

Agriculture MREDI Grant Final Report

Research Center/MAES subproject of the Agriculture MREDI Grant

41W225 – Principal Investigator: Barry Jacobsen; Email: bjacobsen@montana.edu

Executive Summary

All of the funds for the Agriculture MREDI Grant have been expended and the grant has closed with a zero balance and all matching funds have been documented. A final summary report of the grants impacts is in progress.

Expenditures

- Total Personnel Services: \$240,165.68
- Total Operations: \$38,001.32

Pulse Crop Research subproject of the Agriculture MREDI Grant

41W211 – Principal Investigator: Chengci Chen; Email: cchen@montana.edu

Co-investigators: Yesuf Mohammed, Maninder Walia, Perry Miller, Peggy Lamb, Jessica Torrior, Zachariah Miller, Kent McVay, Patrick Carr

List the accomplishments of the project in quantitative and qualitative terms

1) Improve income from lands previously fallowed. Determine what pulse or cover crop mixes, sequences of crops, crop agronomy (variety, fertility, seeding rate, herbicide types and rates to control weeds and avoid carryover to rotational crops) and integrated livestock grazing are ideal to replace the fallow year in diverse environments across the state. Nectar contributions from pulse or cover crops to benefit wheat stem sawfly control will be quantified. This research will be done at the 7 MAES Research Centers to measure responses in a wide range of environments.

- a. Pea and lentil varieties were tested at 7 MAES Research Centers and on-farm locations in 2015, 2016, and 2017. An annual report that summarized the performance of different pea and lentil varieties at diverse environments across Montana was published in 2015 and 2016 and distributed to more than 600 growers in Montana and beyond. The 2017 crop will be harvested in July to August 2017.
- b. Results from 2015 and 2016 were presented to pulse growers at the Montana Pulse Days and the Research Center Field Days.
- c. The Annual Reports were widely used by growers and seed dealers as a guide for selecting pulse varieties to grow in different regions of Montana.
- d. Soil samples were taken from several testing sites for water use, nutrient, and microbial community analysis.
- e. A pea-wheat crop rotation was established at EARC to test water use of pulse crop and how pea as a rotation crop affecting wheat yield and water use.

2) Develop new, improved or quality differentiated products or crops. New products include 1) optical sensor-based spray nozzle controllers that allow spraying of only weeds, 2) peas with improved productivity under low moisture conditions, 3) improved protein content and starch characteristics and

low levels of saponins (off-flavor components) for end users in the food processing industry (current pea varieties have protein contents of 17-28% and it is likely that protein content will become a factor in the pricing of peas), 4) better nitrogen fixing microbial inoculants, 5) microbial inoculants to treat forages to prevent nitrate poisoning, 6) site specific weather sensors and weather-based decision tools for cropping, fertility and pest management decision making. Research on crop improvement will focus on Montana adapted cover crops that can be used for livestock grazing or silage and development of pea and durum wheat varieties that best fit Montana's production environment.

- a. We analyzed the adaptability and stability of different pea and lentil varieties in Montana.
- b. We analyzed the protein and starch contents of different pea varieties grown in different environments of Montana in 2015 and 2016.
- c. One research paper was published in Agronomy Journal in 2017, which was featured by American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, and published in news media. This paper presents the results of pea adaptability, protein and starch contents, and resistant starch when grown in Montana, and factors that affect yield, protein, and resistant starch of peas.

3) Develop OFPE research based on: use of data-intensive site specific monitoring to manage decision making relative to crop yield, crop protein content and site specific fertility and weed management (spraying only where weeds occur) while efficiently using soil water resources. This system will serve as proof-of-concept sites for hypothesis driven research projects and will be a mechanism for defining, implementing and organizing research and results in concert with stakeholders. A **participatory research network (PRN) will be used to engage growers in new technologies to improve environmental and economic sustainability.** The six OFPE sites represent a range of environments, histories of management and potential for visibility to a high number of farmers using wheat/fallow, or wheat/pulse crop rotations. We will develop software that automates data recovery from OFPEs, integrating climate, weather and soil moisture predictions into crop response functions to develop prescription maps for future OFPE and field-wide crop management while addressing input costs, crop prices, protein premiums and livestock integration. An innovative participatory research network (PRN) based on the OFPE work will be developed that will focus on helping farmers and ranchers overcome barriers to the use of new technology by making it locally relevant.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

1. Pea and lentil have been widely adopted by Montana growers. These crops not only are important to Montana economy, but also are beneficial to soil health, pest management, and sustainability of Montana agricultural system.
2. Research on pea and lentil nutrient compositions will result in development of new varieties and new health food products or ingredients.
3. We'll continue to evaluate pea and lentil varieties, and develop cropping systems. We will collaborate with breeders to develop new varieties.

Final Metrics

- Total additional grants received: One statewide pulse crop variety evaluation grant from USASPL
- Total additional grants in progress: one grant proposal was submitted to USDA Specialty Crop Initiative, but was not funded

- Number of partnerships formed (private and public sector): have been working with many private and public sectors on pulse crops for many years.
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: varieties were recommended to growers
- Jobs created: one postdoc researcher, at least 7 part-time research technicians were funded by this grant, at least 10 college and high school students were funded by this grant.

Expenditures

- Total Personnel Services: \$83,672.52
- Total Operations: \$27,877.48

Soil Microbiology and Pea Protein subproject of the Agriculture MREDI Grant

1) 41W212 – Principal Investigator: Perry Miller, Email: pmiller@montana.edu

List the accomplishments of the project in quantitative and qualitative terms

The project objectives were to: a) determine standard management and environmental effects on yellow pea protein, and identify if management variation impacted yellow pea protein content; and b) evaluate the precision of NIR for yellow pea protein predictions. In order to achieve our first objective, over 74 Montana producers provided us with 138 independent yellow pea samples and associated management details from the 2013-2016 growing season. (Thank You!) Observed standard practices for yellow pea growers include, 1) no-till seeding in wheat stubble in April, 2) use of rhizobial inoculant, and 3) use of synthetic fertilizers and pesticides. Protein concentration ranged from 18 to 29%, with the 22-23% category representing the median, and with an overall mean of 23.6%. Yellow pea management varied importantly for rhizobial inoculant type (granular vs. powder), variety, and nutrient management (application of N, P, K, or S fertilizers). Our results showed that severe drought environments increased pea seed protein by ~1.5%-units over wet environments, and that granular inoculant boosted protein by ~1.6%-units relative to powder seed coatings in severe drought environments. The top two yellow pea varieties (CDC Meadow and CDC Treasure) accounted for 52% of all samples collected, and come from the University of Saskatchewan Crop Development Center. The remaining 48% of samples came from more than 18 different pea varieties. Application of N, P, K, or S fertilizers did not have a detectable effect on yellow pea protein.

Our second objective, validating NIR predictions with protein measurements, was accomplished by first setting up a controlled experiment to assess laboratory measurement uncertainty in yellow pea. Specifically, we tested how sample size (1, 2, or 3 Tbsp.) affected differences in duplicated whole seed and flour measurements, using wheat as a control. Results from this experiment showed that there was a tendency for error in protein measurements to become smaller as sample sized increased, especially using pea flour. Measurement error (i.e. differences between duplicate subsamples from the same pea sample) averaged 0.82 and 0.65% for whole seed and flour, respectively, compared to 0.29 and 0.28% in the wheat control. Protein measurement uncertainty was much greater in yellow pea relative to wheat. At this time, we would recommend a minimum of 3 tablespoons of peas be ground prior to standard combustion analysis of pea protein.

Finally, 46 yellow pea samples previously measured using the combustion method were compared with protein predictions made on NIR. Results showed that measured and predicted protein content were

precise to a mean absolute error (MAE) of 1.02%. It may be difficult to achieve greater precision with NIR considering the high laboratory measurement uncertainty in yellow pea, reported above. The degree of precision in current commercial NIR instruments is not known, but may even be less precise than what we reported here.

This observational data has been useful to light pathways for needed research to improve management and measurement of pea protein. Agronomic research into timing and amounts of nitrogen provision to yellow pea is needed to better understand protein formation in this legume crop. In order to generate more precise NIR calibration, more work should be focused at pinpointing sources of protein measurement uncertainty in yellow pea. A standard set of samples could be developed to test NIR prediction precision, if this is of interest to commercial entities who buy peas for protein fractionation.

Project Scope and Objectives

Consumer demand for 'clean label' plant-based protein is rising. This adds intrinsic value for producers growing yellow pea in Montana through protein fractionation. Specifically, if Montana establishes itself as a source of yellow pea with consistently high protein, it is feasible that markets will target yellow pea grown in Montana via bid price and location of delivery facilities for protein fractionation. This will translate to greater revenues for the Montana agricultural sector.

Currently little scientific information is available relating environment (e.g. soils and climate) and management (e.g. nutrient rates, inoculation, seeding date, etc.) to yellow pea protein across Montana. This project's **primary objective** therefore is to identify *standard management* of yellow pea and identify if *standard management* is affecting yellow pea protein across Montana's water-limited growing environments.

Further, if pea protein becomes an important marketing factor, it will be necessary to verify that traditional laboratory control methods for measuring yellow pea protein are in agreement with streamlined technologies used to measure pea protein on an industrial scale. This will ensure that both researchers and industry provide consistent yellow pea protein measurements to producers and consumers alike. Hence a **secondary project objective** is to assess uncertainty in protein **measurements** made by the control laboratory method, or combustion method, (Abatzoglou, 2013) and verify that protein **predictions** made by the streamlined near-infrared (NIR) method commonly used on an industrial scale agree with one another.

Primary Objective Methodology—Comparing the Effects of Standard Management and Drought on Yellow Pea Protein Content.

In order to identify standard management of yellow pea and determine if standard management has an impact on yellow pea protein across Montana, two steps were taken. **First** producers were contacted and asked to complete surveys as well as provide yellow pea samples from their farms. **Second** yellow pea samples were tested for protein, and statistical analysis was performed to identify if the combination of management and environment (e.g. soils and climate) affected yellow pea protein. These steps are detailed below.

Establishing Producer Contact, Surveys, and Sample Collection

Yellow pea producers were informed of the study via flyers, radio/web announcements, phone calls, extension agents, industry contacts, and presentations at pulse grower meetings and field days. Once informed of the study, producers were asked to complete a short survey covering field legal location and

management of their yellow peas. Producers were then asked to send a representative yellow pea field sample (~ a 1 qt. Ziploc Bag) corresponding to each survey to Bozeman for protein testing.

Yellow Pea Protein Testing and Statistical Analysis

Once in Bozeman, yellow pea samples were tested for protein using the combustion method. Put simply, this means that yellow peas were ground into a fine flour, combusted in a crucible, and the amount of nitrogen gas detected from the combusted pea flour was used to calculate the percent protein in each ground sample.

The combustion method only requires a small volume of seeds to make a protein measurement, so in order to get a better estimate of the protein in the overall sample or *bulk sample*, protein was measured twice per sample or in *duplicate*. Duplicated protein measurements were then averaged to estimate the bulk sample protein.

Bulk pea protein measurements were then linked to respective survey responses to address how growing season conditions and management affected protein. Notably seeding date and field legal location information was used in conjunction with available climate (Abatzoglou, 2013), soils (Soil Survey Staff-NRCS, 2015), and pea growing degree day models (Miller and Holmes, unpublished data 2004) to simulate drought stress patterns over the crop cycle. Cluster analysis was then used to group similar drought patterns into discrete drought environments, and select management variables were tested to assess how protein was affected across drought environment using ANOVA.

Primary Objective Results

General Protein Content and Standard Management

A total of 138 yellow pea samples were collected from 73 Montana farms spanning the 2013-2016 growing seasons. The average protein content of these samples was 24%, but protein ranged from 18-29%. (Fig 1.). The primary management variables that were **similar** across farms were as follows.

1. Yellow pea is seeded in April
2. Yellow pea is grown with conventional fertilizer and pesticide inputs
3. Yellow pea is grown on no-till ground
4. Yellow peas are inoculated prior to seeding
5. Yellow peas are seeded following a cereal—generally spring wheat, winter wheat, or durum.

Management variables that were **not similar** across farms are as follows:

1. Variety selection varies both within and across farms. The two predominant varieties are CDC Meadow and CDC Treasure. These varieties constitute 29, and 23% of field samples respectively, while the remaining 48% are comprised of Delta (~11%), Montech 4193 (~7%), AC Agassiz (~6%), Montech 4152 (~5%), Mellow, Korando, Spider, Nette, Salamanca, Trapeze, Bridger, CDC Golden, Capris, Early Star, Jet Set, Admiral, Proseper, and Navarro, and unreported varieties (~19%) (n=138 total samples).
2. Most farms use either granular or peat-powder inoculant. Forty-four percent of farms use granular inoculant and the remaining 54 % use peat-powder inoculant. One farm reported using liquid inoculant, and two farms did not specify if they used inoculant (n=73 separate farms).
3. Nutrient management varies across farms. Thirty-eight percent of farms do not use fertilizer and 62% use various blends and rates of N-P-K-S fertilizer. Of the 62 % of farms that **do** apply

fertilizer (n=45 separate farms that use fertilizer), the proportion that apply N-P-K and S are as follows:

- N: 93 %--Reported rates vary from 2 to 11 lbs ac⁻¹
- P₂O₅: 100 %--Reported rates vary from 15 to 52 lbs ac⁻¹
- K₂O: 18 %--Reported rates vary from 5-10 lbs ac⁻¹.
- S: 64 %--Reported rates vary from 3-8 lbs ac⁻¹.

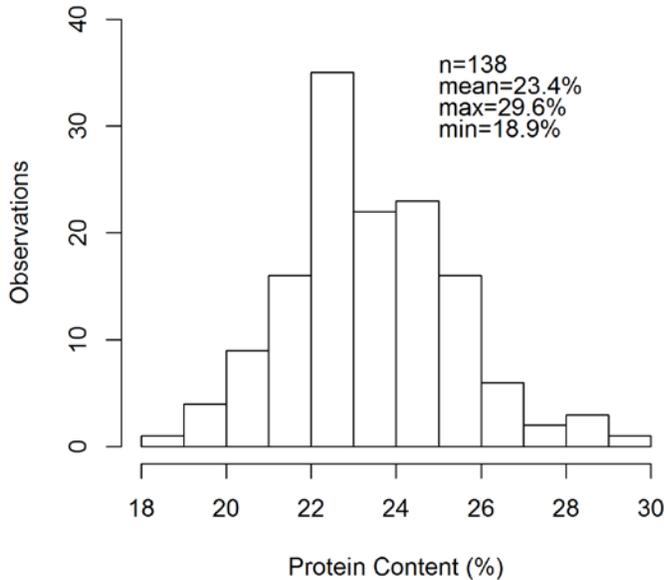


Figure 1. Summary of yellow pea protein content from on-farm samples

The above mentioned management can be considered **current** standard management for yellow pea grown in Montana.

Typical Drought Environments for Yellow Pea Grown Across Montana

Individual drought stress patterns were simulated for each yellow pea sample (n=138) based on seeding date and field legal locations from producer survey, soils (Soil Survey Staff, 2015), climate data (Abatzoglou, 2013), as well as growing degree models to estimate crop growth stages (Miller and Holmes, unpublished data 2004). Each line in Fig. 2 A. represents a simulated drought stress pattern. Drought intensity shown on the vertical axis is expressed as a ratio of 0-1 with a value of 0 indicating no drought stress and a value of 1 indicating extreme drought stress. Growing degree days determined from reported seeding dates and daily temperature data are shown on the horizontal axis. A more detailed description of the mechanics of the simulated drought patterns can be found in (Bestwick, 2016).

Clustering techniques were applied to group simulated drought stress patterns into three drought environments (Fig. 2 B.). The three drought environment can be interpreted as favorable (green), moderate (yellow), and severe (red). In the low stress drought environment, pea did not undergo significant drought stress until after flowering. Low drought stress was due to timely precipitation, heavy soils, and mild temperatures or any combination any combination of these environmental factors among others. Conversely, in the high drought stress environment, pea was subjected to drought stress beginning in the V-stages, increasing to R-stages (e.g. flowering), and lasting to maturity. A high drought

stress environment is indicative of lacking rainfall, hot temperatures, and soils with low water holding capacity.

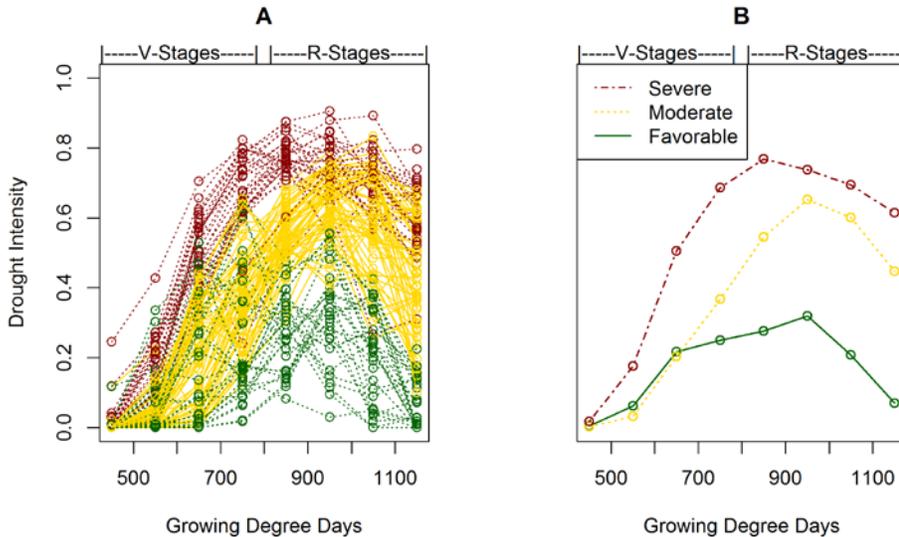


Figure 2. (A) Individual drought simulations, and (B) typical drought patterns derived from clustering techniques. Based on these simulations and characterization techniques, Montana producers can anticipate that their yellow pea crop will typically be subjected to either a favorable, moderate, or severe drought environment. It is further possible that differences in management within each of these drought environments could impact pea protein differently.

Effects of Drought Environment and Management on Pea Protein

Because variety selection, inoculant type, and application of fertilizer represented the most variable standard management factors across farms (*see General Protein and Standard Management*), these were the select management variables tested to address how protein content was affected across typical drought environments.

The specific effects of management by drought environment on pea protein were made as follows:

1. The effect of inoculant type (granular vs. peat powder) and drought environment.
2. The effect of variety and drought environment. Only the varieties CDC Meadow and CDC Treasure were compared since they provided a adequate sample size.
3. The effect of nutrient management and drought environment. The specific nutrient management comparisons that were made were:
 - a. Producers that applied N vs. Producers that did not apply N.
 - b. Producers that applied P vs. Producers that did not apply P.
 - c. Producers that applied K vs. Producers that did not apply K.
 - d. Producers that applied S vs. Producers that did not apply S.

In general, neither drought environment nor management affected yellow pea protein content (Table 1.). However, we did observe that when granular inoculant was used in a severe drought environment, protein increased by 1.64% compared to when peat powder was applied in a severe drought environment. Granular inoculant has been reported to be superior to peat in dry growing conditions at increasing nitrogen fixation (Clayton et al., 2004). Use of granular inoculant in a severe drought environment may have led to better nitrogen fixation and thereby greater protein compared to peat powder.

We also observed that drought environment influenced protein content produced by CDC Meadow and CDC Treasure. Specifically, the highest average protein content across these varieties was 24.4% and was associated with the severe drought environment. Conversely, the lowest average protein content across these varieties was 22.9% and was associated with a favorable drought environment. However, because

neither variety produced greater protein relative to the other across drought environments, it does not appear that choosing to use CDC Treasure or CDC Meadow will have an impact on final protein content.

Nutrient management did not have an effect on yellow pea protein. After a comprehensive review of protein formation in pea, however, these results are expected. Specifically studies throughout the Canadian prairies have found that nutrient management can have a significant effect on yield, but protein is often unaffected (McKenzie et al., 2001a; b). The possibility for yield variation but no change in protein may be due to the indeterminate growth habit of pea. That is, unlike in wheat, pea seed and protein formation occur simultaneously. For instance, under a favorable drought environment, both the rate of nitrogen transferred to seeds which builds protein and seed number are high. This means yields may be high due to large seed number, but protein does not change since nitrogen is distributed among more seeds. Alternatively, with a severe drought environment, the rate of nitrogen transferred to the seed and seed number is lower. This means nitrogen is distributed to fewer seeds, so protein is unaffected, yet yield diminishes. For more details on protein formation in pea and a review of how management has affected protein in pea.

Table 1. Effects of Classified Drought Environments and Select Management Factors on Yellow Pea Protein Content.

