT.

Hatfield, P.G., R.A. Field, J.A. Hopkins, and R. W. Kott. 2000. Palatability of wethers fed an 80% barley diet processed at different ages and of yearling wethers grazed on native range. J. Animal Sci. 78:1779-1785.

Gerik, T., B. Bean, and R. Vanderlip. 2003. Sorghum Growth and Development. Agric. Comm. Texas A&M University. College Station, TX.

Hopkins, L., 1977. Methods for generating land suitability maps: a comparative evaluation. J. Am. Inst. Plan. 34 19–29.

Housman, M.L. 2016. Multi-species cover crops in the northern Great Plains: An ecological perspective on biodiversity and soil health. MS Thesis. Montana State University, Bozeman, MT. 160 pp.

Hsu, F.H., C.J. Nelson, and A.G. Matches. 1985. Temperature effects on germination of perennial warm-season forage grasses. Crop Sci. 25: 215-220.

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger. 2014. Cover crops in the upper Midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. J. Soil Water Cons. 69: 279-291.

Langell, G., B. Montgomery, and R. Stonebraker. 1998.Establishing warm-season grasses in Indiana. Indiana DNR, Division of Fish & Wildlife. Indianapolis, IN. pp. 6.

Lenssen, A.W., and S.D. Cash. 2011. Annual warm-season grasses vary for forage yield, quality, and competitiveness with weeds. Archives Agron. Soil Sci. 57: 839-852.

Lu, Y.C., K.B. Watkins, J.R Teasdale, and A.A. Abdul-Baki. 2000. Cover crops in sustainable food production. Food Rev. Intern. 16: 121-157.

Malczewski, J. 2004. GIS-based land-use suitability analysis: A critical overview. Progr. Plan. 62: 2-65.

McVay, K., M. Burrows, F. Menalled, and K. Wanner. 2010. Montana wheat production guide. Montana State University Extension – Publication. Bozeman, MT. 32 pp.

Miller, P.R., and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the Northern Great Plains. Agron. J. 97:189-200.

Montana Department of Revenue. 2016. Montana agricultural land classification manual 2017-2018. MDR – Property Assessment Division. Helena, Montana. https://revenue.mt.gov/Portals/9/property/appraisal_manual/2017-2018_agricultural_land_classification_manual.pdf. [verified: 1 Jun 2017].

Montana State Library Cadastral Parcel Data. 2016. Published land ownership and usage data layer [ArcGIS]. Available at: http://geoinfo.msl.mt.gov/Home/msdi/cadastral. [Verified: 11 Nov 2016]. State of Montana, Helena, MT.

NASP. 2010. A pivotal time in agriculture. (pp. 43–82). In: Toward Sustainable Agricultural Systems in the 21st Century: The National Academies Press.

Russelle, M.P., M. H. Entz, A. J. Frazluebbers. 2007. Reconsidering Integrated Crop-Livestock Systems in North America. Agron. J. 99: 325-334.

Sanderson, M.A., M.A. Liebig, J.R. Hendrickson, S.L. Kronberg, D. Toledo, J.D. Derner, and J.L. Reeves. 2015. Long-term agroecosystem research on Northern Great Plains mixed-grass prairie near Mandan, North Dakota. Can. J. Plant Sci. 95: 1101-1116.

Snap, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping systems niches. Am. Soc. Agric. J. 97: 322-323.

Sulc, M.R., and A.J. Franzluebbers. 2014. Exploring integrated crop-livestock systems in different ecoregions of the United States. Euro. J. Agron. 57: 21-30.

Tallman, S.M. 2014. Cover crop mixtures as partial summerfallow replacement in the semi-arid northern Great Plains. MS Thesis, Montana State University, Bozeman, MT. 146 pp.

Tanaka, D.L., A. Bauer, and A.L. Black. 1997. Annual legume manures and conservation tillage for grain sorghum production on prairie soil. Soil Sci. Soc. Am. J. 58: 1518-1524.

Tanaka, D.L., D. J. Lyon, P. R. Miller, S. D. Merrill, and B. G. McConkey. 2010. Soil and Water Conservation Advances in the Semiarid Northern Great Plains. In: Soil and Water Conservation Advances in the United States. Eds: T.M. Zobeck, and W.F. Schillinger. SSSA – Spec. Pub. 60. SSSA, Madison, WI. pp. 81-102.

Tiemen, R., T. Fairhurst, S. Zingore, M. Fisher, T. Oberthur, and A. Whitbread. 2016. Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. Euro. J. of Agron. 81: 1-14.