Drought Environment	Management Factor				
	Inoculation				
	Granular	Peat	Env. Avg.	P-Values	
Severe	24.53 A	22.89 B	23.74	Drought Environment	NS*
Moderate	23.32 B	23.91 AB	23.62	Inoculation	NS
Favorable	23.13 B	22.83 B	23.02	Drought Environment x Inoculation	P < 0.05
Mgmt. Avg.	23.55	23.45			
	Variety				
	Meadow	Treasure	Env. Avg.		
Severe	24.36	24.33	24.35	A Drought Pattern	P<0.1
Moderate	24.01	23.48	23.75	AB Variety	NS
Favorable	22.59	23.12	22.85	B Drought Environment x Variety	NS
Mgmt. Avg.	23.69	23.53			
	Nitrogen (N)				
	Applied N	No Applied N	Env. Avg.		
Severe	24.31	23.41	23.85	Drought Environment x Nitrogen	NS
Moderate	23.64	23.60	23.62	Nitrogen (N)	NS
Favorable	22.87	23.05	22.99	Drought Environment x Nitrogen	NS
Mgmt. Avg.	23.40	23.67			
	Phosphorous (P)				
	Applied P	No Applied P	Env. Avg.		
Severe	23.33	24.56	23.85	Drought Environment	NS
Moderate	23.61	23.64	23.62	Phosphorous (P)	NS
Favorable	23.15	22.62	22.99	Drought Environment x Phosphorous	NS
Mgmt. Avg.	23.42	23.68			
	Potasium (K)				
	Applied K	No Applied K	Env. Avg.		
Severe	22.18	24.02	23.85	Drought Environment	NS
Moderate	23.86	23.59	23.62	Potasium (K)	NS
Favorable	23.08	22.98	22.99	Drought Environment x Potasium	NS
Mgmt. Avg.	23.30	23.54			
	Sulfur (S)				
	Applied S	No Applied S	Env. Avg.		
Severe	23.13	24.19	23.85	Drought Environment	NS
Moderate	24.13	23.29	23.62	Sulfur (S)	NS
Favorable	23.06	22.92	22.99	Drought Environment x Sulfur	NS
Mgmt. Avg.	23.60	23.46			

*NS=Not significant at the $\alpha=0.1$ level.

Different letters within the same groupings are statistically different at the $\alpha=0.1$ level by Least Square Means

A final reason why relatively few statistical differences were established about how management and drought environment affect yellow pea protein may be due to uncertainty in yellow pea protein measurements. Of the 138 yellow pea bulk samples measured in duplicate, the average difference in duplicate measurements was 1.1% (Fig. 3). Put simply, this means that there is potential for large measurement uncertainty in yellow pea protein, so establishing statistical differences in management and environment would require a larger sample size.

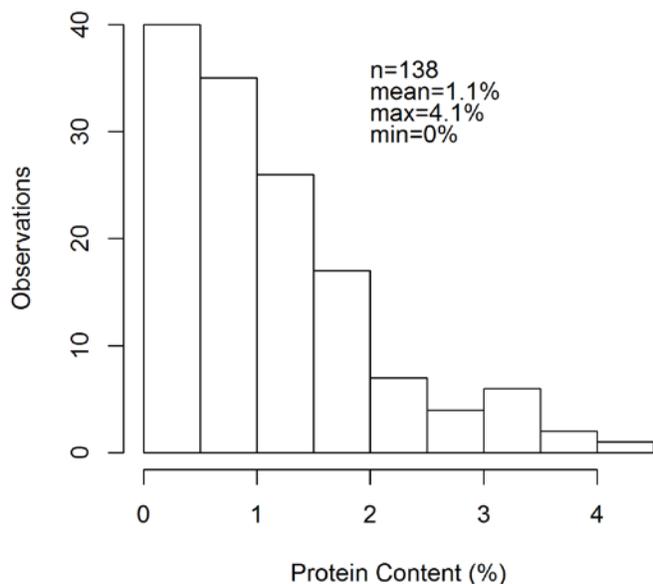


Figure 3. Summary of average difference between duplicated yellow pea protein measurements by the combustion method.

In summary, our results suggest that use of granular inoculant may increase protein, particularly under drought conditions. When comparing only CDC Meadow and CDC Treasure, protein content is determined greatly by growing conditions—higher protein should be expected as drought increases. Use of N, P, K, or S do not appear to influence protein, but the lack of response may be due to the indeterminate growth habit of pea and/or uncertainty in measuring protein content in yellow pea.

Secondary Objective Methodology—Uncertainty in Yellow Pea Protein Measurements by The Standard Laboratory Method and Protein Predictions made by NIR.

There are two primary sources of uncertainty associated with measuring protein using the standard combustion procedure. First there is uncertainty associated with sampling different seeds from the bulk sample (Fig. 4 Left). Second, once seeds have been milled to flour for combustion analysis, there is uncertainty from sampling different portions of the ground sample (Fig 4. Right). One factor that could affect these uncertainties is sample size. For instance, if a duplicate pair of fifty seeds were sampled from the same bulk sample, their respective difference in protein may be larger than a duplicate pair of 100 seeds.



Figure 4. Uncertainty in yellow pea protein measurements may arise from sub sampling different seeds from the bulk sample (left) or sub-sampling different portions of pea flour after whole seeds have been ground (right).

Testing how Subsample volume Affects Uncertainty in Protein Measurements with the Combustion Procedure

To test how sample size affected protein measurement uncertainty, a controlled experiment was established. Four yellow pea and four spring wheat bulk samples were randomly taken from Montana farms. From each bulk sample, four subsample sizes of 1, 2, and 3 tablespoons were ground in a Udy mill with a 1mm screen. Each subsample was then run for total nitrogen using combustion analysis. Protein was then determined by multiplying total nitrogen by 5.80 and 6.25 for wheat and pea respectively. It should be noted that spring wheat was included in the experiment to serve as a control. In other words, we wanted to determine if there was similar protein measurement uncertainty between yellow pea and spring wheat.

The response of interest was the absolute difference in measured protein for the two subsampled pairs corresponding to each crop type by sample volume combination. Analysis of variance (ANOVA) used to test the effects of crop type and sample volume on absolute differences between protein measurements.

Validating Yellow Pea Protein Predictions with Near Infrared (NIR)

Forty-six of the 138 yellow pea samples that had previously been tested for protein using the combustion method (see part A.) were randomly selected. Selected samples were then run on NIR (FOSS Infratec 1241), and protein predictions made by the NIR were compared against protein measurements made by the combustion method. The distance measure, or metric used to gauge the average difference between NIR predictions and combustion measurements, was the mean absolute error (MAE). A low value for the MAE indicates that predicted and measured protein are precise relative to one another, whereas as a high MAE indicates that predicted and measured protein do not agree with one another.

Secondary Objective Results

Effect of Crop and Sample Size on Protein Measurement Uncertainty

Only crop had a significant effect on differences in protein measurements among duplicates (Table 2.). The average difference in protein measurements for ***duplicated whole seed samples*** was 0.29% and

0.82% for wheat and pea respectively. Similarly the average difference for duplicated ground samples was 0.28 and 0.65% for wheat and pea respectively.

Whole Seed Samples					
Sample Size	Crop		Sample Size Avg.	P-Values	
	Wheat	Pea		Sample Size	Crop
One Tbsp.	0.22	1.24	0.73	Sample Size	NS*
Two Tbsp.	0.37	0.50	0.44	Crop	P < 0.05
Three Tbsp.	0.26	0.71	0.49	Sample Size x Crop	NS
Crop Avg.	0.29 A	0.82 B		Seed Lot (Crop)¶	NS
				Sample Size x Seed Lot (Crop)¶	NS
Ground Samples					
Sample Size	Crop		Sample Size Avg.	P-Values	
	Wheat	Pea		Sample Size	Crop
One Tbsp.	0.36	0.99	0.68	Sample Size	NS
Two Tbsp.	0.37	0.59	0.48	Crop	P < 0.05
Three Tbsp.	0.11	0.35	0.23	Sample Size x Crop	NS
Crop Avg.	0.28 A	0.65 B		Seed Lot (Crop)¶	NS
				Sample Size x Seed Lot (Crop)¶	P < 0.05

NS*-no significant differences at the $\alpha=0.05$ level

¶-Indicates random effect

(Crop)-Nested within crop

Different letters within the same groupings are statistically different at the $\alpha<0.05$ by Fisher LSD

There was a tendency to see smaller differences among duplicated measurements with increasing sample size across crop type for both whole seed and ground samples. That is, differences in protein were smaller as sample sized increased. However, our results did not provide strong statistical evidence to verify that increasing sample size would decrease protein measurement uncertainty. Combined these results simply suggest that there is greater protein measurement uncertainty in yellow pea relative to spring wheat.

Uncertainty in yellow pea protein may arise from multiple sources. For instance, All-Khan and Youngs (1972) observed protein could range to ~ 9% among different pea plants. Likewise, Atta et. al. (2004) showed that protein could range by ~10% depending on seed nodal position and variety. Considering that the yellow pea samples for this analysis were taken from different Montana farms, they were undoubtedly inconsistent in location and variety, and it's possible these inconstancies contributed to yellow pea protein uncertainty. Future studies could assess how both variety and location affect uncertainty in yellow pea protein measurements.

Validation of NIR Predictions with Yellow Pea Protein Measurements

Predicted and measured yellow pea protein content determined by NIR and the combustion method agreed with one another with a mean absolute error of 1.02% (Fig. 5). A MAE of 1.02% suggests that yellow pea protein predictions are not highly precise. Lack of precision, importantly, is most likely due to natural variation in yellow pea content as opposed to poor NIR calibration. That is, considering that duplicated protein measurements in pea whole seeds and flour averaged 0.82 and 0.65% (*see above—Effect of Crop and Sample Size on Protein Measurement Uncertainty*), it would be impossible to calibrate NIR with greater precision.

Other researches have in fact had similar difficulty in producing precise calibration for pea protein with NIR. For instance, Tkachuk et al. (1987) calibrated NIR with a 1.34% standard error of prediction for pea

protein. Similarly, Arganosa et al. (2006) achieved a standard error of prediction of 0.94%. Conversely, in wheat, standard error of prediction between measured and predicted protein content has ranged from 0.24% (Williams and Sobering, 1993) to 0.48% (Williams et al., 1985). The better prediction accuracy in wheat relative to pea may simply stem from the lower measurement uncertainty associated with wheat compared to pea.

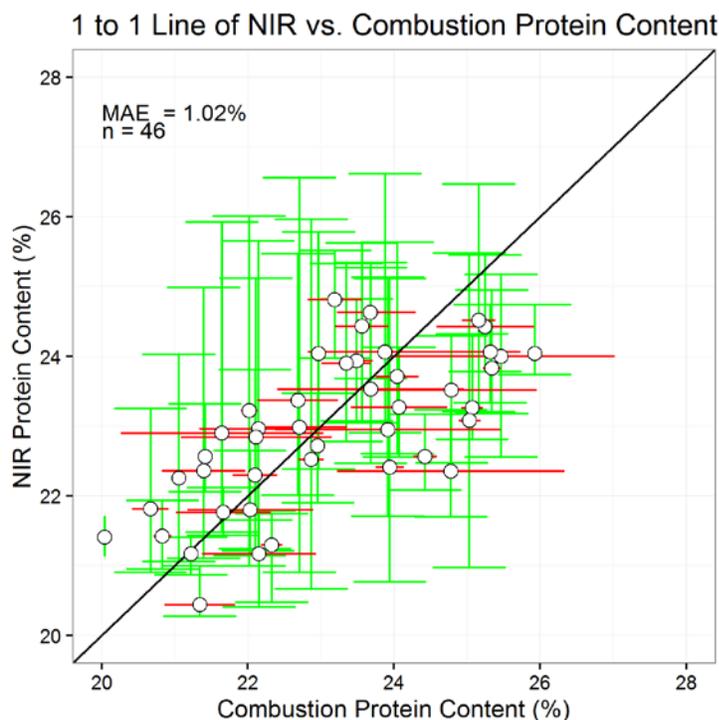


Figure 5. Predicted (NIR) and measured (Combustion) yellow pea protein content. The red horizontal error bars show the range in duplicated measurements from combustion analysis. The green vertical error bars are the range in protein from 5 NIR predictions. The circles represent the averaged protein content.

Based on these protein testing findings, more work could be focused on pinpointing the source of protein measurement uncertainty. For instance, if it could be determined that certain varieties demonstrate greater protein variability relative to others, then it may be worthwhile making variety-specific NIR calibration curves. Better understanding the sources of protein variability in yellow pea measurements could ultimately help ensure that both researchers and industry provide precise yellow pea protein measurements to producers and consumers alike

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: None
- Number of partnerships formed (private and public sector): one main one, and then general with many producers around Montana
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: 1 Research Associate and one occasional, seasonal employee

Expenditures

- Total Personnel Services: \$93,347.66
- Total Operations: \$17,352.34

2) 41W220 – Principal Investigator: John Peters; Email: john.peters@chemistry.montana.edu

List the accomplishments of the project in quantitative and qualitative terms

Background: Montana pulse crops have been a growing section of Montana agriculture for decades. The ability of pulse crops to restore nitrogen reserves in the soil is due to the bacteria they are associated with the pulses. The bacteria that perform nitrogen fixation are called diazotrophs and these diazotrophs not only are symbiotic with the pulse crops but some are free-living. Free-living diazotrophs will produce additional ammonia (NH₃) that can then be used by other non-leguminous plants like wheat. By studying the effects of the wheat/pulse cropping system on the soil microbiome we have determined agricultural characteristic that contribute to changes in the bacterial community structure and direct effects on the diazotrophs.

Accomplishments of the project: The main goals of this project was to monitor and use intervention to discover and maintain an ideal soil microbial community. Through this process of identifying the optimal microbial community for wheat/pulse rotation, farmers will be able to cultivate their soil to provide the best microbiome for their crops of choice. Over the term of the grant we have collected 157 soil samples from 7 agriculture research center (ARC) around Montana. DNA from these samples were extracted and sequenced for overall bacterial diversity, using 16sRNA sequencing, and specific diazotrophic diversity, using nifH sequencing. The soil samples were also chemically tested for all fertility variables (pH, P, K, NO₃, NH₄, organics) and trace elements. Along with argo-economic data collected by collaborators for the different ARCs our lab has collected an immense amount of data covering numerous aspects of the pulse crop agriculture strategies. We have accomplished the main goal of this grant to understand key soil characteristics and start to develop parameters of an ideal nitrogen fixing microbiome. Through the large data sets correlation between multiple variables and microbiome diversity have been made. There is clustering of soil communities from each plot that lead to Changes in the microbiome (Figure 1). Within the diazotrophic community there is distinct community characteristics that are due to essential bacteria (Figure 2). Knowing the bacteria that are directly affected by changes in the farming strategies we can discover inoculants for future studies.

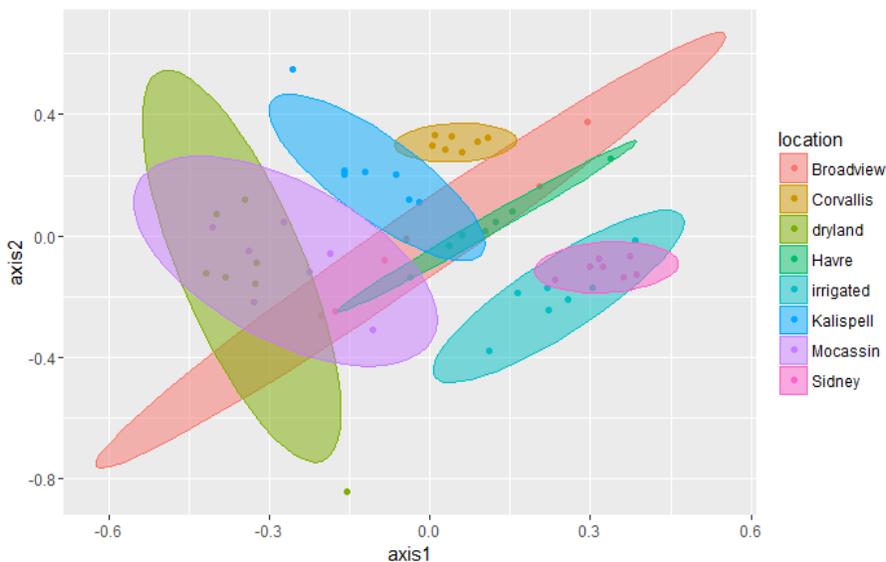


Figure 1: nMDS plot shows the distance characteristics between each plot and variety sample. Each point is a single pea variety at a single sample site. The ellipse statistics (confidence = 95%) shows grouping of geographical variables within in the community structure data. The higher yielding stations (SARC irrigated and EARC) are grouped together with positive influence contributed from axis 1. While other stations show large stratifications across the plot which is due to the large distances in the community trees present in the soil.

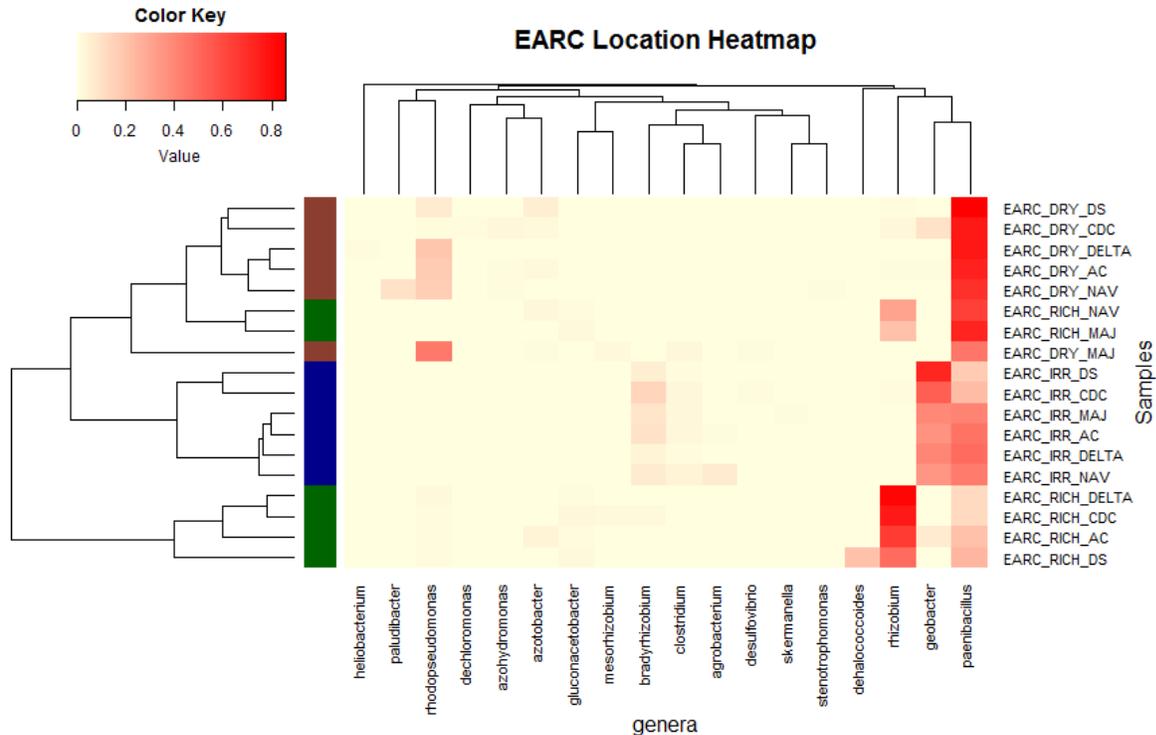


Figure 2: A heat map of the diazotrophic genus that have a larger than 1% abundance in the soil show distinct grouping in different farm plots. The first difference is the presence of the genus *geobacter* in the irrigated soil and its absence or low abundance in others. This is consistent with the idea that in moist soils there is less diffusion of molecular oxygen which will create an environment that favors strict anaerobes. These strict anaerobes have the ability to process N_2 into NH_3 without the added difficulty of compartmentalizing nitrogenase to avoid oxygen. We also see an abundance in the genus *rhizobium* in the Richland plot, this genus is a free living bacteria till it senses exudates from legumes where they can create a symbiotic relationship. Further analysis will lead to soil characteristics that might promote this relationship.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

The collection of microbiome data from across the state will have a large impact on the future farming practices in the state of Montana. With DNA sequencing technologies becoming more accurate and affordable, farmers will be able to assess the health of their soil microbiome and intervene to produce the best bacterial community for their crops. With these future technologies near on the horizon it is important to record and interpret data that help understand the complexity of the soil ecosystem. Our project looked at the particulars in promoting diazotrophic conditions in pulse cropping systems through our studies we have discovered some key indicators that affect the ammonia-producing bacteria. Our data will provide evidence not only on best farming practices for a healthy microbiome but key indicator species that could help offset the use of fertilizers after the pulse rotation.

Expenditures

- Total Personnel Services: \$81,185.52
- Total Operations: \$21,014.48

3) 41W213 – Principal Investigator: Carl Yeoman; Email: carl.yeoman@montana.edu

List the accomplishments of the project in quantitative and qualitative terms

Direct-Fed Microbials To Reduce Rumen Nitrate & Nitrite Levels

Significant opportunities exist to more productively use Montana's 4.6 million acres of crop fallow land each year. One opportunity being explored is terminating fall or spring seeded cover crop mixtures by grazing or ensiling, which could result in substantial economic benefits through delaying the turnout of livestock on summer pastures (increasing carrying capacity and livestock production), and allowing both crop and cattle producers to capture significant market revenues within an integrated production system. However, common cover crops such as brassicas and small grains can accumulate high levels of nitrates (up to 20,000 ppm) which can be toxic to livestock species in doses >5,000 ppm. Under normal physiological conditions, lower levels of ingested nitrate are efficiently converted to nitrite, then to ammonia, amino acids, and finally protein by rumen bacteria. Some bacteria are more efficient at this process and may therefore be useful as direct-fed microbials applied during periods of cover crop grazing to bolster the numbers of these bacteria to mitigate the risk of nitrate poisoning during cover crop termination. This project set out to i) identify and isolate microbes that could be stably introduced to the rumen of cattle and sheep and efficiently reduce nitrate and nitrite to microbial protein; and ii) test the efficacy of 1-2 of these strains for use as direct-fed microbials (**DFMs**) in an animal trial.

Results

The initial phase of the trial set out to isolate nitrate and nitrite utilizers and screen each to determine the rates at which they were able to carry out this process. As these strains would ultimately be required to successfully colonize and carry out these metabolic processes in the rumen of domestic livestock species, we only attempted to isolate microbes from rumen samples. These included rumen samples maintained in our collection from domestic cows (n=2), domestic sheep (Rambouillet, n=4), Bison (n=8), Goat (grass-fed Nubian cross n=4), Elk (n=6), Whitetail deer (n=2), Mule deer (n=1), Moose (n=3) and Antelope (n=2). As a positive control, two strains of rumen-isolated bacteria (*Selenomonas ruminantium* and *Wollinella succinogenes*) previously reported to degrade nitrate and nitrite (IWAMOTO, ASANUMA, & HINO, 2002) were purchased from the American Type Culture Collection (ATCC) for comparison. Isolation of bacteria was performed with media adapted from that described by (Kenters, Henderson, Jeyanathan, Kittelmann, & Janssen, 2011). Briefly, (cas)amino acids and peptone were replaced with 5mM sodium nitrate and 3mM sodium nitrite, rumen fluid was allowed to ferment at room temperature for 24h following collection to reduce background levels ammonia, amino acids, and protein, and solutions were cooled under 95% CO₂, 5% H₂ to make anoxic. For plates, media were solidified with the addition of 15g/L of agar for plates. For each sample (cow, sheep, bison, goat, deer, elk, moose, and antelope), 0.5ml was serially diluted 10³ – 10⁷ in anaerobic broth media (without addition of agar) and spread plated in an anaerobic chamber (95% CO₂, 5% H₂). Plates were incubated for 24h at 39 °C. Fifty microbial colonies were selected from all plates and each colony was transferred to fresh plates and streaked for isolation. Streak plates were again incubated for 24h at 39 °C. Of the fifty plated colonies, 23 grew and were able to be isolated (Table 1). Cell isolates were inoculated in stoppered serum bottles containing 50ml fresh broth containing 5mM nitrate and 3mM nitrite. Growth was monitored by subsampling 200ul hourly for evaluating optical density (absorption at $\lambda=600$ nm) using our labs Biotek spectrophotometer. When cultures were found to be in the exponential growth phase, additional 100ul samples were collected and snap frozen at -80 °C. These samples were divided into two 50ul aliquots and diluted 125x and 75x and assayed for nitrate and nitrite levels, respectively, using the Abnova nitrate/nitrite colorimetric assay kit (Abnova, Walnut Creek, CA). Rates of nitrate and nitrite reduction (Table 1) were then determined using linear regression across all points that were collected during the exponential growth phase. Seventeen of our isolates and the two ATCC strains were found to reduce

nitrate concentrations in the media at rates ranging from 0.03 – 0.21 mM/h and eight isolates and the ATCC strains were found to reduce nitrite at rates of 0.01 – 0.16 mM/h. The rates determined for the two ATCC strains were similar to those previously reported (IWAMOTO et al., 2002) and were greater than those of any of our isolates and so were selected for further study as DFMs. Alongside, the DNA of all isolates were extracted using PowerFecal DNA isolation kits (MoBio Laboratories, Inc., Solana Beach, CA) and following manufacturer’s protocols, amplified for the V3-V4 region of the 16S rRNA gene by 25 cycles of PCR using the KAPA HotStart PCR Kit (Kapa Biosystems, Wilmington, MA), and pooled and sequenced by Illumina MiSeq with a V3 600 cycle sequencing kit. Reads were assembled with PandaSeq (Masella, Bartram, Truszkowski, Brown, & Neufeld, 2012) using default settings curated to remove low quality (<Q30) sequences using the FASTX Toolkit (http://hannonlab.cshl.edu/fastx_toolkit/index.html) and chimeric sequences using mothur’s implementation of UCHIME (Edgar, Haas, Clemente, Quince, & Knight, 2011) and then classified using mothur’s implementation of the RDP classifier using the SILVA database (Release 123), and further examined by BLASTn alignment of the most representative sequence (by mothur’s definition this is the sequence that is closest to all other sequences clustered into the OTU) to Genbank’s refseq_RNA database. If best BLASTn alignments were $\geq 97\%$ species identity was inferred, otherwise genera were only reported. The RDP classifier only reports genus level classifications (Cole et al., 2009) and no disagreements were seen between RDP and BLASTn identities at the genus level. Taxonomic identities inferred from this process for each isolate are shown in Table 1.

Table 1. Microbial Isolates Obtained

Source	Isolate ID	Nitrate (mM/h)	Nitrite (mM/h)
ATCC	<i>Wollinella succinogenes</i>	0.21	0.16
ATCC	<i>Selenomonas ruminantium</i>	0.16	0.09
Sheep 3	<i>Selenomonas ruminantium</i> S3.3	0.14	0.05
Sheep 1	<i>Veillonella</i> sp. S1.2	0.14	0.01
Sheep 3	<i>Selenomonas</i> sp. S3.2	0.13	0.02
Cow 2	<i>Prevotella ruminicola</i> C2.3	0.13	n/d
Mule deer 1	<i>Propionibacterium</i> sp. MD1.1	0.12	n/d
Sheep 3	<i>Megasphaera elsdeni</i> S3.4	0.11	0.03
Cow 2	<i>Megasphaera</i> sp. C2.2	0.11	0.03
Cow 1	<i>Prevotella</i> sp. C1.3	0.11	0.01
Cow 2	<i>Prevotella ruminicola</i> C2.4	0.11	n/d
Goat 4	<i>Veillonella parvula</i> G4.2	0.11	n/d
Bison 1	<i>Selenomonas</i> sp. B1.2	0.10	0.06
Goat 2	<i>Coprococcus</i> sp. G2.1	0.10	n/d
Bison 1	<i>Propionibacterium</i> sp. B1.1	0.09	0.01
Sheep 1	<i>Prevotella</i> sp. S1.1	0.09	n/d
Mule deer 1	<i>Propionibacterium</i> sp. MD1.2	0.09	n/d
Sheep 3	<i>Veillonella alcalescens</i> S3.5	0.09	n/d
Cow 1	<i>Prevotella</i> sp. C1.1	0.03	n/d
Cow 2	<i>Anaerovibrio</i> sp. C2.1	n/d	n/d
Sheep 1	<i>Butyrivibrio</i> sp S1.3	n/d	n/d
Goat 4	<i>Clostridium</i> sp. G4.1	n/d	n/d
Goat 1	<i>Prevotella bryantii</i> G3.1	n/d	n/d
Sheep 3	<i>Prevotella ruminicola</i> S3.1	n/d	n/d
Cow 1	<i>Ruminococcus</i> sp. C1.2	n/d	n/d

Animal Trial

The second part of the trial was carried out with five graduate students as part of the ARNR521 class Advanced Ruminant Nutrition. Therein 20 Rambouillet smut lambs were transported to the Montana State University (MSU) Bozeman Agricultural Research and Teaching (BART) farm, fitted with electronic

transponder ear identity tags, and co-housed in a single pen with access to four GrowSafe nodes to monitor intake (Fig. 1C). The GrowSafe system (GrowSafe Systems Ltd., Airdrie, AB, Canada) measures intake by recording the presence of each ear tag at the feed bunk and every second assesses feed disappearance by reductions in total feed bunk weight. The system has previously been shown to be effective in assessing feed intake in both cattle (DeVries, Keyserlingk, Weary, & Beauchemin, 2003) and sheep (Redden, Surber, Grove, & Kott, 2014). Access to feed bunks was limited to individual animals using head gates and elevated platforms (Fig. 1C).



Figure 1. Animal Trial: Twenty Rambouillet Lambs (A) were provided one of three DFM treatments or a control (B) and fed a nitrate-enriched hay feed. Feed intake was measured by GrowSafe system (C) and rumen (D) and blood serum samples were collected weekly to measure nitrate and nitrite levels and microbial community composition.

Lambs were fed a grass hay with 2000 ppm Nitrate added to the hay by spray bottle at 10 ml / Lb of a 100g/L solution of Sodium Nitrate and mixed prior to feeding. Over the first week lambs were stepped up to final nitrate levels as follows (0 ppm day 1, 300 ppm day 2, 600 ppm day 3, 900 ppm day 4, 1200 ppm day 5, 1500 ppm day 6, 1800 ppm day 7, 2000 ppm days 8 – 21). After the first week lambs were sorted into one of four treatment groups: T1) Lambs were given a 20ml dose of 10^6 cells/ml *S. ruminantium* ($\sim 2 \times 10^7$ total cells/day) daily; T2) Lambs were given a 20ml dose of 10^6 cells/ml *W. succinogenes* ($\sim 2 \times 10^7$ total cells/day) daily; T3) Lambs were given 10ml each of 10^6 cells/ml *S. ruminantium* and 10^6 cells/ml *W.*

succinogenes ($\sim 1 \times 10^7$ cells of each bacterium/day, $\sim 2 \times 10^7$ total cells/day) daily; and a control group received sterilized spent-media and no direct-fed microbial daily (i.e. A 50:50 mix of the two culture media that the two bacteria were grown in following autoclave-sterilization to kill those bacteria) (Fig. 2B). Lambs were sorted to ensure groups did not differ in weight ($P > 0.33$), in daily-intake measured over the first week of acclimation ($P > 0.4$), or in intake adjusted to metabolic rate using Kleiber's law ($P > 0.34$) (Kleiber, 1932). These measures were balanced to, as best possible, attempt to ensure groups consumed and endogenously metabolized Nitrate in the feed at a near-identical rate. These measures are shown in Table 2. Treatments were given once daily between 06:00 and 08:00 through week 2 (days 8 – 14). Rumen samples were collected by stomach tube and blood serum samples were collected by jugular venipuncture at day 8 prior to lambs receiving treatment and then at days 14 and 21. No treatment was given the final week to determine if DFMs would persist in the rumen and effectively reduce ruminal and serum Nitrate and Nitrite levels over that period (both considered essential features of any potential product). Rumen and blood serum samples were measured for nitrate and nitrite concentrations using MQuant colorimetric test strips. Initial tests were run using strips with a standard concentration range (2 – 80 mg/L of nitrite and 5 – 225 mg/L of Nitrate) and these assays were repeated with high-sensitivity kits with concentration ranges of 0.5 – 10 mg/L for both Nitrite and Nitrate. All rumen and blood serum samples failed to show any detectible nitrate or nitrite concentration with the exception of a single control animal (M6558) at week 2 (Fig. 2). The week 2 sample of M6558 revealed a concentration of 10 mg/L Nitrate and 5mg/L Nitrite in in rumen samples. However, based on the absence of detection in other animals the trial was determined to be inconclusive.

Table 2 Lamb Treatment Group Metrics

Treatment	Lamb	BW _i	Intake _{w1}	Intake/BW ^k
Control	M6410	9.75	4.25	0.77
Control	M6499	11.65	3.40	0.54
Control	M6558	8.45	1.23	0.25
Control	M6448	8.45	2.30	0.46
Control	M6461	9.85	2.14	0.38
Average		9.63 ± 1.32	2.66 ± 1.17	0.48 ± 0.19
T1	M6557	9.15	3.60	0.68
T1	M6459	10.2	2.90	0.51
T1	M6421	7.6	1.30	0.28
T1	M6444	11.8	3.00	0.47
T1	M6434	11.6	2.70	0.43
Average		10.07 ± 1.75	2.70 ± 0.85	0.48 ± 0.14
T2	M6562	14.75	5.00	0.66
T2	M6518	7.55	2.20	0.48
T2	M6408	9.5	1.90	0.35
T2	M6463	9.4	2.70	0.50
T2	M6441	9.1	2.30	0.44
Average		10.06 ± 2.73	2.82 ± 1.25	0.49 ± 0.11
T3	M6458	9.55	3.60	0.66
T3	M6520	13.8	3.80	0.53
T3	M6486	7.85	1.70	0.36
T3	M6533	9.90	2.60	0.47
T3	T6191	7.85	2.50	0.53
Average		9.79 ± 2.43	2.84 ± 0.86	0.51 ± 0.11

BW_i = Initial Body Weight (Lbs); Intake_{w1} = Intake during Week 1 (Lbs); Intake/BW^k = Metabolism adjusted Intake (Intake / Weight ^{0.75} as per Kleibers law)

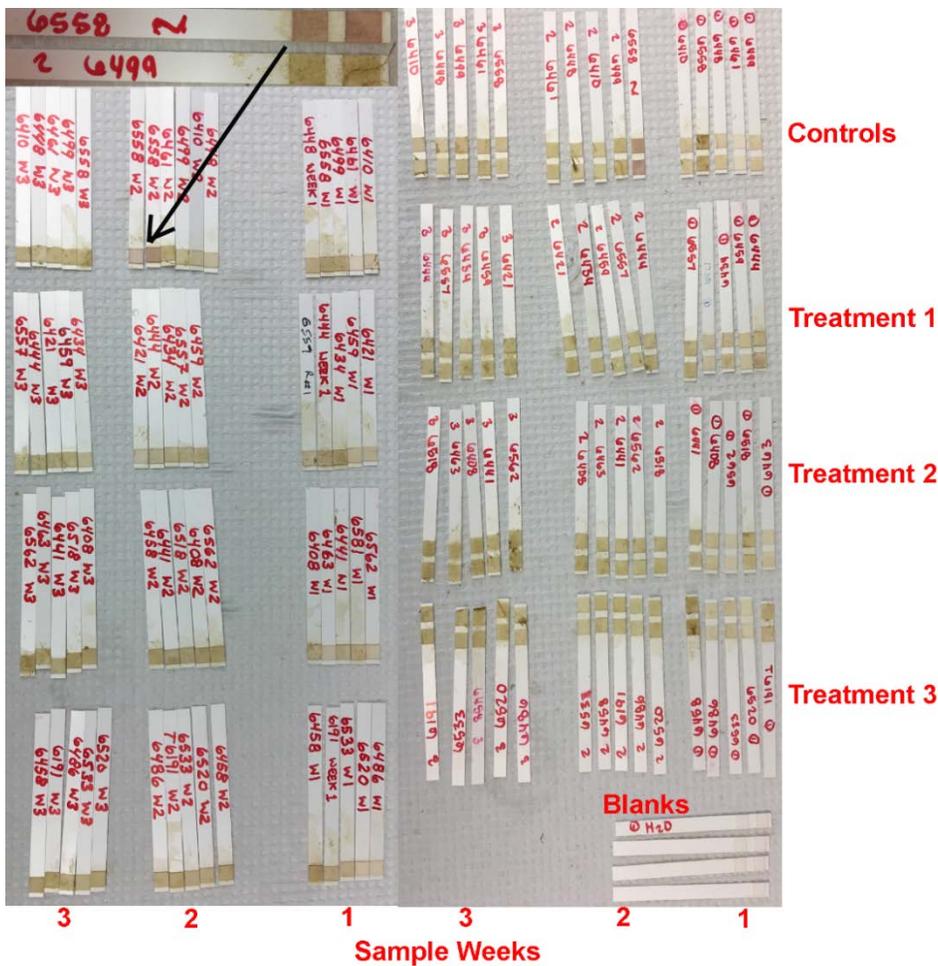


Figure 2. Ruminal Nitrate and Nitrite Colorimetric Tests: Blood serum and ruminal samples were evaluated for nitrate and nitrite levels. Increasing concentrations of nitrate are determined by a more intense shade of pink to purple as seen in our one positive animal M6558 at week 2.

Re-evaluation of the trial has led us to conclude the following factors likely limited the success of our trial and should be improved in future trials:

1. Nitrate levels added to feed were too low

In an abundance of caution we selected 2000 ppm nitrate to feed trial animals. This was just 40% of the toxic levels described in the literature. As our objective for this first animal trial was simply to determine the rates of nitrate and nitrite reduction in DFM-treated animals we believed these levels to be sufficient while also avoiding any negative effects on animal health.

2. Stepping up levels of Nitrate in Feed Over the First Week May Have Enabled Animals To Acclimate To The High Nitrate Levels In Feed

Although this was again used in an abundance of caution to avoid poisoning animals, the gradual stepping up of nitrate levels in feed may have favored the enrichment of nitrate/nitrite-reducing ruminal bacteria, allowing more rapid reductions of nitrate levels than would otherwise be expected. We are hoping to get a clearer indication of this through on-going work where we are profiling the ruminal microbes of each animal at each time-point to see how the nitrate diet and treatments affected microbial ecology.

3. Feeding Times Should Have Been Constrained and Sampling Times Should Have Occurred Immediately After Feeding

Allowing animals to spread feed events across the day also spread their exposure to nitrate. Preliminary evaluation of the GrowSafe data further suggests that animals had only ingested small quantities of feed in the hours leading up to sampling times and many had not eaten in the past 6-12 h. For example, on our first sample day (d 8), 3/20 animals were recorded consuming a total of 70g in the 4 hours before sampling, with the most recent consuming 10g approximately an hour prior to sampling. On the second sampling day (d 14), M6558 (the animal with measurable ruminal nitrate and nitrite on this sample day) was recorded at the feed bunk five times in the hours leading up to sampling, including a feeding event where 60g was consumed just minutes before being sampled. The third sample day (d 21) involved 15 different animals consuming a total of 310 g in the 4 hours prior to sampling, with the largest feeding event being 60g approximately an hour before sampling. Because sampling times were between 08:00 and 10:00, these small feeding events likely reflect the feed bunks having little remaining feed after the overnight period. We therefore seek to determine the efficacy of these bacteria supplied as direct-fed microbials to sheep individually and together on rumen nitrate and nitrite levels.

On-going Work

While results from the animal trial were found to be inconclusive, we did obtain rumen fluid from all animals at the three time points (d 8, 14, 21) before, during, and after treatment with DFMs. As an alternative way to examine the efficacy of these DFMs to efficiently reduce nitrate and nitrite levels, we are currently planning in-vitro experiments to longitudinally measure rates of nitrate and nitrite reduction. Undergraduate student, Cassidy Wong has recently joined the lab and is being trained in appropriate techniques to carry out this project.

Laboratory technician, Sarah Olivo, who was partially funded by the MREDI grant is currently preparing ruminal samples for 16S rDNA sequence profiling to determine: i) the relative abundances of the DFMs throughout the trial to assess their background levels, and ability to persist in the rumen after treatment cessation; ii) the longitudinal effect of the nitrate enriched feed on the rumen microbial community (controls); and iii) the ecological effect of the DFMs on the rumen microbial community (Treatments 1 & 2). The first of these outputs will inform us of the viability of these DFMs in a practical setting, as if DFMs are unable to persist beyond the period of inoculation it is likely the daily inoculation regimen would prove too expensive for application in the field. The second and third outputs are of interest to the potential broader impacts of these DFMs as a future product. Specifically, recent research has shown that increasing ruminal Nitrate concentrations can reduce methanogenesis by both replacing CO₂ as a terminal electron acceptor and with Nitrate-reducing bacteria competing with Methanogens for hydrogen (Yang, Rooke, Cabeza, & Wallace, 2016). The broadened benefit of these observations is that by reducing ruminal methane production, we reduce the potential energy lost to this wasteful process (estimated at 2 – 12%) and instead make it available for animal production. As methane is a significant greenhouse gas, its reduction also reduces the environmental impact of animals employed to this system and thereby increases environmental sustainability and stewardship.

Future Direction

We plan to further pursue this project as part of a USDA-NIFA funded SBIR (small business innovation research) grant and are currently looking for potential commercial partners. Our ability to obtain SBIR funding will be greatly increased if our planned in-vitro experiments are successful and demonstrate efficient breakdown of the nitrate and nitrite in rumen samples of DFM-treated animals. Lessons acquired from our animal trial have informed us that we have underestimated the basal potential of the

sheep ruminal microbiota to utilize nitrate and nitrite and give us a better foundation to propose higher feed inclusion levels of nitrate for ethics approval. These lessons will also allow us to better design future animal trials that may be funded through a phase I SBIR or other funding opportunity. The grant also provided us with additional technologies, in the form of a bioreactor that will allow us to optimize growth conditions and potentially perform directed evolution experiments to create improved strains – each of these may be proposed in the phase I SBIR.

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: We plan to further pursue this project as part of a USDA-NIFA funded SBIR (small business innovation research) grant
- Number of partnerships formed (private and public sector): We are currently looking for potential commercial partners
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: 1 Lab Technician

Expenditures

- Total Personnel Services: \$38,500.01
- Total Operations: \$19,544.35
- Equipment: \$8,737.64

Cover Crop/Grazing subproject of the Agriculture MREDI Grant

1) **41W214 – Principal Investigator:** Darrin Boss; Email: dboss@montana.edu

List the accomplishments of the project in quantitative and qualitative terms

Statewide MREDI

In the statewide cover crop trial, targeted mono- and polycultures were evaluated at the seven stations. Species represented cool season species, warm season species and polycultures made up of cool season, warm season, a blend of cool and warm season and an alternative polyculture thought to be very novel in current rotations around the state. The species were determined by input of local agronomists and animal scientists that appeared to have the best opportunity to germinate and produces either above ground biomass or a favorable root structure. There were two planting dates, one appropriate for cool season planting and on appropriate for the warm season plantings. Each of the four polycultures were planted at each planting date. Harvesting occurred when the first species began to head, triticale in most cool-season environments and millet in the warm season planting. Thereby preventing additional viable seed production from the cover crop that might contribute to further water use and “weed” problems in future crops.