Toy, T.J., A.J. Kuhaida, and B.E. Munson. 1978. The prediction of mean monthly soil temperature from mean monthly air temperature. Soil Sci. 126: 181-189.

Tracy, B. F., and Y. Zhang. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Sci. 48: 1211-1218.

USDA, National Agricultural Statistics Service. Montana 2016 Agricultural Statistics, 2014-2015 County Estimates. USDA-NASS, Washington, DC. https://www.nass.usda.gov/Statistics_by_State/Montana/Publications/Annual_Statistical_Bulletin/2016/Montana_Annual_Bulletin_2016.pdf.

USDA, National Agricultural Statistics Service Cropland Data Layer. 2017. Published crop-specific data layer [ArcGIS]. https://nassgeodata.gmu.edu/CropScape/. [Verified 11 Nov 2016]. USDA-NASS, Washington, DC.

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68: 1403-1409.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, F. Selles, R. Lemke, P.G. Jefferson, and Y. Gan. 2004. Long-term assessment of management of an annual legume green manure crop for fallow replacement in the Brown soil zone. Can. J. Plant Sci. 84: 11–22.

CHAPTER FOUR

EPILOGUE

Background

I have always been curious. It was my curiosity that led my research away from a wildlife biology/management focus and toward agroecology. My first research project, as an undergraduate, examined montane amphibian and fish population dynamics in the Absaroka-Beartooth Mountains of Montana. When offered the opportunity to continue my amphibian research or pursue a new project the following spring, my curiosity won out and I began work studying weed vectors and native rangeland plant communities' resistance to weed invasion in eastern Montana. A couple years later, after mulling over graduate school and project options, my curiosity won out again and I took a position studying a mostly foreign concept to me – agroecology. Thankfully, with the guidance of my advisor, Perry Miller, and other committee members, and with help from several research technicians and associates, graduate students, and friends, I was able to put together an interesting and relevant thesis examining how cover crop seasonality and grazing cover crops affect cash crop yields and edaphic parameters. Additionally, with the help of Luke Ward, I was able to conduct a fairly novel analysis predicting land suitability for warm-season cover crop and integrated crop-livestock adoption. It is my hope that this thesis, in some small way, adds valuable knowledge along the path toward more sustainable agroecosystems in Montana and the Northern Great Plains.

Conclusions and Research Moving Forward

One of the big take-aways from this research is that, after one year of cover cropping, wheat yields in cover copped treatments were not statistically different from fallow. This was a result of adequate soil water recharge as Fort Ellis, Montana receives 500 mm of annual precipitation, making it a high outlier for most of Montana's wheat-producing regions. However, the fallow treatment did have higher protein wheat than cover cropped treatments – a result of short-term soil Nitrate-N uptake by cover crops and soil microbes. It is likely that, with additional rotations, cover cropped treatments would accumulate more soil Nitrate-N that the fallow treatment.

While Fort Ellis is an anomaly in terms of annual precipitation when compared to most of the major wheat-production regions of Montana, the second field site in the northern Gallatin Valley (NGV), Montana, receives similar precipitation to the major wheat-producing regions of Montana with a long-term annual average of 350 mm. The NGV field site will continue to be studied and produce further insights as to how cover cropping and grazing both cool- and warm-season cover crop polycultures affect soil and wheat yield parameters.

Cover crops performed well as a forage in terms of biomass production and quality indicating high potential for grazing cover crops as means for offsetting the marginal costs associated with cover cropping over the short-term. However, the results of my research may have been skewed by the two incredibly dry Junes experienced at both field sites. Warm-season treatments produced much less biomass than did warm-season treatments – a direct result of the drought conditions. Further research investigating warm-season cover crops as both a forage and a means of adding diversity to crop rotations may tell a more complete story than my findings.

One of the largest limitations of my field research was its short duration. Soil changes slowly and, while I found some interesting trends in soil nutrient pools and cycling, it may take several wheat-cover crop/grazing rotations to fully understand how both cover cropping and grazing affect dryland systems in Montana. Few edaphic differences were noted between grazed and non-grazed treatments. However, after multiple rotations, I suspect that a greater number of and more defined differences between grazed and non-grazed treatments would be observed.

The Land Suitability Analysis (LSA) I conducted in four exemplary Montana counties produced promising results for warm-season cover cropping and integrated crop-livestock adoption. Both Fergus and Fallon Co.'s appear to have regions that are highly suitable for warm-season cover crop production, while all four study counties also have areas where integrated crop-livestock systems (ICLS) are a logistical possibility. Further plot- and field-scale research testing the warm-season model as well as producer surveys probing for interest in and ways to create ICLS would build upon this research and help refine future LSA's related to Montana agriculture.

BIBLIOGRAPHY

Acosta-Martinez, V., T.M. Zobeck, and V. Allen. 2004. Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci. Soc. Am. J. 68: 1875-1884.

Acosta-Martinez, V., M.M. Mikha, and M.F. Vigil. 2007. Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat-fallow for the Central Great Plains. App. Soil Eco. 37:41-52.

Acosta-Martinez, V., R. Lascano, F. Calderon, J.D. Booker, T.M. Zobeck, and D.R. Upchurch. 2011. Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil. Bio. Fert. Soils 47: 655-667.

Akinci, H., A.Y. Ozalp, and B. Turgut. 2013. Agricultural land use suitability analysis using GIS and AHP technique. Comp. Elec. Agric. 97: 71-82.

Allen, B.L., J.L. Pikul, Jr., J.T. Waddell, and V.L. Cochran. 2011. Long-term lentil green-manure replacement for fallow in the semiarid northern Great Plains. Agron. J. 103:1292-1298.

Amiri, F., A.R.B.M. Shariff, and T. Tabatabaie. 2012. Monitoring land suitability for mixed livestock grazing using Geographic Information Systems (GIS). (pp.241-266). *In:* Application of Geographic Information Systems. ed: B.M Alam. InTech Publishing, Rijeka, Croatia.

Anderson, R.L. 2008. Diversity and no-till: Keys for pest management in the U.S. Great Plains. Weed Sci. 56: 141-145.

Applied Climate Science Lab at the University of Idaho. 2016. Gridded surface meteorological data. University of Idaho, Moscow, ID. http://climate.northwestknowledge.net/METDATA/. [Verified: 21 Mar 2017].

Arbuckle Jr., J.G, and G. Roesch-McNally. 2015. Cover crop adoption in Iowa: The role of perceived practice characteristics. J. Soil Water Cons. 70: 418-429.

Arzanie, H., A. R. Mousavi, M. J. Shalamzary, G. Ajdary. 2014. Range suitability model for livestock grazing. Intern. J. Sust. Develop. 7: 105-112.

Assmann, T.S, M. A. de Bortolli, A.L. Assmann, A. B. Soares, C. S. Rocha Pitta, A.J. Franzluebbers, C. L. Glienke, J.M Assmann. 2014. Does cattle grazing of duel purpose wheat accelerate the rate of stubble decomposition and nutrients released? Agric., Ecosyst., & Envi. 190: 37-42.

Baccara, M., D. Backus, H. Bar-Isaac, L. Cabral, and L. White. 2003. Monsanto's Roundup®. New York Univ. L.N. Stern School of Business, Firms and markets mini-case. 14 July 2003. http://pages.stern.nyu.edu/~lcabral/teaching/monsanto.pdf.

Barbari, M., L. Conti, B.K. Koostra, G. Masi, F. Sorbetti Guerri, S.R. Workman. 2006. The use of Global Positioning and Geographical Information Systems in the management of extensive cattle grazing. Biosyst. Engin. 95: 271-280.

Barman, D., D.K. Kundu, S. Pal, S. Pal., A.K. Chakraborty, A.K. Jha, S.P. Mazumdar, R. Saha, and P. Bhatttacharyya. 2017. Soil temperature prediction from air temperature for alluvial soils in lower Indo-Gangetic plain. Int. Agrophys. 31: 9-22.

Bardgett, Richard D., David A. Wardle, Gregor W. Yeates. 1998. Linking above-ground and below-ground interactions: How plant responses to foliar herbivory influence soil organisms. Soil Bio. & Biochem. 30: 1867-1878.

Bardgett, R. D., D. A. Wardle. 2010. Ecosystem-level significance of aboveground consumers. (pp 113-167). In: Aboveground-Belowground Linkages: Biotic Interactions, Ecosystem Processes, and Global Change. Oxford University Press. Oxford, U.K.

Bedell, T.E. 1967. Estimated digestibility of diets of cattle and sheep grazing two pasture mixtures. Pro. West. Sect. Amer. Soc. Anim. Sci. 18: 225-230.

Berry, J.K. 2013. "GIS evolution and future trends. *In:* Beyond Mapping III. Basis Press, Fort Collins, CO. Available at: [http://www.innovativegis.com/basis/mapanalysis/Default.htm]. [verified: 15 Dec 2016].

Biederbeck V.O., O.T. Bouman, C.A. Campbell, L.D. Bailey, and G.E. Winkleman. 1996. Nitrogen benefits from four green-manure legumes in dryland cropping systems. Can. J. Plant Sci. 76: 307-315.