In seven location the cool season species produced from 615 to 2267 pounds above ground biomass on a dry matter basis with oats being the greatest across all environments. With the polycultures being lower than the monoculture producing the greatest amount of biomass. In all locations when the polycultures were compared across planting dates the warm season outperformed the early planting, however the early harvest was completed around July 8 and the late season harvest date occurred well into August thereby

using more soil available water and mimicking a season long cash crop. Nutrient content of the monocultures and polycultures across all locations and both planting dates were very high quality and were across all sites, higher in Crude Protein (CP) and Lower in Acid Detergent Fiber (ADF) than a normal brome hay produced in similar locations. Although not as high in CP or as low in ADF as a first cutting Alfalfa hay but in some cases it was equal to or higher than alfalfa. The forage quality of cover crops followed the well documented forage nutrient quality pattern of as the plant matures CP and other nutrient quality is reduced. Nitrates for the project followed the same maturity patterns. Nitrates for the trial ranged within the guidelines for generally safe for non-pregnant animals (1,000 to 5,000 ppm NO₃), however if fed to pregnant cattle as hay it is recommended to be blended at least 50:50 with hay that does not contain any nitrate. No soil health measurements or the following wheat yields could be determined in the short window of time however, if managed like a cash crop and if the cover crop is allowed to be harvested at the peak of nutrient quality and yields as would an annual forage, it would appear in areas that had via moisture the targeted cover crop species performed well throughout the state.

Large Termination Cover Crop Project

In the large plot termination trial where alternative economics streams of cover crop usage were evaluated, there are some cover crops when used as either a dry forage (hay) or grazing that have shown a \$100/acre return over what a transitional winter or spring wheat/fallow rotation. Uses current wheat, hay and grazing prices. There are also cover crops returning less than the traditional wheat/fallow rotations. It should be noted that the harvest date for the cover crops has average July 10 across the entire trial from 2012 to 2016. By harvesting the cover crops as either a dry forage (hay) or grazing at this time point the deep soil moisture is protected for the following cash crops. No cover crop is allowed to produce viable seed if at all possible, and it allows winter wheat to have a chance to be included in the rotation, since the cover crop is terminated after the grazing or haying to allow for fall planting of winter wheat should that be the desire. Over all the years of the trial there has been timely rains during the wheat years and both above and below in crop normal rainfall. There has not been a devastating drought or a below normal rainfall without timely rains during the wheat years. So no assumption can be made about the overall economic two-year rotation should a severe drought occur in this rotation.

Soil bulk densities and water infiltration rates were generally unaffected by long term cover crop inclusion in comparison to traditional wheat fallow rotation. However, it should be noted changes in soil parameters and how a soil equilibrates to long term rotations takes substantial time, as an example it took several years to alter organic matter as producers adopted chemical fallow or other conservation tillage practices.

Associated Deliverables

The project team along with several Specialists and County agents are targeting an extension report and webpage for integrating managed grazing of cover crops in Montana diversified livestock and farming operations. The guideline will discuss recommendations for species selection, managing elevated nitrate levels or other potential hazards. Educational opportunities from this project are still on-going and will for an extended period to have locally adapted, tested individual species and polycultures at each Research Center to allow producers to meet their goals for utilizing a cover crop. Whether that be to graze the available forage, or to provide cover rather than fallow. If the goal of the producers is to graze late fall, their recommended cover crop selection would be much different than a July grazing period. The biomass from the cool season cover crops would definitely out yield the warm season species in early to mid-July and produce an outstanding amount of biomass and excellent nutrient profile for the cattle. However, letting that cool season crop go to seed and graze after a frost or late fall would only add to the seedbank load although it would be tame seed rather than wild the opportunity for volunteer is large. When in fact a choice of warm season species would increase the amount of available biomass and retain higher amount

of forage nutrients than the mature cool season species. To date through location field days and industry tours the MREDI cover crop project personnel have presented data and project details to upwards of 700 industry professionals, NGOs and producers around the state about the termination cover crop trial conducted statewide. The data from the statewide project has been accepted as a presentation for the American Society Agronomy Nation I meeting in Tampa Bay, Florida, October 2017. Montana County Agricultural Agents are participating in an in-service learning opportunity at NARC for selecting, implementing and grazing cover crops in Montana. Their county outreach education programs will impact producer selection and implementation. Seed dealers are implementing and using data to provide appropriate seed polycultures to producers, specifically a simple Montana locally adapted blend of oat, or triticale as the cereal, radish, canola safflower, vetch and a modest amount of millet. This blend being less than \$20/acre sold by local triangle area seed dealer. Which allows producers to have a positive experience with locally adapted cover crop blends. The project team from the long term termination trial has been invited to present an invited talk at the national Symposium--Cover Crops and Forage Utilization in Integrated Crop-Livestock Systems at the National American Society of Agronomist in Tampa Florida. Currently new faculty scientists have been able to leverage the current MREDI projects by integrating and expanding mini-rhizotron work to elucidate why of how multispecies polycultures alter root and soil interactions. A diversified group of researchers from MSU are leveraging this long term unique to the western states project to prepare a \$2.5 million, 5-year proposal to the USDA current Agriculture and Food Research Initiative Competitive Grants Program for Foundational knowledge of agricultural production systems A1102 thereby enhancing the understanding of biotic an abiotic stressors of wheat and their effects on different production systems including cover crops.



Figure 1. Pictures representing the termination techniques but also the alternative economic endpoints when cover crops are used in a winter or spring wheat rotation.

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: Coordinating with other MSU researchers to prepare a \$2.5 million 5-year proposal to the USDA current Agriculture and Food Research Initiative Competitive Grants Program for Foundational knowledge of agricultural production system
- Number of partnerships formed (private and public sector): Area seed dealers are implementing and using data to provide appropriate seed polycultures to producers
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: 1 Research Associate

Expenditures

- Total Personnel Services: \$28,780.97
- Total Operations: \$36,215.03

2) 41W227 – Principal Investigator: Emily Glunk; Email: emily.glunk@montana.edu

This research shows promise in utilizing cover crops as a forage source throughout Montana. Several items can be taken away from the data:

Annual forages have the potential to be a strong competitor to perennial forages as a grazing source.

As evidenced by the data published in the manuscript “The preference and forage quality of 13 cultivars of forage barley and 2 cultivars of oats when grazed by sheep” (published in the International Journal of Experimental Agriculture 15 (2): 1-7, 2017), many annual forages in use and being developed for livestock grazing have exceptional forage quality and palatability. All forage cultivars sampled in this particular project have the ability to meet or exceed nutrient requirements of livestock at most reproductive stages. This is encouraging for producers, and their ability to include annual forages into their livestock management program.

When evaluating the utility of annual forages compared to commonly-used perennial forages, we see the competitiveness, and similarities between the two. The nutrient quality of most cultivars tested are comparable to good (crude protein between 18-20%, acid detergent fiber between 29-32%, and total digestible nutrients between 52.5-54.5%) or premium (crude protein between 20-22%, acid detergent fiber between 27-29%, and total digestible nutrients between 54.5-55.9%) quality alfalfa (Table 2; USDA, 2016). In fact, if just evaluating the total digestible nutrients and fiber values, as we know alfalfa is a legume and a better source of protein, the cultivars tested would be similar to fiber and energy values of a supreme quality alfalfa, the highest quality of alfalfa available, meaning they are extremely high quality livestock forage sources.

The other benefit of annual forages, making it potentially more competitive to perennial forages, is that we expect higher yields than compared to their perennial counterparts. A study conducted over an 11 year period at Central Ag Research Center (CARC) in Moccasin, MT found that winter cereals produced about 10 T/ ac more than alfalfa grown at the same station compared to alfalfa or intermediate wheatgrass, a commonly-used cool-season perennial grass. At CARC, they were averaging approximately 2.45 T/ ac. The cultivars evaluated in Bozeman were ranging from 3.5- 5.36 T/ ac. Comparing that to

average alfalfa production for the state, which is approximately 1.5 T/ ac on dryland and 3.2 T/ ac on irrigated, we see a huge yield boost with the annual forages. When combining the yield advantage with the high nutrient quality, it is evident that these perennial forages show a strong ability to be competitive in Montana as a grazing and preserved forage source.

Table 2. Nutrient quality analysis of the fifteen cultivars of cereal forage cultivars tested

Cultivar	Species	CP	ADF	CF	TDN	NEm	Nitrate
				%			% NO ₃
Haybet	Barley	18.7	30.2 ^a	2.6	63.4 ^{acd}	0.64 ^{abd}	1.02 ^{ab}
Hays	Barley	21.4	26.7 ^b	3.5	63.3 ^a	0.64 ^a	1.19 ^a
Haymaker	Barley	20.1	28.0 ^{ab}	2.5	62.9 ^a	0.64 ^{ab}	0.98 ^{ab}
Lavina	Barley	18.7	29.3 ^{ab}	3.4	64.1 ^{abc}	0.65 ^{abde}	0.82 ^b
MT103083	Barley	21.5	29.3 ^{ab}	2.9	60.5 ^{cd}	0.61 ^{cb}	1.11 ^{ab}
Haxby	Barley	17.8	26.9 ^{ab}	4.3	64.3 ^a	0.66 ^d	0.89 ^b
Horsford	Barley	16.2	30.4 ^a	2.8	62.1 ^{abcd}	0.63 ^{abcde}	0.77 ^b
Pronghorn	Barley	18.5	33.4 ^{ac}	3.9	63.0 ^{ac}	0.64 ^{ab}	0.46 ^b
MT10397-1	Barley	20.0	29.6 ^{ab}	2.9	62.7 ^{acd}	0.64 ^{abcd}	1.19 ^{ab}
MT103038-6	Barley	20.8	25.9 ^b	2.7	62.8 ^{ac}	0.64 ^{abd}	1.23 ^{ab}
MT103038-4	Barley	19.1	26.5 ^{ab}	3.2	62.6 ^{abc}	0.63 ^{abd}	1.09 ^{ab}
MT103089-3	Barley	18.6	31.3 ^a	3.1	61.4 ^{acd}	0.62 ^{abc}	0.97 ^b
MT103101-5	Barley	17.3	27.8 ^{abc}	3.0	65.0 ^b	0.66 ^e	0.76 ^b
Otana	Oats	18.5	35.0 ^c	2.7	62.3 ^c	0.63 ^b	2.53 ^c
Stampede	Oats	20.3	27.0 ^{ab}	3.7	60.3 ^d	0.60 ^c	2.10 ^c

^{a,b} Means without a common superscript within a column differ ($P \leq 0.05$)

CP: crude protein, ADF: acid detergent fiber, CF: crude fat, TDN: total digestible nutrients,

NEm: net energy for maintenance

Annual forages have potential to be an economically viable alternative, particularly in dry years

Based on the information above, we can see the economic implications of producing more tonnage per acre, with that tonnage being high-quality forages. Seeding costs do need to be considered, as seeding will need to occur every year versus every couple of years. However, there are other advantages of using annual forages. One is that they can be very resilient in dry environments compared to perennial cool-season forage species, and often use less water per ton of dry matter produced.

We often observe a “summer slump” in cool-season perennial forages immediately after the summer equinox due to root shedding, as well as high rates of evapotranspiration, and low rates of precipitation. Annual crops may use more available soil moisture during establishment due to their rapid growth, but are typically considered very water efficient later in maturity. Because of this, they are often called “emergency forages” for drought years, because they can grow with relatively low moisture requirement.

Forage quality in species evaluated meets requirements for most livestock in Montana

As outlined above, the forage quality of the cultivars tested meets or exceeds that which is required for most classes of livestock. A cow at her peak requirement, typically early lactation, will usually require a maximum of 13-14% crude protein. All cultivars tested meet and exceed that requirement. Total digestible nutrients, an estimate of energy availability, is also said to be “good” if above 60%, which all cultivars tested in this trial were.

An important part of the quality of harvested or grazed annual forages is the maturity at which those forages are at harvest. The more mature the forage, the less digestible and nutrient dense that forage will be. Based on this research, harvesting within 5-10 days after heading is appropriate for producing a high-yielding, high-quality forage source.

Evaluation of anti-quality components (nitrate levels) is important information for producers, particularly concerning not just acute, but chronic nitrate toxicity.

Anti-quality factors are an important part of forage evaluation. The data is in agreement with previous research, finding that oats typically have the highest risk of nitrate accumulation (Bolan and Kemp, 2003; Crawford, et al., 1961; Gul and Kolp, 1960). All cultivars evaluated were at elevated levels, which may need to be dilute fed to animals that are being used for reproduction, as it may cause abortions and other complications. However, the oat entries were at levels almost double that of the forage barley varieties tested. These should not be fed at all to reproductive livestock, and should be limit-fed to other livestock in order to avoid acute toxicities.

Final Metrics

- Total additional grants received: None as of yet, but using the data to apply for one in the next year. Tony actually I think had another one that he coupled with this project.
- Total additional grants in progress: Will be submitting a grant in Spring 2018
- Number of partnerships formed (private and public sector): I had the opportunity to work with at least 2 faculty members that I haven't worked with before. In addition, I will be presenting this info quite a bit and creating many handouts, so it is hard to quantify just yet.
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: None

Expenditures

- Total Personnel Services: \$18,060.35
- Total Operations: \$20,291.65

On-Farm Precision Experiment subproject of the Agriculture MREDI Grant

1) 41W215 – Principal Investigator: Bruce Maxwell; Email: bmax@montana.edu

Co-Principal Investigators:

Bruce Maxwell, Project Director, Agroecology
Anton Bekkerman, Economics
Clemente Izurieta, Computer Science
Kelsey Jencso, Climate Science

Rob Payn, Hydrology/Data Management
Lisa Rew, Weed Ecology/Precision Ag
John Sheppard, Computer Science
Nick Silverman, Adaptive Hydrology

Technician:

Philip Davis

Graduate students:

Janette Rounds
Amy Peerlinck

Collaborators:

Casey Bailey, farmer
Gary Broyles, farmer
Chuck Merja, farmer
Mark Van Dyke, farmer

Jesse Wood, farmer
Ryan Helmar, Wilbur Ellis
Delmna Hieken, Triangle Ag.
Neil Fehringer, consultant

Problem Statement and Introduction:

The economic resilience of Montana farms is dependent on maximizing the efficiency of input use. Input decisions influencing efficiency are increasingly complicated and subject to significant uncertainty. These uncertainties are driven by input cost variability, crop price variability, spatial and temporal variability in crop response to the environment and increasing variability in climate. We believe that farm managers can take advantage of the “big data” flowing into and from modern agriculture technologies and advanced analytics to make input management more profitable. Optimizing inputs to maximize producer profits is our goal. The optimization process strives to remove a major aspect of uncertainty by experimentally determining input performance on each field thereby addressing spatial variability and repeating the experiments to gain understanding of temporal variability in crop response. We imagine that when a farmer pulls the combine out of the field after harvest that the data will be analyzed and next year’s experiment map will be created and a best estimate of what the profit maximizing strategy for that field will be presented.

We used MREDI funding to demonstrate the beginning of the optimization process by examining nitrogen fertilizer input as a top dress spring application on winter wheat and use this as a proof of concept. Nitrogen fertilizer applied to winter wheat in the spring is thought to increase grain protein and yield. However, every farmer is frustrated with the inconsistency in response to fertilizer across years and within each field. Therefore, we have designed within field nitrogen fertilizer rate experiments that can be automatically applied with variable rate application (VRA) technologies and results determined with georeferenced yield and protein monitoring. Our goal is to produce a fully automated mechanism (software) to conduct in-field experimentation with current technologies that will improve the profitability of nitrogen fertilizer management decisions in Montana wheat production.

Research questions:

1. Is site-specific parameterization of winter wheat yield and protein response functions required to maximize profits?
2. Did the use of site-specific nitrogen application show potential to increase net returns to the farmers and at the same time decrease nitrogen use on the farm?
3. Will future incorporation of precipitation and temperature improve crop response functions and net returns at critical nitrogen fertilizer decision points?

Experimental Design:

In order to address the research questions above we recruited farmers that had experience with obtaining yield monitor data on their combine harvesters. In an initial state-wide request for farmer collaborators we were overwhelmed with nearly 40 farmers from across Montana indicating interest in participating in our study. We sifted collaborators to four primarily based on geographical spread, willingness to participate for up to 10 years, experience with precision agriculture technologies and VRA in dryland winter wheat production (Table 1).

Table 1. Collaborator farms, fields, previous 3 years of crops plus 2017 crop, crop used for nitrogen treatment stratification in OFPE year and weed maps for fields with enough weeds to map.

Farm	Field	Field size	Crops: 2014 / 2015 / 2016 / 2017 ¹	Crop used for N rate treatment stratification	Weed density high enough to map
Broyles	Sec35mid	158	WW / CF / WW / CF	2014 WW	Weed map
	Sec1west	233	WW / P / WW / CF	2014 WW	
	Sec35west	111	CF / WW / P / WW	2015 WW	
	Sec1east	194	SF / WW / CF / WW	2015 WW	

Merja	SRE 13-14	155	WW / CF / WW / CF	2015 WW	
	Rosie	98	P / CF / WW / CF	2013 WW	
	SRE 9-10	232	P / CF / CF / SW	2013 WW	Weed map
	Grams/Moms	318	P / WW / CF / SW	2015 WW	
Van Dyke	Davidson midwest 2	66	MB / WW / WW / MB	2016 WW	
	Portnell south 1	59	MB / WW / WW / MB	2015 WW	
Wood	Henrys	118	WW / SW / WW / CF	2015 SW	
	Minnies	49	SW / SW / WW / CF	2015 SW	
	Carlin west	113	CF / WW / CF / WW	2013 WW	
Bailey	Bailey-1	105	WW / SW / WW / WW	- (No prev. info.)	
	Bailey-2	98	AL / AL / AL / WT	-	

¹WW = winter wheat, CF = chemical fallow, P = peas, MB = malt barley, SW = spring wheat, OK = organic Kamut spring wheat, SF = safflower; **bold** = 2016 OFPE experiments, red = 2017 OFPE experiments

Process for site-specific application top-dress nitrogen using VRA technologies. See Appendix 1 for detailed information on optimization of treatment placement.

Field attributes are determined from GIS analysis of the digital elevation model (DEM) and prior crop year response is used to stratify input experimental rates of the input. In this case nitrogen fertilizer rates.

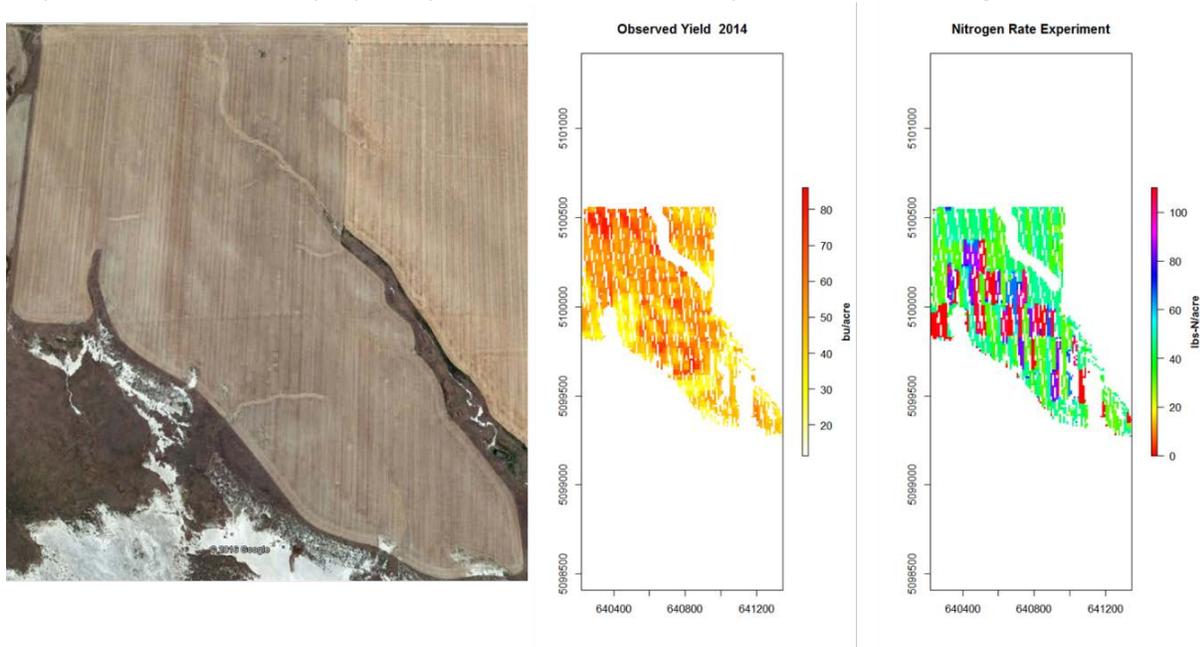


Figure 1. Aerial imagery of sec1west field on Broyles farm, yield map from previous winter wheat crop used to stratify experimental treatments and as-applied experimental nitrogen top dress rates on field. This project is highly dependent on data organization, quality assurance (cleaning), protection and easy availability for modeling. Thus, a major aspect of the project has been construction of a database with all of these constraints. See Appendix 2 for details.