Biederbeck V.O., C.A. Campbell, V. Rasiah, R.P. Zentner, G. Wen. 1998 Soil quality attributes as influenced by annual legumes used as green manure. Soil Biol. & Biochem.30:1177-1185.

Biederbeck, V.O., R.P. Zentner and C.A. Campbell. 2005. Soil microbial populations and activities as influenced by legume green fallow in a semiarid climate. Soil Biol. and Biochem. 37: 1775-1784.

Blanco-Canqui, H., and R. Lal. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil Till. Res. 95: 240-254.

Boitt, M.K., C.N. Mundia, P. K. E. Pellikka, and J. Kapoi. 2015. Land suitability assessment for effective crop production, a case study of Taita Hills, Kenya. J. Agric. Inform. 6: 23-31.

Calderon, F.J., D.C. Nielsen, V. Acosta-Martinez, M.F. Vigil, and D. Lyon. 2016. Cover crop and irrigation effects on soil microbial communities and enzyme activity in semiarid agroecosystems of the central Great Plains of North America. Pedosphere. 26: 192-205.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80: 179-192.

Carr, P.M., R.L. Anderson, Y.E. Lawley, P.R. Miller, and S.F. Zwinger. 2012. Organic zero-till in the northern US Great Plains Region: Opportunities and obstacles. Renew. Agric. Food Sys. 27:12-20.

Clark, J. T., J.R. Russell, D. L. Karlen, P.L. Singleton, W. D. Busby, and B. C. Peterson. 2004. Soil surface property and soybean yield response to corn stover grazing. Agron. J. 96:1364-1371.

Collins, M. 1988. Composition and fiber digestion in morphological components in alfalfa-timothy sward. Anim. Feed Sci. Tech. 19:135-143.

Costa, S.E.V.G.A, E.D. Souza. I. Anghinoni, P.C.F. Carvalho, A.P. Martins, T.R. Kunrath, D. Cecagno, F. Balerini. 2014. Impact of an integrated no-till crop-livestock system on phosphorous distribution, availability and stock. Agric., Ecosyst., & Environ. 190: 43-51.

Cutforth, H.W., B.G. McConkey, D. Ulrich, P.R. Miller, and S.V. Angadi. 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian prairie. Can. J. Plant Sci. 82: 681-686.

Dick, R.(ed.). 2011. Methods of Soil Enzymology. SSSA Book Ser. 9. SSSA and ASA. Madison, WI.

Dunbabin, V., A. Diggle, and Z. Rengel. 2003. Is there an optimal root architecture for nitrate capture in leaching environments? Plant, Cell, Environ. 26: 825- 844.

Dwyer, L.M., H.N. Heyhoe, and J.L.B. Culley. 1990. Prediction of soil temperature from air temperature for estimating corn emergence. Can. J. Plant Sci. 70: 619-628.

El Baroudy, A.A. 2016. Mapping and evaluating land suitability using a GIS-based model. 2016. Catena. 140: 96-104.

Engel, R.E., P.R. Miller, B.G. McConkey, R. Wallander, and J.A. Holmes. 2017. Soil organic C changes to ten years of increasing cropping system intensity and no-till in a semiarid climate of the northern Great Plains. Soil Sci. Soc. Am. J. 81:404-413.

ESRI. 2016. “Tools – Majority Filter” webpage. Available at: http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/majority-filter.htm. Verified: 2 Apr 2016. Redlands, CA.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: The significance of cropping intensification. Soil Sci. Soc. Am. J. 62: 984-991.

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Hardwood, J.M. Squire, and C.C Sheaffer. 2000. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93: 319-325.

Fiskel, J. 2003. Designing resilient, sustainable systems. Environ. Sci. Tech. 37: 5330-5339.

Florence, A. 2016. Cover crop mixture diversity and function. Ph.D. dissertation. University of Nebraska, Lincoln. 141 pp.

Fracasso, A., L.M. Trindade, S. Amaducci. 2016. Drought stress tolerance strategies revealed by RNA-Seq in two sorghum genotypes with contrasting WUE. BMC Plant Biol. 16: 1-18.

Ford, G. L., J.L. Krall. 1979. The history of summer fallow in Montana. Volume 704 Montana Agric. Exper. Bull. Montana State University. Bozeman, MT.

Ford, G. L., J.L. Krall. 1979. The history of summer fallow in Montana. Volume 704 Montana Agric. Exper. Bull. Montana State University. Bozeman, MT.

Fornara, D.A., and D. Tilman. 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. J. Ecol. 96: 314–322.

Fraase, A.R., B.W. Neville, D.L. Whitted, P.E. Nyren, G.P. Lardy, and K.K. Sedivec. 2010. Utilizing annual forages in a single and dual cropping system for late-fall and early winter grazing: Impacts on forage production and quality, cow performance, soil health , and economics. pp 1–12. https://www.ag.ndsu.edu/centralGrasslandsREC/cgrec-annual-reports-1/2010-report/Cover_crops_2010.pdf. [Verified: Dec 1, 2016].

Gerik, T., B. Bean, and R. Vanderlip. 2003. Sorghum Growth and Development. Agric. Comm. Texas A&M University. College Station, TX.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Till. Res. 82: 121-145.

Hatfield, P.G., R.A. Field, J.A. Hopkins, and R. W. Kott. 2000. Palatability of wethers fed an 80% barley diet processed at different ages and of yearling wethers grazed on native range. J. Animal Sci. 78:1779-1785.

Hatfield, P.G., H.B. Goosey, T.M. Spezzano, S.L. Blodgett, A.W. Lenssen, and R.W. Kott. 2007. Incorporating sheep into dryland grain production systems: III. Impact on changes in soil bulk density and soil nutrient profiles. Small Rumin. Res. 67: 222-232.

Helms, T.C., E.L. Deckard, and P.A. Gregoire. 1997. Corn, sunflower, and soybean emergence influenced by soil temperature and soil water content. Agron. J. 89:59-63.

Hendrix P.F, D.A. Crossley, Jr., J.M. Blair, and D.C. Coleman. 1990. Soil biota as components of sustainable agroecosystems. (p 637-654). In: Sustainable Agricultural Systems, editors C.A. Edwards, R. Lal, P. Madden, R.H. Miller, and G House. Soil and Water Conservation Society, Ankeny, IA.

Hilimire, K. 2011. Integrated crop/livestock agriculture in the United States: A review. J. Sust. Agric. 35:376-393.

Hopkins, L., 1977. Methods for generating land suitability maps: a comparative evaluation. J. Am. Inst. Plan. 34 19–29.

Housman, M.L. 2016. Multi-species cover crops in the northern Great Plains: An ecological perspective on biodiversity and soil health. MS Thesis. Montana State University, Bozeman, MT. 160 pp.

Hsu, F.H., C.J. Nelson, and A.G. Matches. 1985. Temperature effects on germination of perennial warm-season forage grasses. Crop Sci. 25: 215-220.

Hudson, B.D. 1994. Soil organic matter and available water capacity. J. Soil Water Cons. 49: 189-194.

Jones, C., R. Kurnick, P. Miller, K. Olson-Rutz, C. Zabinski. 2015a. 2015 Montana cover crop survey results. Montana State University, Bozeman, MT. http://landresources.montana.edu/soilfertility/documents/PDF/reports/2015CCSurveyReport.pdf.

Jones, C., P. Miller, M. Burgess, S. Tallman, M. Housman, J. O'Dea, A. Bekkerman, and C. Zabinski. 2015b. Cover cropping in the semi-arid west: Effects of termination timing, species, and mixtures on nitrogen uptake, yield, soil quality, and economic return. Proc. Western Nutrient Manag. Conf. 5-6 Mar 2015. Reno, NV. 11:39-45. https://www.ipni.net/ipniweb/conference/wnmc.nsf/e0f085ed5f091b1b852579000057902e/4be3031d1d87927a85257e37004fa7a8/$FILE/00%20WNMC15%20Title%20Page%20&%20Table%20of%20Contents.pdf.

Keeney, D. 1982. Nitrogen – availability indices. (pp. 711–733) In: Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. ed. S. Segou. SSSA, Madison, WI.

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger. 2014. Cover crops in the upper Midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. J. Soil Water Cons. 69: 279-291.

Kott, R.W. 2007. Montana farm and flock sheep production handbook. Montana State University Extension Publication. Bozeman, MT. [http://animalrangeextension.montana.edu/sheep/handbook-TOC.html].

Kou, S. 1996. Phosphorous. p. 869-915. In: Methods of Soil Analysis, Part 3. Chemical Methods. Eds D.L. Sparks. SSSA Book Ser. 5. SSSA and ASA. Madison, WI.

Lalman, D. 2004. Nutrient requirements of beef cattle. Oklahoma State University Extension Publication. Stillwater, Ok. pp. 24.

Langell, G., B. Montgomery, and R. Stonebraker. 1998. Establishing warm-season grasses in Indiana. Indiana DNR, Division of Fish & Wildlife. Indianapolis, IN. pp. 6.