At harvest we obtain georeferenced yield point data from each field providing a measurement on average every 3 seconds which translates to 1-3 m distance along a combine harvester path. We obtained protein data from the CropScan 3000H analyzer on average every 10 seconds (10-14 m between points). The monitoring data is cleaned using Yield Editor, an open source software developed and made available by the USDA-ARS in Missouri. The cleaned data is mapped (Figure2).

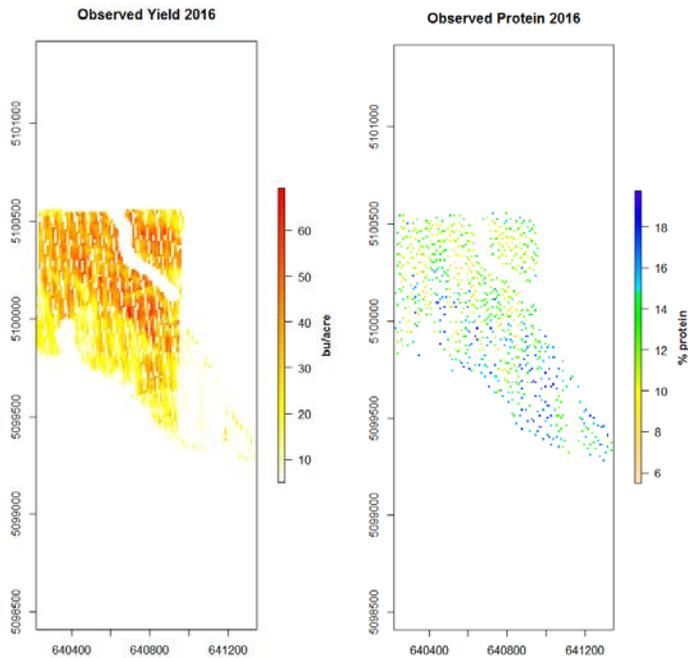


Figure 2. Example of yield and protein monitor data from 2016 harvest of winter wheat in field sec1west on the Broyles farm.

Methods for addressing research questions:

The first research question was addressed by determining if the same suite of parameters were significant in predicting grain yield and protein across different fields. In addition, we determined if the parameter values remained constant over the different fields. If the same parameters and their corresponding values come into the equations for each field there would be no need for experimentally determining field-specific response functions and we could simply rely on the current approach of utilizing small plot experiments at Research Centers to make nitrogen fertilizer rate recommendations. A universal non-linear regression function was fit to the grain yield and protein data from each field and parameters as well as their values were compared for spatial consistency (Table 2 and 3). The non-linear equation was selected for comparison because it was logical considering past research and experience with yield and protein response to nitrogen rates.

Universal equation fit to data from each field for comparison:

$$Yield = \alpha + \frac{(\beta - \alpha)Nrate}{\frac{1}{\gamma} + Nrate}$$

β = upper limit of yield

α = yield at 0 Nrate (intercept)

γ = slope of yield increase

β is assumed to be a linear function of a set of independent variables including the previous crop year grain yield, current year NDVI at the point in time (March) when a nitrogen fertilizer rate decision is typically made, peak NDVI in the two years previous to the current year. α is assumed to be a linear function of the geographic variables that would be explanatory independent of fertilizer and include the aspect of the point where the degree of

north and south facing is the cosine of aspect and the degree that the point is facing east or west is the sin of aspect. In addition, the slope, elevation, topographic position index (TPI) and weed abundance at the monitor points were included as independent variables to predict α . All of these variables except weed abundance are estimated from the digital elevation model (DEM) which is a gridded map that is draped over the land surface and widely available for the whole state of Montana. TPI is a quantification of the terrain water capturing potential surrounding a point. These independent variables are all associated with each crop grain yield and protein content monitor point in the field to help predict yield and protein.

The second research question was examined by utilizing the best grain yield and protein response functions to compare current net returns for different top-dress nitrogen fertilizer application strategies (listed below).

1. Site-specific optimized (profit maximized) application rate at each yield monitor point in the field.
2. No nitrogen application anywhere in the field.
3. The farmer selected uniform nitrogen application rate across the entire field.
4. The uniform nitrogen rate applied over the field that would maximize the full-field net return.

By comparing the average net return per acre for each strategy under the historically observed variability in prices received for grain (\$/bu) and cost of nitrogen (\$/lb) we determined the probability of each strategy outperforming the site-specific optimized strategy in each field.

The third research question could only be preliminarily addressed with just one year of results, because ultimately one requires multiple years representing different climate scenarios for each field to draw appropriate conclusions. However, we did substitute the different climates at the different sites (farms) for years to determine the relative importance and predictive power gain from inclusion of climatic variables in the crop response functions.

Results:

In spite of controlling nitrogen rates in the fields the yield data and the protein data is exceptionally noisy indicating that response to the top dress nitrogen input was highly variable depending on where the yield was measured in the field (e.g. Figures 3 and 4). This spatial variability in grain yield and protein content is strong evidence for the potential of using VRA fertilization to increase profits on the field. Clearly, there is a need to understand what drives the spatial variability in these economically significant response variables and be able to adjust fertilizer application rates to decrease uncertainty in economic return.

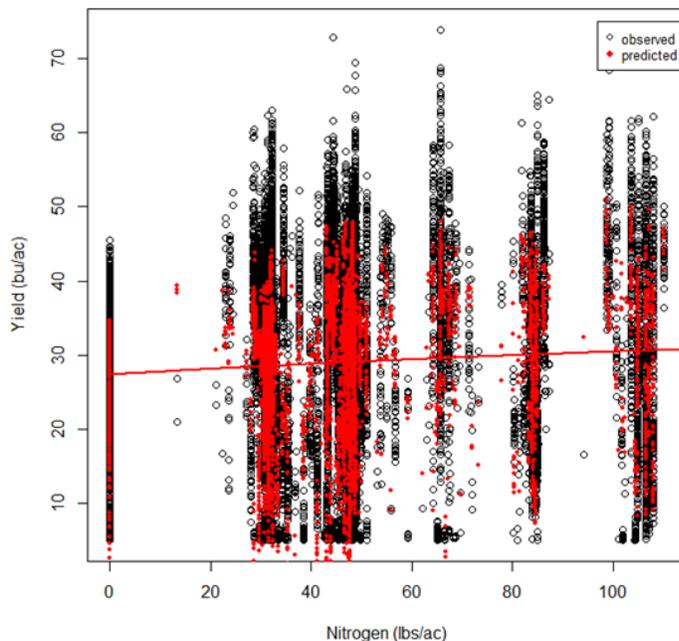


Figure 3. Yield monitor data from Broyles farm field sec1west plotted against nitrogen rate (black empty circles) and showing the average predicted values with the fit yield function (red line) and predicted values for each yield monitor point given all of the independent variable values at each point (solid red points).

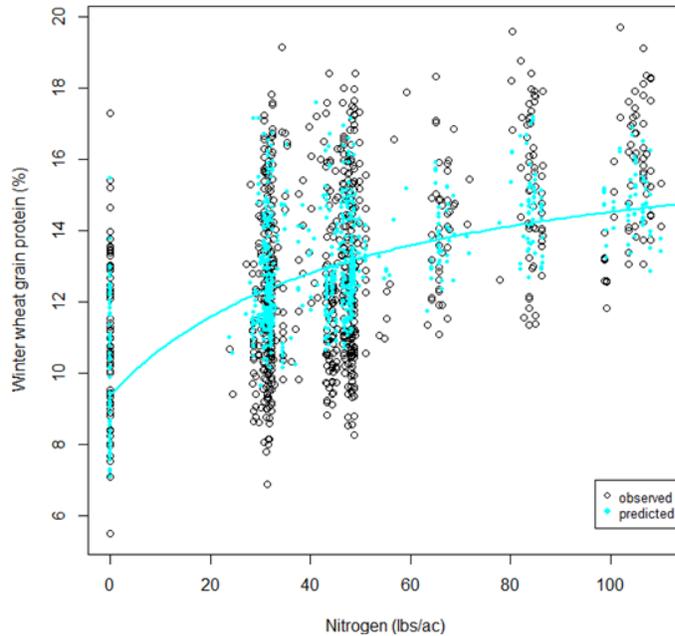


Figure 4. Protein analyzer (monitor) data from Broyles farm field sec1west plotted against nitrogen rate (black empty circles) and showing the average predicted values with the fit yield function (blue line) and predicted values for each yield monitor point given all of the independent variable values at each point (solid blue points).

Winter wheat grain yields were consistently predicted in 2016 by all the independent variables, however the non-linear estimated regression values for those parameters were highly variable (Table 2). Winter wheat grain protein response functions were inconsistent for which independent variables were included and were also extremely variable across fields even within a farm (Table 3). These results are strong evidence that yield and protein functions need to be independently fit for each field and thus verifies the value of the on-farm experimentation to identify and quantify the response functions field by field.

A great deal of effort went into identifying the best response functions and advanced analytic methods for characterizing the data. The results presented in this report use our best functions using linear and non-linear regression analysis. Preliminary assessment of Bayesian regression, random forest and neural networks (stacked encoders) show great promise for these approaches to better account for the full variation in the yield and protein data (see appendix to this report).

The second research question that we addressed was: Did the use of site-specific nitrogen application increase the net returns to the farmer?

Using our best regression functions for predicting winter wheat grain yield and protein concentration we examined this question by finding the optimum top dress nitrogen rate at each yield monitor point for each field. To estimate variation in the response due to annual economic variation we selected from the distribution of crop prices received and cost of nitrogen values over the period 2000 to 2016. Thus, a crop price and corresponding nitrogen cost value would be selected corresponding to a random year in that period and nitrogen rates from 0 to 200 lbs per acre would be tried to determine which rate maximized the net return at that point and became the site-specific optimum nitrogen application strategy. Adding no nitrogen, determining the uniform nitrogen rate that maximized net returns, the farmer selected uniform nitrogen rate were also simulated. This process was repeated 1000 times to estimate the variation in response without considering the temporal climatic variation that is likely to occur, but we do not yet have that data until we examine these fields for a few years.

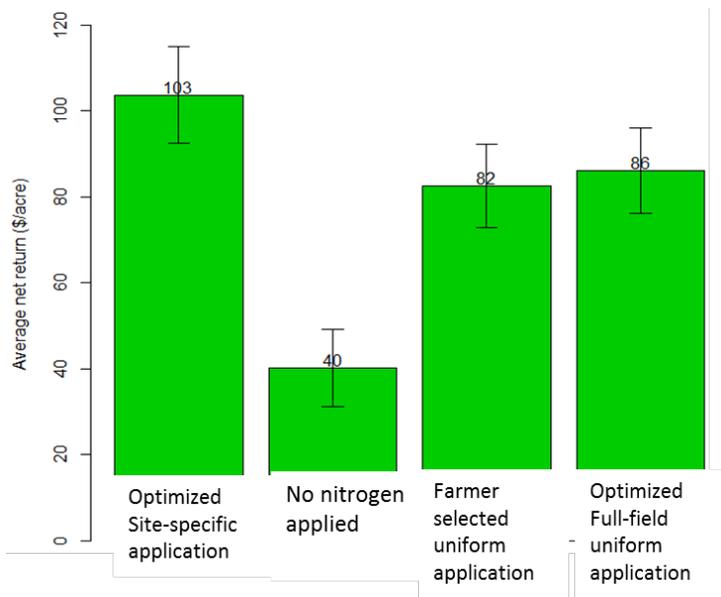


Figure 5. Example of simulated average net returns for different top dress nitrogen application strategies in the sec1west field on the Broyles farm.

Our results using the simulation approach suggests that site-specific optimized nitrogen application rates outperform the other strategies providing increased net returns in 100% of the fields tested even after adding a \$2.00 per acre technology cost for the VRA and other technology (Figure 5).

In addition, the amount of nitrogen fertilizer used by the site-specific nitrogen top dress application was mostly reduced from a strategy that would use a uniform rate that would maximize profit (Figure 6).

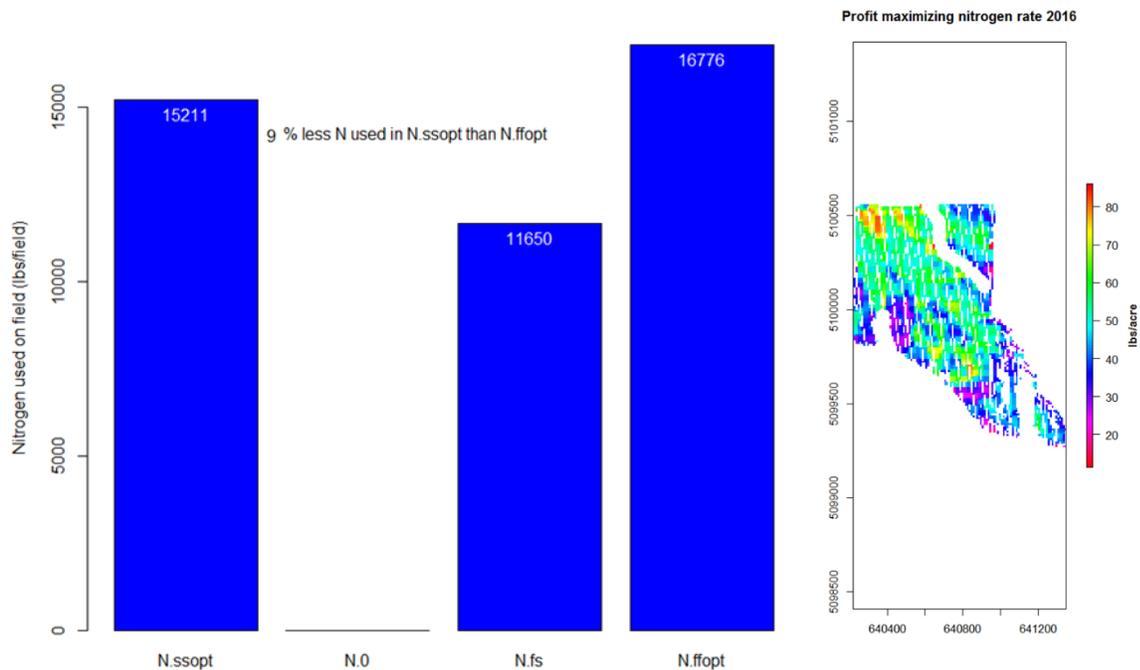


Figure 6. Total nitrogen used by each top-dress nitrogen application strategy and the top-dress nitrogen prescription map that would have maximized net return in 2016.

The final research question that we considered was: Will future incorporation of precipitation and temperature improve crop response functions and net returns at critical nitrogen fertilizer decision points?

A preliminary assessment of this question using combined data from all fields and the weather stations installed at the fields indicated that when winter precipitation in the period between planting winter wheat and resumption of spring growth is the strongest independent variable predicting winter wheat grain yield. This result which coincides with the top dress nitrogen application rate (strategy) decision time is encouraging for not just improving predictive capacity but also for improving prediction at a critical time.

Other variables in the combined dataset that improved predictive capacity were harvest year growing season precipitation, preceding year precipitation, harvest year growing degree days up to end of March, NDVI for early spring and nitrogen fertilizer rate. We believe that these results are strong evidence for the potential for incorporating climate information into the yield and protein functions. Further examination of the spatial and temporal variability in yield and protein and the impact on improving input decisions is limited with our study until we have a few more years of information from each field to thoroughly analyze this aspect. The combination of spatial and temporal variability was examined in one field with multiple years of yield and protein data (Figures 7 and 8).

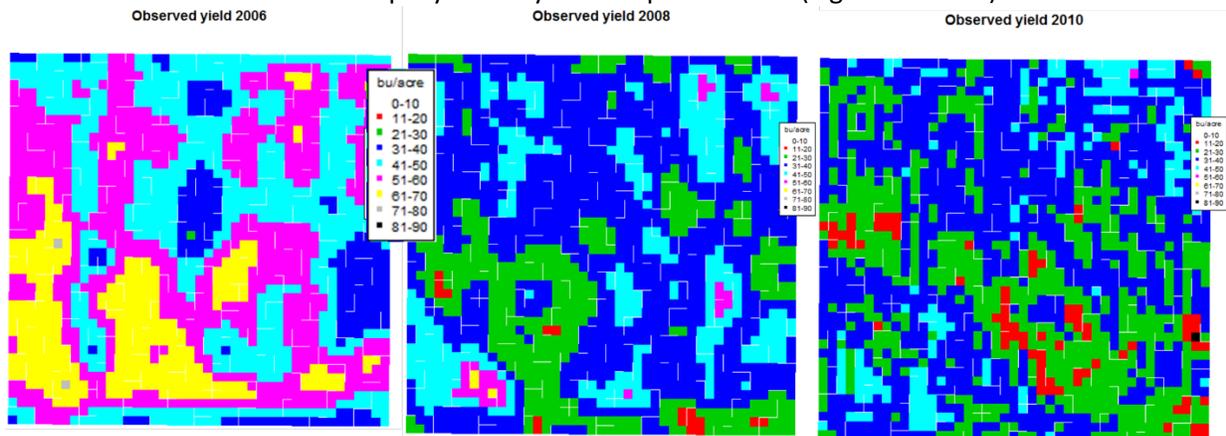


Figure 7. Variation in wheat grain yield in Rosie field on Merja farm in crop fallow system from 2006 to 2010.

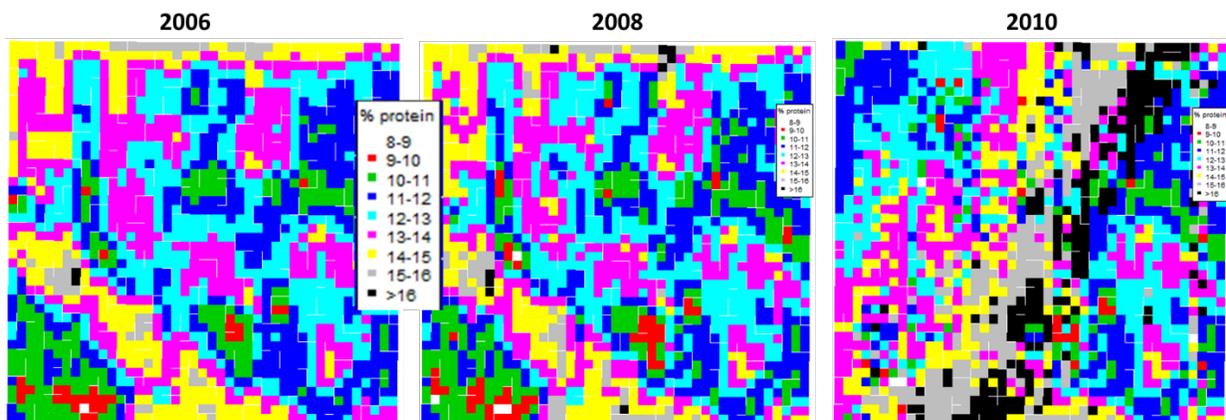


Figure 8. Variation in wheat grain protein content in Rosie field on Merja farm in crop fallow system from 2006 to 2010.

Variability in wheat grain yield at each point in the field over time was determined by calculating the coefficient of variation (CV = variance in yield/ mean of yield) at each point and then mapping the CVs of each point to determine the spatial distribution of relative stability (Figure 9a). The same calculation was made for grain protein content variation over time and mapped (Figure 9b). One can think of this as yield and protein stability over time. In addition, the variation in prices received for grain as well as the cost of nitrogen fertilizer in each of the years was brought in to calculate the net returns (\$/bu) at each point and the temporal CVs calculated for each point (Figure 9c). Black and blue cells on the map are most stable and yellow and white are least stable with red in the middle. These maps indicate that crop yield was less stable than protein over the period 2006 to 2010 and the spatial correlation of stability between yield and protein was low ($r = -0.074$). When economic uncertainty (variability in net return to the producer) was added to the observed variability in wheat yield and protein there was a significant increase in CV values throughout this example field further indicating the need for in depth discovery of the drivers of variation and the interactions between spatial and temporal drivers.

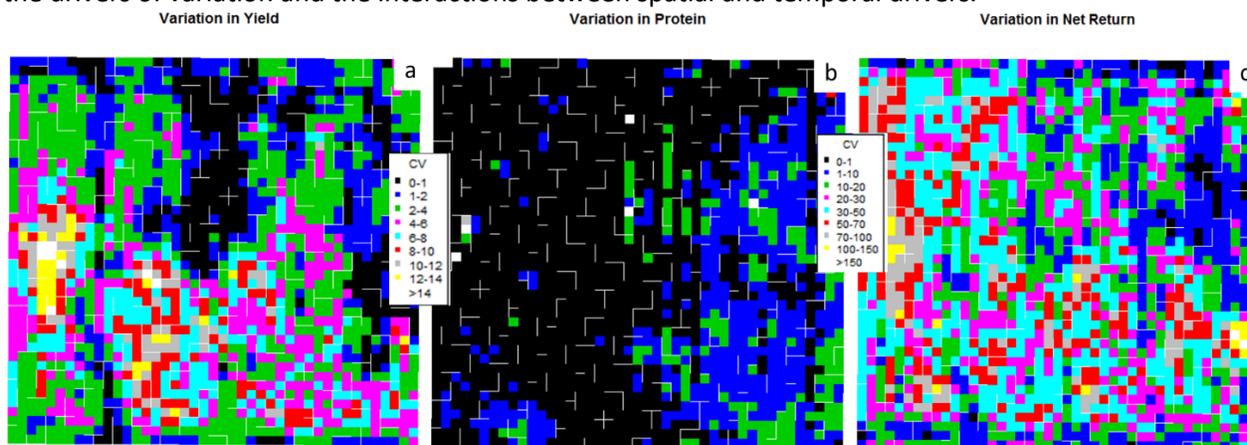


Figure 9. Temporal variation (CVs) in wheat grain yield (a), grain protein content (b) in Rosie field on Merja farm in crop fallow system from 2006 to 2010.

Summary of results

Our results strongly suggest that our OFPE approach applied to nitrogen fertilizer management in winter wheat can improve understanding of the drivers of variability and subsequently provide analytics that can provide probabilities of one management approach being more profitable than another. The relationships between driving variables and the key response variables yield and protein varied significantly within fields and between fields and preliminary analysis indicated between years in the same field. Thus, on farm experimentation can be an important addition to refining recommendations from first principles determined from small plot research at Research Centers. We can be far more confident about recommendations for input performance on any given field when the data is based on OFPE.

The first research question was: Is site-specific parameterization of winter wheat yield and protein response functions necessary to maximize profits? Our analysis indicates a consistent and resounding “YES” answer to this first question. The second question: Did the use of site-specific nitrogen application show potential to increase net returns to the farmers and at the same time decrease nitrogen use on the farm? In nearly all fields, site-specific nitrogen management of winter wheat in Montana should increase net returns to producers and often will reduce nitrogen fertilizer use improving efficiency. The third research question was: Will future incorporation of precipitation and temperature improve crop response functions and net returns at critical nitrogen fertilizer decision points? We will not know the answer to this question until we have several fields with a time-series of data to thoroughly examine this

question. However, when we substituted space for time by using the different climatic data from each field in one year there was a clear signal that site-specific weather data will improve our ability to predict winter wheat grain yield and protein. In addition, when we looked at the one field where we have 3 years of data for winter wheat production we learned through stability analysis that portions of fields will more reliably produce and respond to inputs than other portions of the fields and that will allow us to calculate site-specific probabilities of response to inputs.

Final Metrics

- Total additional grants received: 1
- Total additional grants in progress: 3, plus are writing an additional 3 more for submission to USDA AFRI
- Number of partnerships formed (private and public sector): the four initial OFPE farms, plus an additional fifth farm, the Bailey farm, west of Fort Benton, MT
- Number of new Montana businesses created: None, however, in addition to fields in conventional winter wheat, we will add a spring wheat field that is certified for organic production as on-going research. In place of varying site-specific fertilizer rates, we will vary rotational pulse crop seeding rates across the field to determine impact on following year yields and protein.
- Patents awarded or in progress: None
- Commercial products developed: None
- Publications:
 - Janette Rounds, Amy Peerlinck, Bruce Maxwell and John Sheppard. 201_. Using deep learning in yield and protein prediction of winter wheat based on fertilization prescriptions in precision agriculture. Agriculture, Ecosystems and Environment. Submit August 2017.
 - Robert Payn, Clemente Izurieta and Seth Mason. 201_. An object-oriented data model for contextualizing metadata in ecology and the earth science databases. Journal of Environmental Modelling & Software. Submit July 2017.
 - Bruce Maxwell, Nicholas Silverman, Rob Payn, John Sheppard, Clemente Izurieta and Anton Bekkerman. 201_. Optimizing crop inputs using on-farm experimentation. Agriculture and Environment. In prep. Submit Sept. 2017.
- Jobs created: 2 graduate positions and 1 technical position

Expenditures

- Total Personnel Services: \$261,356.67
- Total Operations: \$233,943.33
- Total Equipment: \$113,460.00

2) **41W226 – Principal Investigator:** John Sheppard; Email: john.sheppard@coe.montana.edu

Appendix 1: Neural network approach to analysis

Optimization and Precision Experimentation

Prescription Maps

General description before alterations

The prescription software is intended to generate nitrogen fertilization rates for a given field that maximize the information able to be gleaned from a field, while also minimizing stress on fertilization

application equipment. Specifically, this software ensures that there is sufficient replication of nitrogen rates in a particular range of yield values. The input data consists of data concerning the specified field and the yield points for that field with their values and location. The field information includes the shape of the field by GPS coordinates, the name of the farmer, and the name of the field. The information used from the yield file is limited to the yield value and its UTM location values; this information is saved into a yield-point data structure.

After reading the CSV files and saving the required information, the field is created from the obtained coordinates, and plots are created within the field based on the desired plot size, which is determined by input from the farmer (based on the size of the equipment). The plots are created based on the largest width and length of the obtained polygon, resulting in a rectangular shape, of the field. This means that some plots are created that fall outside of the field; therefore, the array of plots is iterated over to check

if it falls within the field boundaries and plots outside of the field are deleted. Once the final plots have been determined and saved into an array containing the plots as “rectangle” data structures, yield points are added to the plots. The entire array of yield points is iterated over, and for each yield point, it is determined in which plot it is situated. In other words, for each plot the yield points are saved into the “rectangle” data structure, within the array of the field.

For each block within a field, the average yield is calculated based on the yield points within that block. These averages are used to divide the blocks evenly into three categories: high, medium and low yield (where each category has the same number of blocks). However, sometimes there is no yield-data available for certain blocks, rendering them uncategorized, or “uncat.” This categorization is implemented to make sure there are enough plots within each category so there is a wide range of different circumstances that produce each yield category.

The actual Nitrogen application rates are chosen by the farmers. The first application rate is chosen randomly from these values and applied to the first block within the field array. The next block in the field is assigned the next application rate from the farmer-chosen application values. This continues on until there are no rates left, after which it assigns a zero application rate and starts going back up again. Figure 1 shows an example of a prescription for a particular field.



Figure 1 Prescription for OFPE N-fertilizer experiment on Broyle’s field. Different colors represent different N-fertilizer rates.

Alterations to the model

Strip

The code described above has been altered to include the possibility to add a strip in the field with a uniform application rate. This addition required alterations to the internal data structures to enable easy assignment of a vertical strip that has more than two blocks. Once the strip is chosen, a uniform rate is applied, which is also chosen by the farmer. An example of a prescription with the added strip can be seen in figure 2. In this example, the uniform strips is the second vertical strip from the right (green for color renderings).

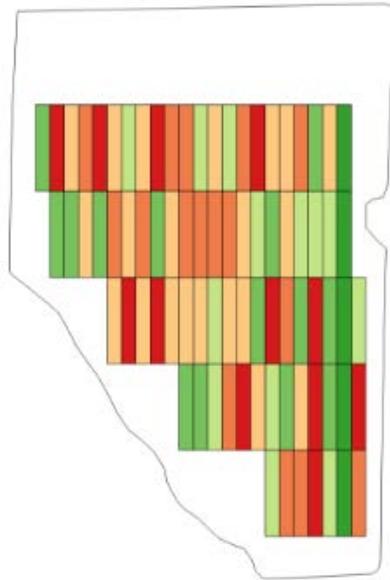


Figure 2 Prescription for OFPE N-fertilizer experiment on a Broyles' field with strip

Protein

Aside from yield, protein values can be included as an extra parameter. The calculation of average protein follows the same logic as described above for yield values.

Zero assignment

Some farmers do not want as many zero assignments as the normal prescription software defines, so the option to reduce the number of zero assignments has been added in.

Command line interface

To enable easier usage of the prescription software, a command line interface has been implemented. Furthermore, code commentary has been added to make the software easier to understand, and guidelines were created to explain how to use the command line interface.

Future work

In the future it would be useful to add a Graphical User Interface so the application becomes more user friendly for farmers. In addition, other ways to create fertilization application prescriptions could be added so farmers can choose the way they wish to apply their nitrogen, based on the equipment they have available. For example, instead of jumping back to zero after the highest value has been reached, the prescription rate would lower back down towards zero and then be raised again. Additional future work would also involve incorporating the yield and protein prediction and optimization as to ensure that farmers would have the option to set yield and protein targets for the field, and have the software optimize nitrogen inputs in an attempt to reach those targets.

Optimization

Multi-Layer Perceptrons

A neural network is defined as a parallel, distributed information processing structure. This structure contains processing elements connected to each other with unidirectional signal channels (connections). Each of these processing elements possess local memory and can therefore process local information, all the processing within an element depends solely on the current value of the input signal and on values stored within the local memory. The elements each have a single output (with an output signal of any mathematical type) branching into as many collateral connections as necessary. (Hecht-Nielsen, 1989)

In a feed-forward neural network (also called a multi-layer perceptron) all nodes of the network pass information forward through a sequence of layers until reaching the output layer. The updates to the weights in the interior of the network are defined by the backpropagation algorithm. An example of a feed-forward neural network is shown in Figure 3. Back propagation is one of the most popular techniques for training neural networks. It was introduced by Rumelhart, Hinton, and Williams. A multi-layer perceptron uses the back propagation algorithm where the updates are propagated from the output layer back toward the input layer. The gradient of them mean squared error with respect to the vector of weights in the network is computed, and this gradient is used to determine how to update the weights to minimize error. (Sheppard, 2016)

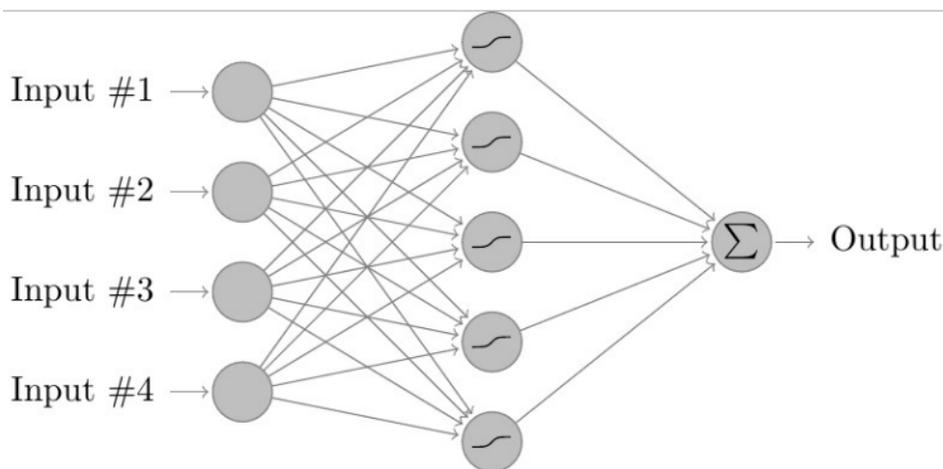


Figure 3 Feed Forward Neural Network

Stacked auto encoder

Deep Learning refers to a set of machine learning algorithms that attempt to model high level abstractions in a set of data. Deep Learning is typically implemented in the form of a multi-layer neural network, but it tends to be more involved, adding more layers to derive better abstractions. A traditional neural network can only have about two hidden layers before the training methods start to fail, and as such is limited in the abstractions it can model. A Deep Learning network (usually called a deep network) can have as many layers as we need.

The Deep Learning method we are using is referred to as a stacked auto-encoder. An example of this network is seen in Figure 4. Auto-encoders take in a set of inputs and transform that input, usually reducing dimensions. In the training process, and then attempt to convert the input back to its original form, using the difference between the original and decoded outputs to modify the transformation. After

training, when we use the auto-encoder, only the input-to-transformed input part is used to generate a new set of training data. This new data is used to train a new auto-encoder.

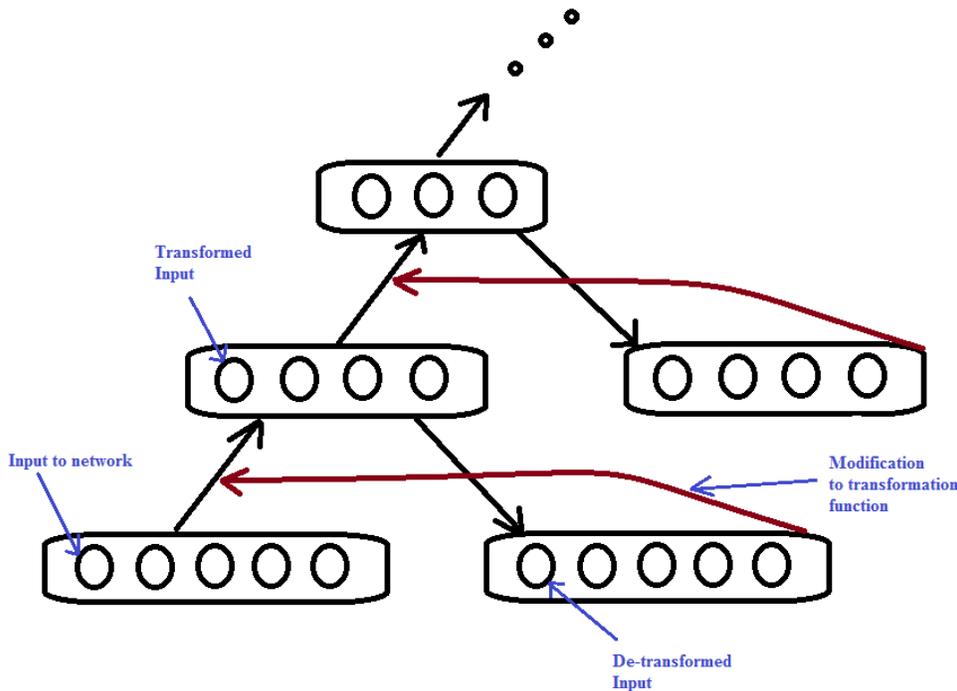


Figure 4 Example of a stacked auto-encoder. Inputs feed into a layer, and get transformed as they go into the next layer (also reducing the dimensions). Then, to make sure the transformation works the way we want, we try to reconstruct the original input. The difference between the original and reconstructed input is used to modify the transformation and make it better.

When we stack the auto-encoders, higher auto-encoders in the stack tend to recognize more abstract features. For example, if we have an image that is being fed through the stacked auto-encoders, the first auto-encoder might identify lines in the image. The next auto-encoder might identify shapes and the auto-encoder after that might identify relationships between shapes. This makes stacked auto-encoders a powerful tool for accurate prediction in very complex systems. As we will discuss later, traditional neural networks can predict protein with an accuracy of about 40% in the best case. We hypothesized and found that stacked auto-encoders would provide much higher accuracy.

The Numerical Intelligent Systems Laboratory at MSU developed a stacked auto-encoder implementation for predicting wind-speeds using TensorFlow and Keras. (McAllister, 2017) The TensorFlow section of the implementation is mostly used for parallelizing the network with Graphical Processing Units. The Keras section is used as scaffolding around network creation and training. The remainder of the framework was created by Richard McAllister in the programming language Python. This framework allows for communication between network primitives (e.g. nodes, layers). The framework also uses json files (JavaScript Object Notation) to store and run different network configurations. For this project, the initial implementation was modified for use in a Precision Agriculture setting.

To evaluate the ability for different neural network methods to predict yield and protein, we performed experiments comparing feed-forward networks, stacked auto encoders, and linear regression models. To compare these models, we applied cross-validation and used both means squared error and the Coefficient of Determination (R^2). R^2 represents the amount of variation in the data that can be explained

by a particular model. Higher R^2 values correspond to more accurate models. We also used Root Mean Squared Error (RMSE) divided by the range of values for each variable. Higher RMSE values indicate less accurate models.

Through a tuning process, we selected the number of layers and the number of nodes in each layer in both the stacked auto-encoder network and the feed-forward network. The highest performing stacked auto-encoder had 3 layers and 1000 nodes in each layer. The highest performing feed forward network had 2 layers and 10 nodes in each layer. We also evaluated the effect of adding spatial context for each point on accuracy. We did this by finding the eight nearest points to each point. The R^2 -values for linear regression, the feed-forward network, the feed-forward network with spatial context, the stacked auto-encoder, and the stacked auto-encoder with spatial context are shown below. The stacked auto-encoder with spatial context had by far the best R^2 for both protein and yield.

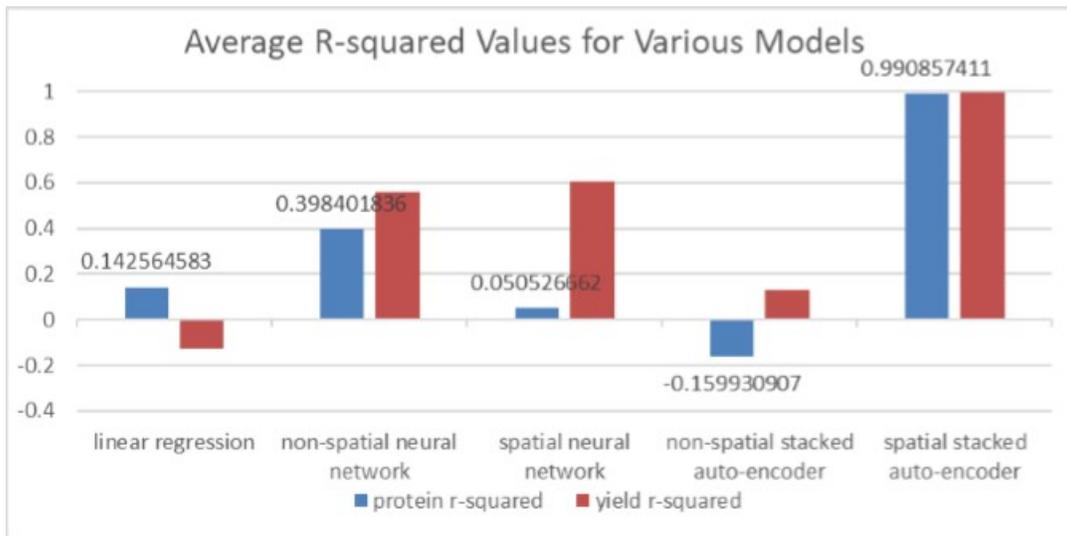


Figure 4 Average R-squared value for various model

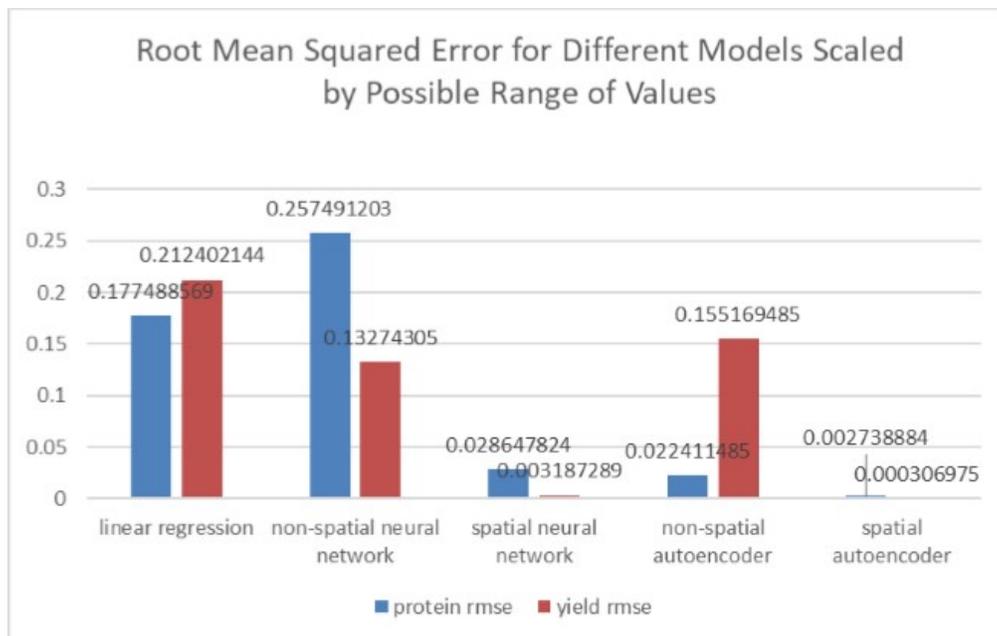


Figure 5: Root mean squared error for different models scaled by possible values

Discussion

As shown in figure 4 and figure 5 above, there is a significant improvement using the spatial stacked auto-encoder. The root mean squared error shows the opposite of the R-squared value, instead of assessing how well the model performs, it shows its error rate. To discover what exactly makes this model perform almost 50% better than all other models, especially where protein is concerned, more research would be necessary. A possible explanation is the fact that the code references to less complex iterations of itself multiple times in different ways due to the larger number of hidden layers, thus improving learning and leading to more accurate results. It would be interesting to investigate whether other types of spatial sampling lead to similar results.

The most interesting and confounding part of the results, are the negative R-squared values. Especially in the linear model, the negative value for yield indicates that the yield values are going in a downward trend and that the line drawn throughout these results is worse than the average line. This may indicate problems with the values or with the way the linear regression is performed. There is also a negative R-squared value for protein when applying the non-spatial stacked autoencoder. This result is especially interesting due to the large contrast to the results from the spatial stacked autoencoder. This makes sense considering all the used data is related to specific locations. However, when looking at the difference between spatial and non-spatial shallow neural networks, the logic behind the results concerning the autoencoders does not hold for protein values. More research into these issues is required to discover the underlying cause for these results.