Lenssen, A.W., and S.D. Cash. 2011. Annual warm-season grasses vary for forage yield, quality, and competitiveness with weeds. Archives Agron. Soil Sci. 57: 839-852.

Lloveras, J. 1990. Dry matter yield and nutritive value of four summer annual crops in north-west Spain (Galicia). Grass For. Sci. 45: 243-248.

Lu, Y.C., K.B. Watkins, J.R Teasdale, and A.A. Abdul-Baki. 2000. Cover crops in sustainable food production. Food Rev. Intern. 16: 121-157.

Malczewski, J. 2004. GIS-based land-use suitability analysis: A critical overview. Progr. Plan. 62: 2-65.

Marchao, R. L., T. Becquer, D. Brunet, L. C.Balbino, L. Vilela, and M. Brossard. 2009. Carbon and nitrogen stocks in a Brazilian clayey Oxisol: 13-year effects of integrated crop-livestock management systems. Soil Till. Res. 103: 442-450.

McCauley, A., C. Jones, P. Miller, M. Burgess, and C. Zabinski. 2012. Nitrogen fixation by pea and lentil green manures in a semi-arid cropping system: Effect of planting and termination time. Nutr. Cycl. Agroecosyst. 92: 305-314.

McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24: 560-570.

McVay, K., M. Burrows, F. Menalled, and K. Wanner. 2010. Montana wheat production guide. Montana State University Extension – Publication. Bozeman, MT. 32 pp.

Mendas, A, and A. Delali. 2012. Integration of multicriteria decision analysis in GIS to develop land suitability for agriculture: Application to durum wheat cultivation in the region of Mleta in Algeria. Comp. Electr. Agric. 83, 117–126.

Miller, P.R., W. Lanier, S. Brandt. 2001. Using growing degree days to predict plant stages. Montana State University Extension – Publication. Bozeman, MT.

Miller, P.R., and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the northern Great Plains. Agron. J. 97:189-200.

Miller, P.R., E.J. Lighthiser, C.A. Jones, J.A. Holmes, T.L. Rick, and J.M. Wraith. 2011. Pea green manure management affects organic winter wheat yield and quality in semiarid Montana Can. J. Plant Sci. 91: 497-508.

Miller, P.R., A. Bekkerman, C. A. Jones, M. H. Burgess, J. A. Holmes, and R.E. Engel. 2015. Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. Agron. J. 107: 541-550.

Montana Dept. Commerce. 2017. Census & economic information center – select Montana agricultural commodities dashboard. http://ceic.mt.gov/Economics/AgricultureDashboard.aspx. [Verified: Jan 2, 2017].

Montana Department of Revenue. 2016. Montana agricultural land classification manual 2017-2018. MDR – Property Assessment Division. Helena, Montana. https://revenue.mt.gov/Portals/9/property/appraisal_manual/2017-2018_agricultural_land_classification_manual.pdf. [verified: 1 Jun 2017].

Montana State Library Cadastral Parcel Data. 2016. Published land ownership and usage data layer [ArcGIS]. Available at: http://geoinfo.msl.mt.gov/Home/msdi/cadastral. [Verified: 11 Nov 2016]. State of Montana, Helena, MT.

NASP. 2010. A pivotal time in agriculture. (pp. 43–82). In: Toward Sustainable Agricultural Systems in the 21st Century: The National Academies Press.

Nielsen, D.C., D.J. Lyon, R.K. Higgins, G.W. Hergert, and J.D. Holman. 2015. Cover crop effect on subsequent wheat yield in the central Great Plains. Agron. J. 108: 243-256.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland dropping systems in the Great Plains. Agron. J. 97: 364-372.

O’ Dea, J.K. 2011. Greening summer fallow: Agronomic and edaphic implications of legumes in dryland wheat agroecosystems. MS Thesis, Montana State University, Bozeman, MT. 145 pp.

O’Dea, J.K., P.R. Miller and C.A. Jones. 2013. Greening summer fallow with legume green manures: On-farm assessment in north-central Montana. J. Soil Water Conserv. 68:270-282.

Ogejo, J.A., S. Wildeus, P. Knight, and R.B. Wilke. 2010. Estimating goat and sheep manure production and their nutrient contribution in the Chesapeake Bay watershed. Appl. Eng. Agric. 26: 1061-1065.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorous. (pp 403-430). In: Methods of Soil Analysis, Part 2, 2nd Ed. Eds: A.L. Page. Agron. Mongr. No. 9 ASA and SSA. Madison, WI.