Future Work

There are several methods of including spatial context not described in this work. We would like to evaluate the relative performance of including spatial context. Currently the only type of spatial sampling that has been applied is the K Nearest Neighbour method, in future research we would also explore Equal Distance and Random Selection as spatial sampling methods. Additionally, multiple linear regression is another method for predicting protein and yield we would like to investigate.

The current stacked autoencoder that is being implemented was designed for a different project, so it may be useful to see whether the autoencoder can be modified to suit this specific project. Furthermore, there are still parts of the code that require more in depth research to fully grasp how it is calculating the results, which could lead to a better understanding and hopefully to improving the model.

Expenditures

- Total Personnel Services: \$55,009.70
- Total Operations: \$14,815.30

3) 41W228 – Principal Investigator: Clem Izurieta; Email: clem.izurieta@gmail.com
Co-investigator: Rob Payn

Progress towards milestones

Payn and Izurieta are managing the team focused on design and implementation of the data management and workflow technology. The underlying software for data management has been named the Object Oriented Environmental Data System (OOEDS). The system is based on state-of-the-art “NoSQL” database technologies, and will handle transfer and storage of digital information for the data import, model calibration, experimental design, yield optimization, and application prescription phases of OFPE process. There have been no new hires to the team managed by Payn and Izurieta during the past quarter (February-May). The larger team, including Thomas Heetderks, Seth Kurt-Mason, and Michael Trenk

continue to meet approximately every other week to track project progress and address the shifting priorities inherent in a research and development project. MSU's "Box" cloud service is being used as a central document repository for the project, and a "Github" service is being employed to provide centralized management of code organization and revision during software development.

The last quarter saw progress on the following activities. In each section, we also include a brief description of what we expect to accomplish by the end of June 2017 (end of funding).

1. OOEDS Data Model

The abstract schema of the data model is complete. We have made minor modifications that allow for a future feature-set that will track data quality, though implementation of this feature set is not planned for this round of funding. This design will be communicated in the manuscript being prepared, as described in part 4 of this report. Resources allocated to data model development are currently more strongly allocated to the manuscript development.

Specific objects in the schema will continue to be added and evolve through the life of the project. The schema is designed to be extensible to allow new data types to be added, as required by new datasets or data relationships used in the agronomic models. We expect continual new requirements will force modifications; however, the modifiability by design will make this work simple.

Activity and completed tasks

- Designed the specific "model" and "activity" objects that are necessary for storing collated data that are spatially rectified with wheat yield or protein models.
- Adapted the schema to include a data quality assurance / quality control measurement context. Data may need to be sorted by various quality types that are tied to the measurement of analysis techniques. More than one context for quality assurance may be necessary, so a given evaluation may be associated with objects in multiple QAQC measurement contexts.

Plans through end of funding

- Design evaluation and model classes necessary for storing fertilizer prescriptions.

2. OOEDS Web Interface

We continue to develop a basic data management interface based on an open-standard authentication mechanism (OAuth), using a web development framework (Flask). The interface will provide secure access to the MongoDB database for basic workflow management (Figure 3). The authentication system will be installed on the production server and will be used with MongoDB's user database system to manage data security. Efforts have been focused on implementing the basic features that will be necessary for future construction more detailed user interface tools to a precision agriculture workflow (Figure 5).

Activity and completed tasks

- OOEDS programming interface and the associated back-end software is complete.
- User interface prototype is complete (Figure 4).

Plans through end of funding

- Workflow tools (described below) will be integrated with user interface as they are completed.

3. Workflow software products:

Over the course of the project, an end-to-end OFPE data acquisition and optimization process has been clearly defined. There are now clear abstractions of individual workflows that must occur in order, regardless of the details of what property of a crop is being optimized or the type of optimization model being used. We summarize the input, activity, and output of each of these processes below, along with reporting progress on each one. Note that the output of a given workflow (with the exception of the prescription workflow) is identical to the input of the next workflow in the overall process (with the exception of the yield editor data input workflow).

a. Yield Editor data input workflow

Input (from farm): Raw data from harvest machinery.

Activity: Processing of raw data using external “Yield Editor” software. This is a complex decision process that primarily verifies that data from the harvester is associated with the appropriate location in the field, based on harvester speed, lag time of grain movement through the harvester, etc.

Output (to OFPE database): Tables of yield data appropriately aligned with field locations for a given harvest of analysis. Note that there is a similar process with different software for protein data.

Activity and completed tasks

- Programmers interface features necessary for the yield editor workflow are complete.
- Tools for loading yield editor workflow output to the database have been updated to use the completed OOEDS programmers interface.

Plans through end of funding

- Integrate yield editor workflow tools with the user interface.
- Load existing yield editor outputs to the database.

b. Data rectification workflow

Input (from database): Tables of yield data appropriately aligned with field locations for a given harvest of analysis.

Input (from other data sources): Data (multiple forms) from the associated field that is expected to be a useful explanatory variable for spatial variation in yield or protein within the field.

Activity: Data for explanatory variables are spatially rectified to the yield or protein data points. This rectification is mainly carried out with GIS software, and is necessary to ensure that later application of optimization models are associating the yield or protein at a given location with the appropriate value of the explanatory variable that is driving that yield or protein level.

Output (to OFPE database): Tables of yield or protein data that are appropriately aligned with the spatially associated value for the explanatory variable. There is one additional column in this table for each explanatory variable.

Activity and completed tasks

- Programmers interface features necessary the data rectification workflow are complete
- Tools for loading output of data rectification workflow to the database are complete

Plans through end of funding

- Implement data query tool for rectified data tables
- Integrate data query tool with the user interface
- Load existing rectified data tables to the database.

c. Optimization workflow

Input (from database): Tables of yield or protein data that are appropriately aligned with the spatially associated value for the explanatory variable. There is one additional column in this table for each explanatory variable.

Activity: A calibrated model is created by optimizing parameters for the accurate prediction of yield/protein for the given year of analysis based on data from the previous year. Then, the calibrated model is used to generate a fertilizer prescription that is optimized for both information from experimental plots and yield/protein from production plots.

Output (to OFPE database): A shape file of varied fertilizer application prescription plots across the field.

Activity and completed tasks

- Programmers interface features necessary for the optimization workflow are complete.

Plans through end of funding

- Implement data query tool for extracting rectified data tables from the database.
- Integrate data query tool with the user interface

d. Prescription workflow

Input (from database): A shape file of varied fertilizer application prescription plots across the field.

Activity: The shape file is input into third-party field equipment manufacturer software, which translates it to the file formats necessary to control the application rates in field machinery.

Output (to application equipment): Files controlling application rates.

Activity and completed tasks

- Database schema design for classes necessary to store shape files is complete

Plans through end of funding

- Design tools for downloading prescription in a format suitable for import to third-party nitrogen application software packages.

4. Manuscript

We are actively working on developing a manuscript for an environmental informatics journal (e.g. Environmental Modeling and Software). The topic of the manuscript will be to introduce an extensive objective oriented data model suitable for storing environmental data in NoSQL (or object-oriented) databases. Rob Payn, Seth Mason and Clem Izurieta are meeting on a bi-weekly basis to develop this manuscript.

Activity and completed tasks

- Outline and initial figures have been developed. Figure 1 is the example of the core abstractions of the data model from the manuscript, and Figure 2 is an example of the OFPE case study data model that is being used to demonstrate the utility of the schema.
- Initial draft is approximately one third complete

Plans through end of funding

- We expect that the first complete draft of the manuscript will be complete by the end of the funding period, with submission to the journal by the end of the summer.

5. Documentation

Plans through end of funding

- The design team will be creating technical documentation for the design and implementation of the programmers interface and user interface. These documents are geared toward providing continuity in training new developers for future system development work.

Figures

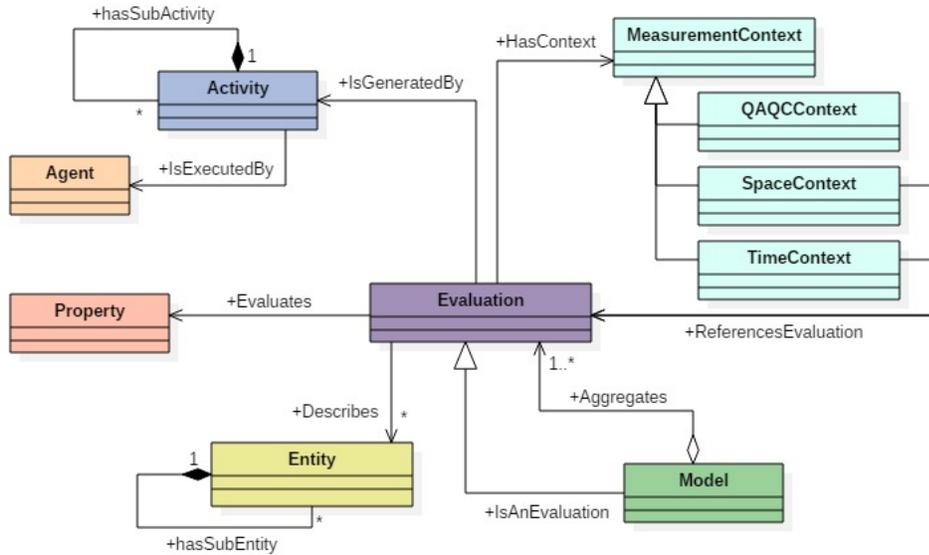


Figure 6. Executive Level Data Model

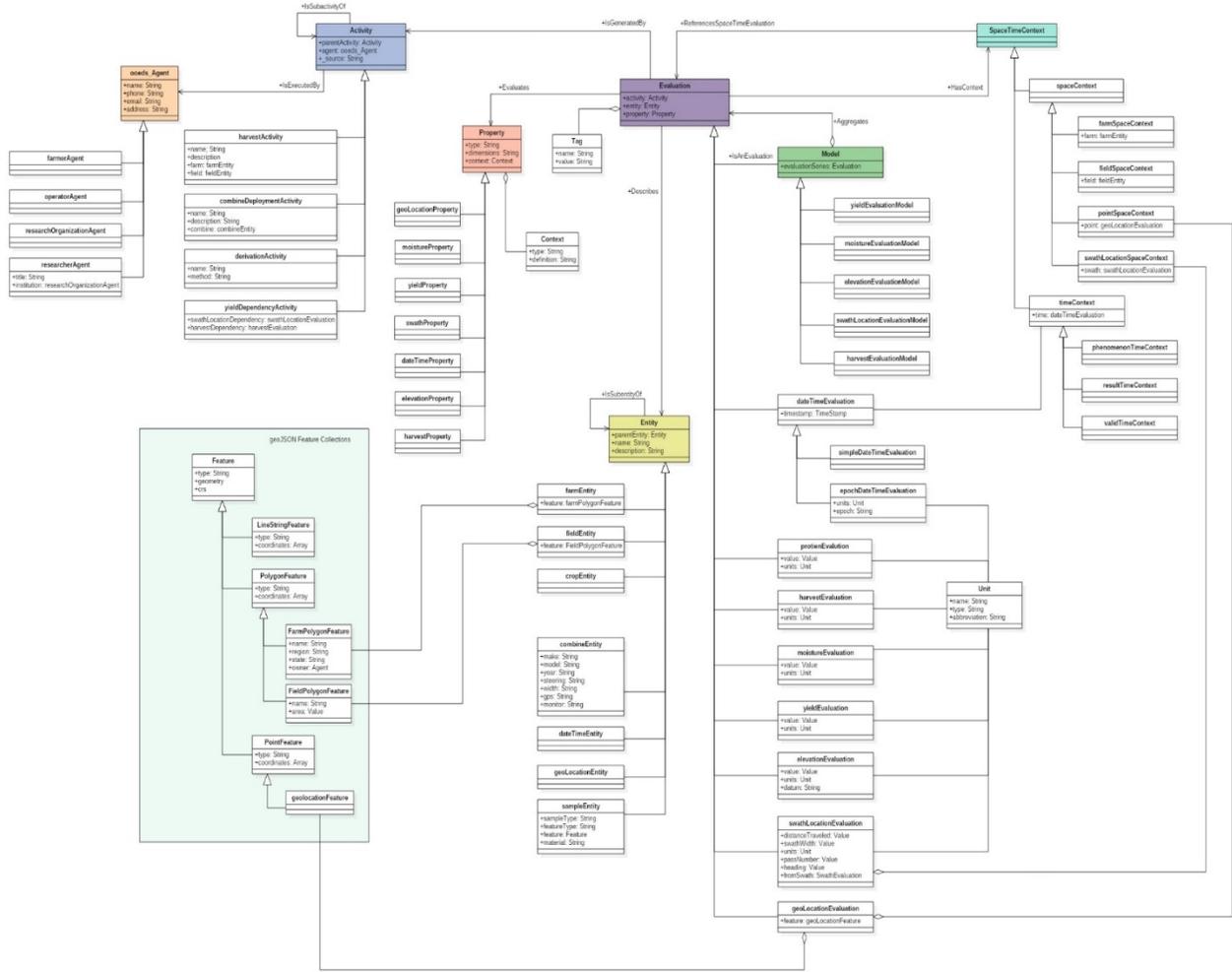


Figure 7. Each component describes an entire subsystem

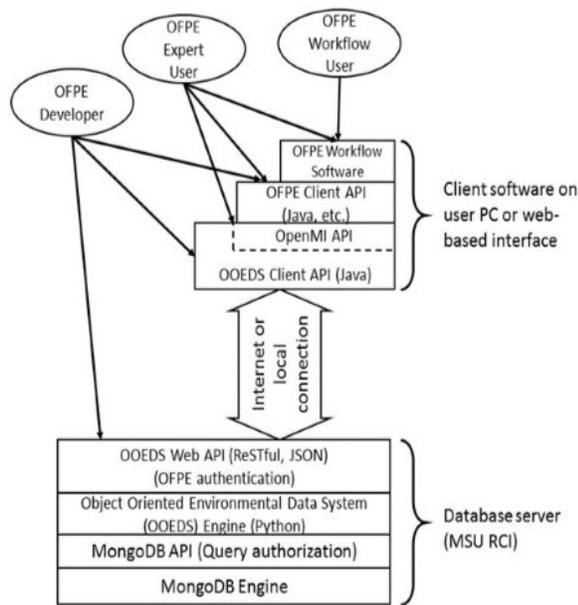


Figure 8. Software Architecture

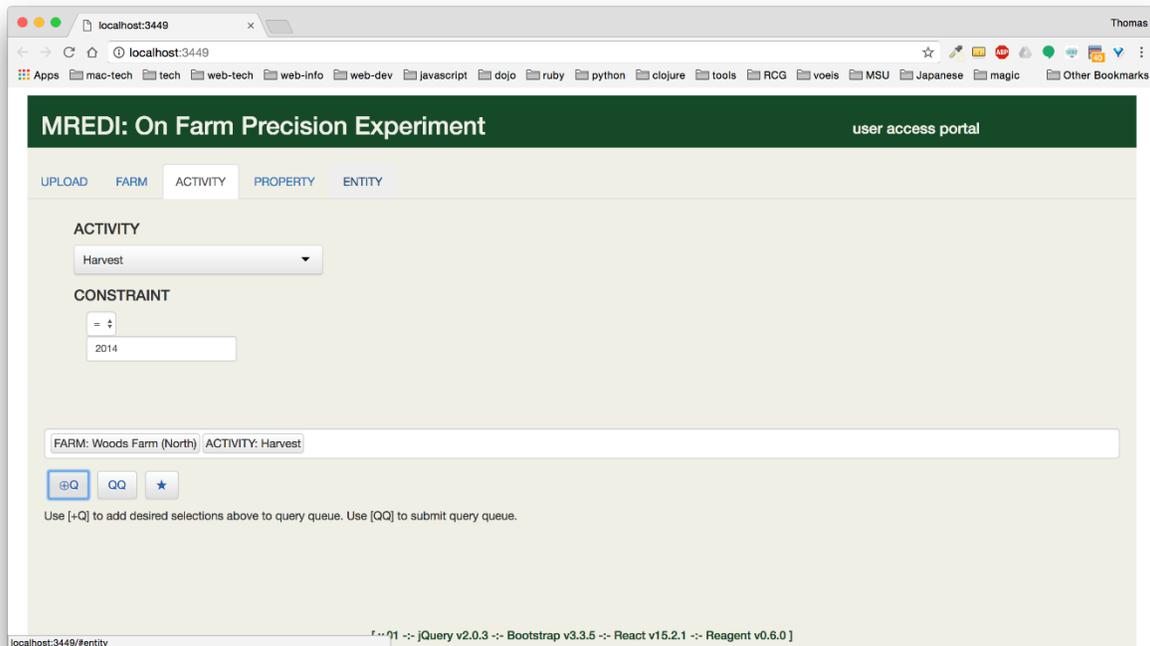


Figure 9. Screenshot from prototype for a basic web interface to the database.

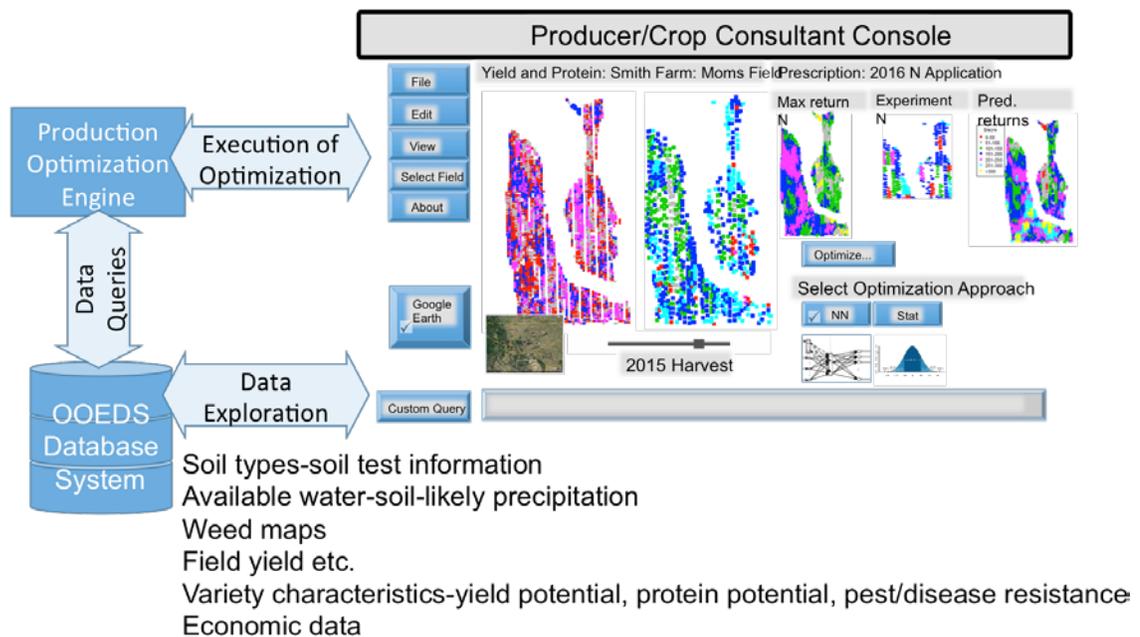


Figure 10. Rough 'mock-up' of the potential user interface for performing optimizations and data explorations for a given field, and the programming interfaces to the lower-level functionality begin developed in this project.

Expenditures

- Total Personnel: \$157,776.77
- Total Operations: \$29,261.19
- Total Equipment: \$3,512.04

4) **Industry Match** - Dr. Nick Silverman (Adaptive Hydrology) in collaboration with Dr. Kelsey Jencso (UM)

Progress towards milestones

- Adaptive Hydrology has continued to maintain all weather stations at the four participant farms. We are working closely with the Climate Office to install and maintain an additional 5 stations that will support the OFPE project. These stations have been ordered and will be installed by the end of June.
- We have aggregated precipitation and growing degree day data using three separate datasets for each field and have used a quantile mapping algorithm to fill gaps in these datasets. We have used these weather data to help inform an "all farms" model where we have traded time for space to acknowledge water limitations during the growing season. Both non-linear least squares and random forest statistical techniques were used to predict yield.
- We continue to provide technical support to all the participant farmers.
- We have been working with Bruce Maxwell to fine-tune the development of a statistical model for yield and protein in winter wheat; we've developed a random forest model to complement the standard non-linear model.
- We are helping to calculate net economic returns using the non-linear least squares models for each field.
- We are supporting the development of the USDA AFRI-NIFA proposal due in July.
- We have been present and active in all meetings over the last three months.

Durum Quality subproject of the Agriculture MREDI project

41W221 – Principal Investigator: Mike Giroux; Email: mgiroux@montana.edu

List the accomplishments of the project in quantitative and qualitative terms

1. Developed capacity to test product quality of durum at MSU Bozeman. This includes the ability to measure durum milling and mixing properties.
2. Create and test durum breeding populations adapted to MT growing regions. This involved intercrossing varieties and germplasm stocks to create populations containing individual lines that may ultimately be released as varieties.
 - a. We identified genotypes having high yield that are low in cadmium and carry an increased pasta firmness trait.
 - b. One or more lines from our initial testing may be ready for varietal release in several years.
 - c. Many other additional populations have been created for future testing.
3. Collaborated with Northern Seed on moving forward with new and current durum breeding populations. Northern Seed is moving forward towards potential varietal release as soon as spring of 2020.
4. All original objectives were completed and continued efforts to select for high yielding and high product quality durum for MT growers will continue.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

1. We anticipate continued efforts to create improved durum varieties for MT growers both at MSU and at Northern Seed.
2. The long term impact should be seen in increased durum acreage and yields as higher yielding new varieties replace some of the lower yielding varieties currently being grown.