Or, D., and J.M. Wraith. 1999. Soil water content and water potential relationships. (pp A53-A85). In: Handbook of Soil Science. Eds. M. Summer. CRC Press, Boca Raton, FL.

Ortiz, R., K. D. Sayre, B. Govaerts, R. Gupta, G.V. Subbaroa, T. Ban, D. Hodson, J.M. Dixon, J. I. Ortiz-Monsaterio, and M. Reynolds. 2008. Climate change: Can wheat beat the heat? Agric., Ecosys., & Environ. 126: 46-58.

Parham, J.A., and Deng, S.P. 2000. Detection, quantification and characterization of β-glucosaminidase activity in soil. Soil Biol. Biochem. 32: 1183–1190.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Ag. 9: 180-186.

Powell, J.M., and M.A. Mohammed-Saleem. 1987. Nitrogen and phosphorus transfers in a crop-livestock system in West Africa. Agric. Syst. 25: 261-277.

Robertson, G.P., and S.M. Swinton. 2005. Reconciling Agricultural Productivity and Environmental Integrity: A Grand Challenge for Agriculture. Front. Ecol. Environ. 3: 38-46

Ruess, L., and H. Ferris. 2004. Decomposition pathways and successional changes. Nematology Monographs and Perspectives. 2: 547-556.

Russelle, M.P., M. H. Entz, A. J. Frazluebbers. 2007. Reconsidering Integrated Crop-Livestock Systems in North America. Agron. J. 99: 325-334.

Sainju, U.M, B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil & Till. Res. 63: 167-179.

Sainju, U.M., A.W. Lessen, H.B. Goosey, E. Snyder, and P.G. Hatfield. 2011. Sheep grazing in a wheat-fallow system affects dryland soil properties and grain yield. Soil Sci. Soc. Am J. 75: 1789-1798.

Sanderson, M.A., M.A. Liebig, J.R. Hendrickson, S.L. Kronberg, D. Toledo, J.D. Derner, and J.L. Reeves. 2015. Long-term agroecosystem research on Northern Great Plains mixed-grass prairie near Mandan, North Dakota. Can. J. Plant Sci. 95: 1101-1116.

Schillinger, W.F., S.E. Schofstoll, and J. R. Alldredge. 2012. Predicting wheat grain yields based on available water. Washington State University Extension Publication. Pullman, MT. pp. 7. http://cru.cahe.wsu.edu/CEPublications/EM049E/EM049E.pdf.

Schomberg, H.H., D.W. Reeves, D.S. Fisher, R.L Raper, D.M Endale, M. Jenkins. Evaluating stocker cattle in a Southern Piedmont conservation tillage cotton-cover crop system to increase productivity. In: Proceedings of 30th Southern Agriculture Systems Conference, and 8th Annual Georgia Conservation Production Systems Training Conference. Eds. D.M. Endale 29-31 July 2008. Tifton, Georgia.

Serba, D.D. and R.S. Yadav. 2016. Genomic tools in pearl millet breeding for drought tolerance: Status and prospects. Front Plant Sci.7. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5118443/.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66: 1296-1303.

Sher, H., M. Ansar, F.U. Hassan, G. Shabbir, and M.A. Malik. 2012. Hydrocyanic acid content variation amongst sorghum cultivars grown with varying seed rates and nitrogen levels. Intern. J. Agric. and Biol. 14: 720-726.

Shrestha, B.M., B.G. McConkey, W.N. Smith, R.L. Desjardins, C.A. Campbell, B.B. Grant, and P.R. Miller. 2013. Effects of crop rotation, crop type and tillage on soil organic carbon in a semiarid climate. Can. J. Soil Sci. 93: 134-146.

Six, J., K. Paustian, E. T. Elliott, and C. Combrink. 2000. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated Carbon. Soil Sci. Soc. Am. J. 64:681-689.

Snap, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O’Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping systems niches. Am. Soc. Agric. J. 97: 322-323.

Sulc, M.R., and A.J. Franzluebbers. 2014. Exploring integrated crop-livestock systems in different ecoregions of the United States. Euro. J. Agron. 57: 21-30.

Tallman, S.M. 2014. Cover crop mixtures as partial summerfallow replacement in the semi-arid northern Great Plains. MS Thesis, Montana State University, Bozeman, MT. 146 pp.

Tanaka, D.L., and J.K. Aase. 1987. Fallow method influences on soil water and precipitation storage efficiency. Soil Till. Res. 9:307–316.

Tanaka, D.L. 1989. Spring wheat parameters as affected by fallow methods in the Northern Great Plains. Soil Sci. Soc. Am. J. 35: 1518-1524.

Tanaka D.L., A. Bauer, and A.L. Black. 1997.Annual legume cover crops in spring wheat- fallow systems. J. of Prod. Ag.10:251-255.

Tanaka, D.L., D. J. Lyon, P. R. Miller, S. D. Merrill, and B. G. McConkey. 2010. Soil and Water Conservation Advances in the Semiarid Northern Great Plains. In: Soil and Water Conservation Advances in the United States. Eds: T.M. Zobeck, and W.F. Schillinger. SSSA – Spec. Pub. 60. SSSA, Madison, WI. pp. 81-102.

Tiemen, R., T. Fairhurst, S. Zingore, M. Fisher, T. Oberthur, and A. Whitbread. 2016. Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. Euro. J. of Agron. 81: 1-14.

Toy, T.J., A.J. Kuhaida, and B.E. Munson. 1978. The prediction of mean monthly soil temperature from mean monthly air temperature. Soil Sci. 126: 181-189.

Tracy, B. F., and Y. Zhang. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Sci. 48: 1211-1218.

USDA Farm Service Agency. 2016. Crop Acreage Data. https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index. [Verified: 2 Jan 2017].

USDA, National Agricultural Statistics Service. Montana 2016 Agricultural Statistics, 2014-2015 County Estimates. USDA-NASS, Washington, DC. https://www.nass.usda.gov/Statistics_by_State/Montana/Publications/Annual_Statistical_Bulletin/2016/Montana_Annual_Bulletin_2016.pdf.

USDA, National Agricultural Statistics Service Cropland Data Layer. 2017. Published crop-specific data layer [ArcGIS]. https://nassgeodata.gmu.edu/CropScape/. [Verified 11 Nov 2016]. USDA-NASS, Washington, DC.

USDA-NRCS. 2009. Radishes: A new cover crop option. Crops & Soils: 14-17. ASA, Madison, WI. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022940.pdf.

USDA-NRCS. 2016. Warm season cover crops and planting specifications. Plant Materials Technical Note (No: TX-PM-16-01). Washington, D.C. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/etpmctn12917.pdf.

van Kessel, C., and C. Hartley. 2000. Agricultural management of grain legumes: Has it led to an increase in nitrogen fixation? Field Crops Res. 65: 165-181.

Vaz, C.M.P., L.H. Bassoi, J. W. Hopmans. 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer -TDR probe. Soil Till. Res. 60: 35-42.

Vigil, M.F. 2013. Standing crop residues and wind erosion. Southeast Area Extension Circular Farm and Ranch Newsletter. 1(3): 1-11.

Wade, T., L. Kurkalova, and S. Secchi. 2016. Modeling field-level conservation tillage adoption with aggregate choice data. J. Agric. and Res. Eco. 41: 266-285.

Wang, G., and M. Danzl. 2014. Annual forage species production on delayed seeding areas in the Missouri Coteau Region of North Dakota. North Dakota State University Extension, Fargo, ND. pp. 1–3.

Wardle, D.A., K.I. Bonner, and G.M. Barker. 2002. Linkages between plant litter decomposition, litter quality and vegetation responses to herbivores. Funct. Ecol. 16: 585-595.

Wardle, D. A., R. D. Bardgett. 2004. Human-induced changes in large herbivorous mammal density: The consequences for decomposers. Front. Ecol. Environ. 2: 145-153.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. Am. J. Altern. Ag. 18: 3-17.

West, A.W., and G.P. Sparling. 1986. Modifications to the substrate-induced respiration method to permit measurement of microbial biomass in soils of differing water contents. J. Microbiol. Meth. 5: 177-189.

Western Regional Climate Center. 2016. Historical climate data. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt1050. [Verified: 20 Dec 2016].

Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68: 1403-1409.

Wilson, J.P. 1999. Local, national, and global applications of GIS in agriculture. (pp. 981-998). In: Geographical Information Systems: Volume 2, Management Issues and Applications. Eds. P.A. Longley, D.J. Maguire, M.F. Goodchild, and D.W. Rhind). John Wiley and Sons, New York, NY.

Yousefi, M. R., and A.M. Razdari. 2015. Application of GIS and GPS in precision agriculture (a review). Intern. J. Adv. Biol. and Biomed. Res. 3: 7-9.

Zentner, R.P., C.A. Campbell, V.O. Biederbeck, F. Selles, R. Lemke, P.G. Jefferson, and Y. Gan. 2004. Long-term assessment of management of an annual legume green manure crop for fallow replacement in the Brown soil zone. Can. J. Plant Sci. 84: 11–22.