Final Metrics

- Total additional grants received:
 - A grant from Montana Wheat and Barley Committee to continue the durum improvement work.
 - Continuing support from a private seed company to work on enhancing durum pasta quality.
 - A grant from the USDA focusing on the role of dwarfing genes in wheat yield.
- Total additional grants in progress:
 - Funding will be requested from the USDA to examine the impact in durum of a gene from bread wheat that increases durum Aluminum and low pH tolerance.
 - Funding will be requested from private companies to work on genes that enhance pasta quality and shelf life.
- Number of partnerships formed (private and public sector): A partnership with a private company on the development of improved pasta quality.
- Number of new Montana businesses created: None
- Patents awarded or in progress: One
- Commercial products developed: No commercial products have been developed, but several in the form of new varieties are in progress.
- Jobs created: One research associate and several undergraduate students work on this project.

Expenditures

- Total Personnel: \$111,210.82
- Total Operations: \$63,865.18
- Total Equipment: \$70,994.00

Wheat Stem Sawfly subproject of the Agriculture MREDI project

41W222 – Principal Investigator: David Weaver; Email: weaver@montana.edu

List the accomplishments of the project in quantitative and qualitative terms

Research Update 1. Laboratory study of sugar and nectar in the longevity and egg dynamics of the wheat stem sawfly parasitoids.

The two species, *Bracon cephi* (Gahan) and *B. lissogaster* Muesebeck have very different responses to sugar resources that might be provided by existing sugar resources. An important ecological point is that studying the role of flowering crop sugars in these two species has discovered that the biology of the two species is quite different. Before this project the two species were known to be spatially and temporally sympatric using the same host, wheat stem sawfly larvae. This doesn't happen often. Sibling species usually don't compete directly for the same resource using the same biology. The more abundant species, *B. cephi*, uses sugar to be more successful in a different way than the less frequently encountered *B. lissogaster*.

Research Update 2. Field study of the role of flowering pulse and cover crops in the abundance of wheat stem sawfly parasitoids.

In these field surveys, there were 5 sites with both cover crops next to wheat and adjacent fallow next to wheat. There were 6 sites with both pulse crops (3 pea, 2 lentil, 1 chickpea) next to wheat and

adjacent fallow next to wheat. Using field trapping, emergence from residue and postharvest dissection, both parasitoids and wheat stem sawflies were detected in all fields. There were 4 sites with abundant sawflies and 4 with abundant parasitoids. Of these, there was 1 site with abundant parasitoids and few sawflies and another with abundant sawflies and few parasitoids. There were 4 sites that had both abundant parasitoids and abundant sawflies. When trapping sawflies in these fields, there was more sawflies and parasitoids caught at the wheat - flowering crop interface or there were no differences between the wheat- flower and wheat – fallow interface. Dissection of stems for a more accurate measure indicated that significantly more parasitoids were present in fallow next to flower source at 3 sites, with no others being different. Allowing insects to emerge from a bulk of overwinter residue indicated greater numbers of sawflies or parasitoids in wheat next to flowers than in wheat next to fallow. One of these fields had more parasitoids next to fallow and more sawflies next to flowers, which was not expected.

1. LABORATORY SUGAR

Longevity

Material and Methods. Here, we tested the effect of adult sugar feeding on the longevity of *Bracon cephi* (Gahan) and *B. lissogaster* Muesebeck (Hymenoptera: Braconidae), both native, idiobiont and host specific larval parasitoids of the wheat stem sawfly (WSS), *Cephus cinctus* Norton (Hymenoptera: Cephidae). Both generations of parasitoid females were reared on diets of sucrose or water only, and daily evaluations were made to check for mortality. Additionally, a preliminary experiment testing the effect of honey feeding on the longevity of the WSS was made to guarantee that carbohydrate-rich diets do not affect survival of females.

Results. Our results generally showed a significant increase in longevity when sucrose was offered to both parasitoid species and generations (Figure 1). Specifically, first generation females of *B. cephi* lived for a mean \pm SE of 11.4 ± 0.7 days with water, and 30 ± 2.5 days when fed with sucrose. Second generation females of *B. cephi* lived for 8.2 ± 2.3 days with water only and 29.2 ± 3.3 days with sucrose. For *B. lissogaster*, first-generation females lived for 8 ± 0.7 days with water and 54.9 ± 8.6 days with sucrose. While second-generation females of *B. lissogaster* lived for 3 ± 0.7 days with water and 46.7 ± 7.3 days with sucrose. Our results also showed significant difference in longevity between generations for both parasitoid species, when females were fed with water. These results suggest that first-generation females could be using more of their metabolic reserves to sustain longevity, compared to second-generation females when they were fed with water only. However, after feeding on sugar, these differences are not significant anymore. Finally, results showed no significant difference in longevity for WSS females treated with water or honey.

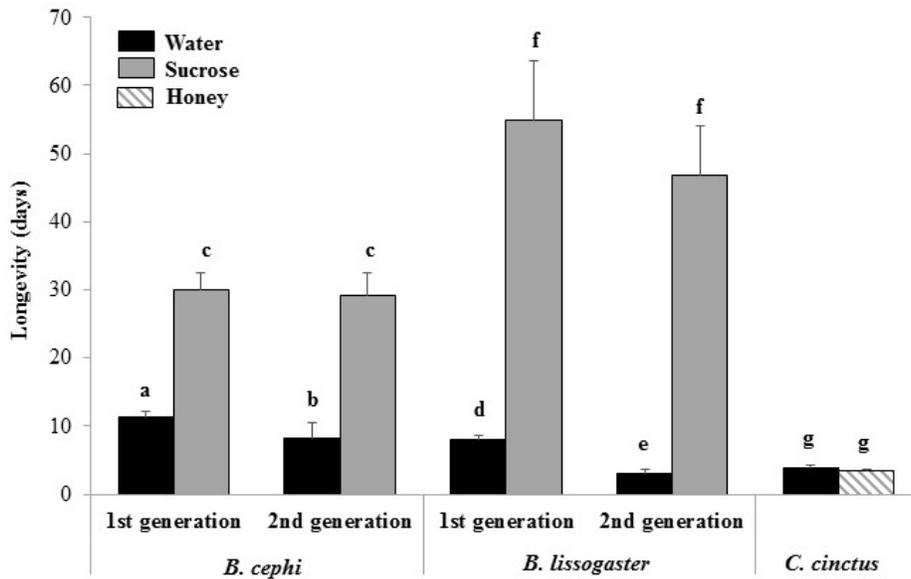


Figure 1. Average longevity of both generations of *B. cephi* and *B. lissogaster* females in response to water and sucrose treatments. Average longevity of *C. cinctus* females in water and honey diets.

Egg Load and Egg Volume

Material and Methods. In this experiment we tested the effect of sugar feeding on the egg load and egg volume of both generations of *B. cephi* and *B. lissogaster*. In this case, “egg load” means the number of matured eggs carried by a female parasitoid at a given moment in her lifetime. We determined the egg load and egg volume of parasitoid females at 3 different ages: 2, 6 and 10 days-old. Females were reared on diets of sucrose and water only. To count the number of matured eggs females were dissected under ethanol using a stereomicroscope. Length and diameter of each matured egg was measured, and the egg volume was estimated as $V = (\pi r^2) (L - 2r) + (4/3) (\pi r^3)$, where L = length, D = diameter and $r = D/2$ (O’Neill et al. 2014).

Results. Our results show a great contrast in egg load and egg volume between the two native parasitoids of wheat stem sawfly. Females of the more abundant species, *B. cephi*, had less mature eggs in the ovaries at ages 2, 6 and 10 days-old, compared to *B. lissogaster* species (Figure 2). In contrast, egg volume of *B. cephi* females is greater than the egg volume of *B. lissogaster* females (Figure 3). Results also showed that water-fed females of first-generation of *B. cephi* and *B. lissogaster*, as well as second-generation of *B. lissogaster* resorb eggs as they age. Female parasitoids usually do that to reallocate energy resources from egg production to longevity. Sugar feeding affected species and generations differently. First-generation females of *B. cephi* significantly increased egg load and egg volume when fed with sucrose, compared to females that were fed with water only. Second-generation females of *B. cephi* also significantly increased egg load when fed with sucrose, but egg volume did not change. Likewise, first-generation females of *B. lissogaster* increased egg load, but egg volume was the same after feeding on sugar. Finally, for second-generation females of *B. lissogaster* egg load and egg volume did not change when sucrose was provided. These results may provide some insight about the difference in reproductive strategies of *B. cephi* and *B. lissogaster*. Egg size is often correlated with offspring success, thus abundance of *B. cephi* in the field could be a result of a greater investment of females in egg volume instead of egg load. In contrast, *B. lissogaster*, which is also known as a gregarious species, produced smaller, but more numerous eggs. In this case, “gregarious”

means that females can lay more than one egg per host. With this strategy, the smaller the eggs, the more change they have to successfully develop in a single host. Therefore, sucrose feeding could potentially enhance reproductive success of *B. cephi* females by increasing egg volume, and for *B. lissogaster* females, by increasing egg load.

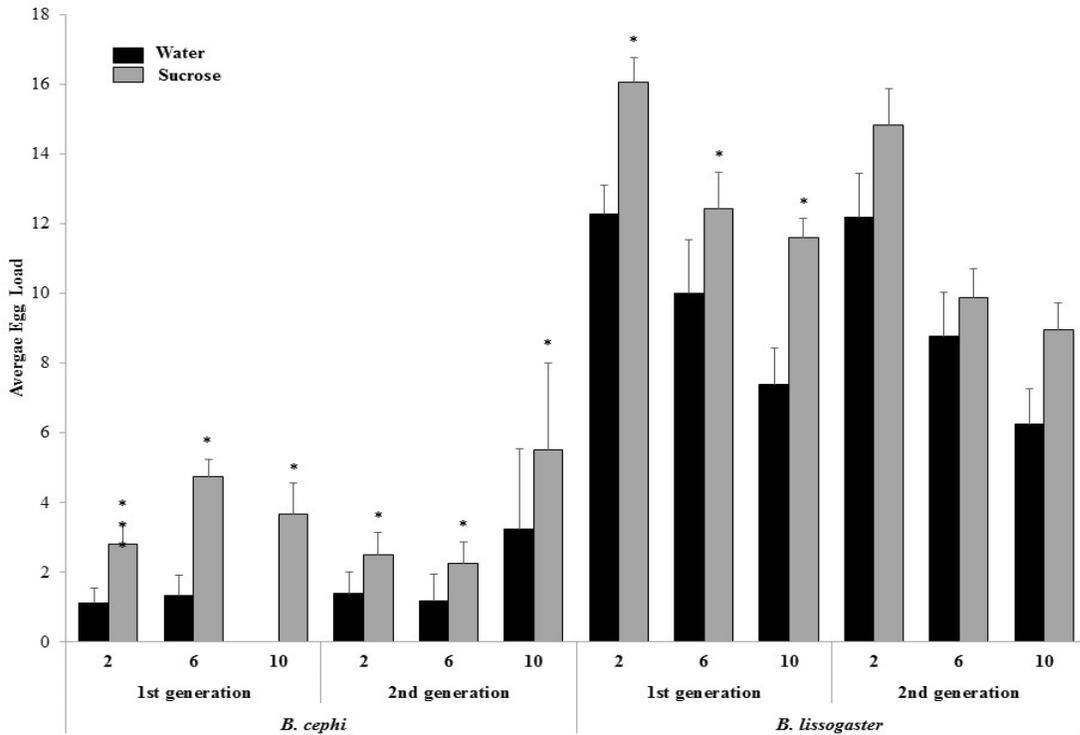


Figure 2. Average egg load of both generations of *B. cephi* and *B. lissogaster* in response to water and sucrose treatments.

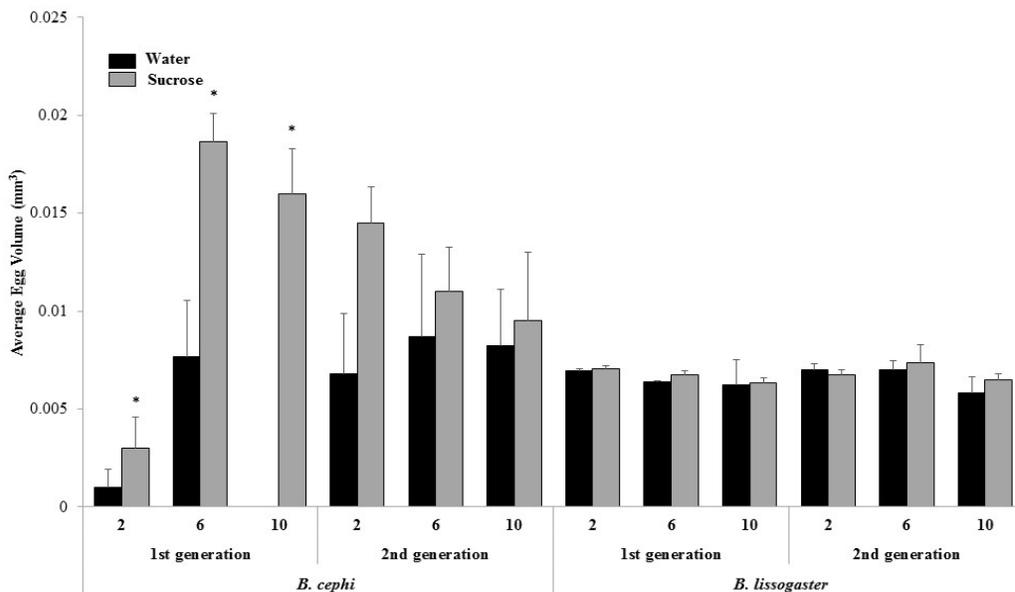


Figure 3. Average egg volume of both generations of *B. cephi* and *B. lissogaster* in response to water and sucrose treatments.

Greenhouse Experiment

Material and Methods. At the greenhouse we tested the effect of flower resources in the longevity, egg load and egg volume of first-generation females of *B. cephi* and *B. lissogaster*. The flowering plants tested in this experiment were: wheat, alfalfa, flax, buckwheat and peas. Water was offered as a control. Newly emerged females were individually released in cages made of plastic cups, with a recently bloomed flower (Figure 4). Parasitoids were checked daily for mortality. At death, parasitoid females were dissected to count the egg load and estimate the egg volume.

Results. Here, our results showed that only buckwheat increased longevity of *B. cephi* (Figure 5-A,B) and *B. lissogaster* (Figure 6-A,B). These results suggest that both species of parasitoids were able to access and consume sugar sources from buckwheat flowers. In contrast, no difference was found between longevity of females of both species treated with control, alfalfa, flax, peas and wheat. No differences in egg load were observed for *B. cephi* females among treatments (Figure 5-C). Because any eggs were found in the ovaries of *B. cephi* females treated with wheat and alfalfa, the egg volume for these two treatments was also equal to zero. Disregarding these two treatments, no difference in egg volume was found in *B. cephi* (Figure 5-D). Egg load of *B. lissogaster* females decreased with buckwheat (Figure 6-C). However, it was previously shown that this species resorb eggs as they age. This could explain why egg load was significantly lower for females that significantly increased longevity in the buckwheat treatment. No difference in egg volume was found in this species (Figure 6-D).



Figure 4. Pictures illustrating the cages, made of plastic cups used to determine longevity of WSS parasitoids in response to flower resources. Females of *B. cephi* and *B. lissogaster* were individually placed inside the cages with a recently bloomed flower.

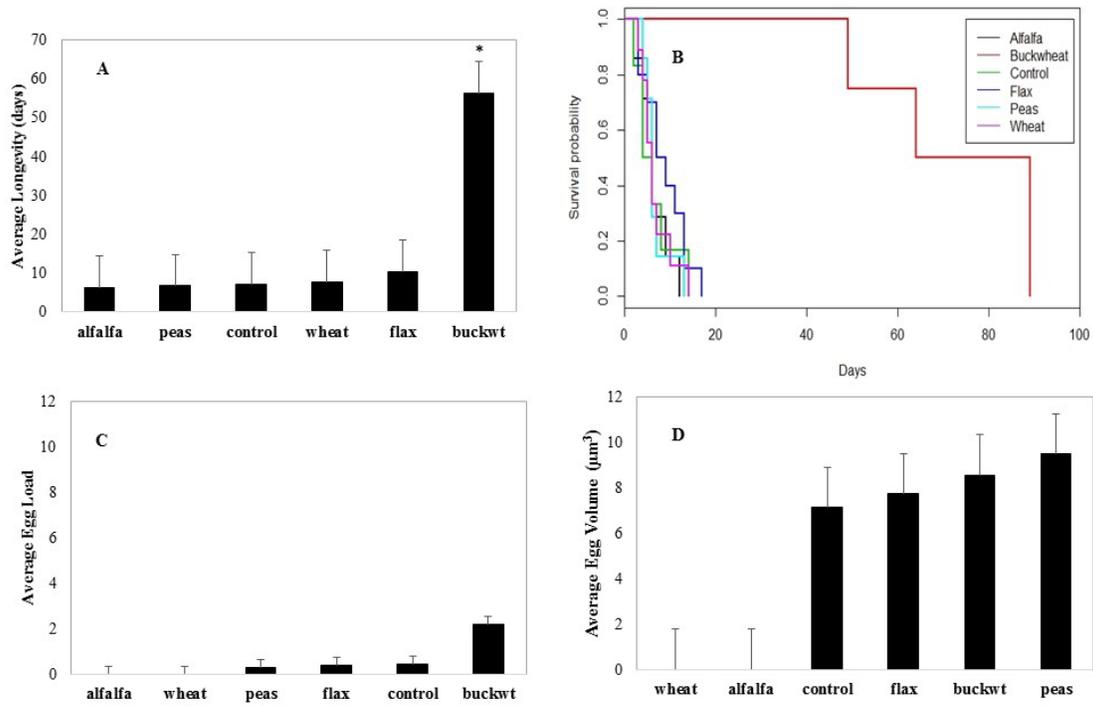


Figure 5. Comparisons of average values of (A) (B) longevity, (C) egg load and (D) egg volume of *B. cepi* females in response to the treatments (control, alfalfa, buckwheat, flax, peas and wheat).

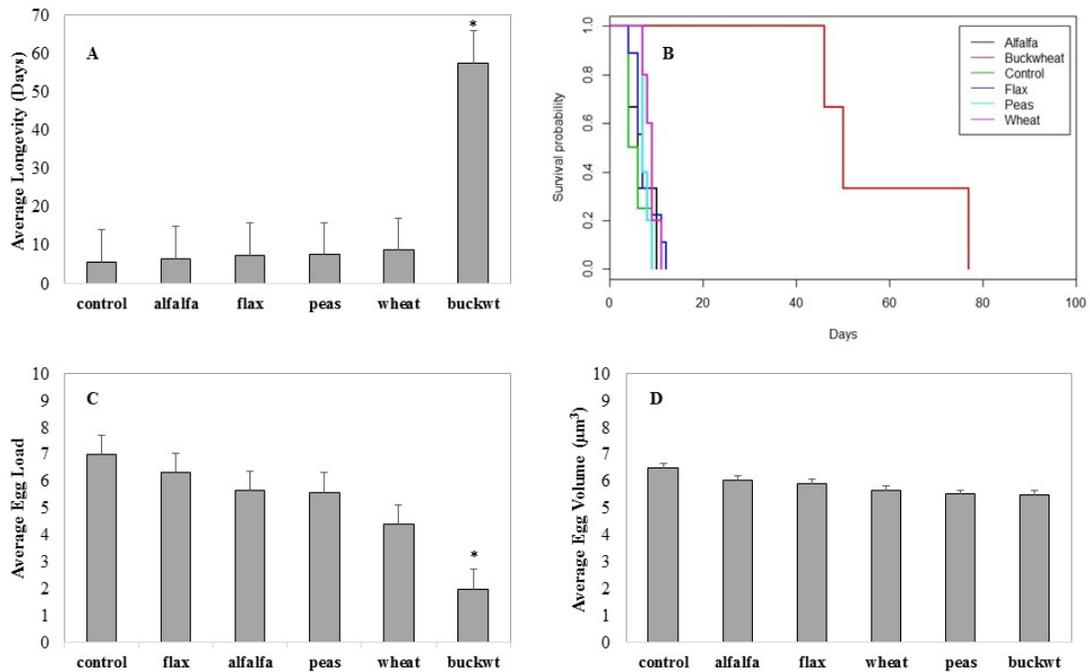


Figure 6. Comparisons of average values of (A) (B) longevity, (C) egg load and (D) egg volume of *B. lissogaster* females in response to the treatments (control, alfalfa, buckwheat, flax, peas and wheat).

2. FIELD SURVEYS

Materials and Methods. Twelve research sites with wheat growing next to pulse crops or cover crops, as well as wheat growing next to fallow fields were selected for this study (Figure 1). Emergence barrels, stem dissection and trapping were all utilized to compare the health and size of the parasitoid populations in the fallow-adjacent wheat compared to flower-adjacent wheat. Emergence barrels and trapping were used to monitor adult populations of sawfly and parasitoids.

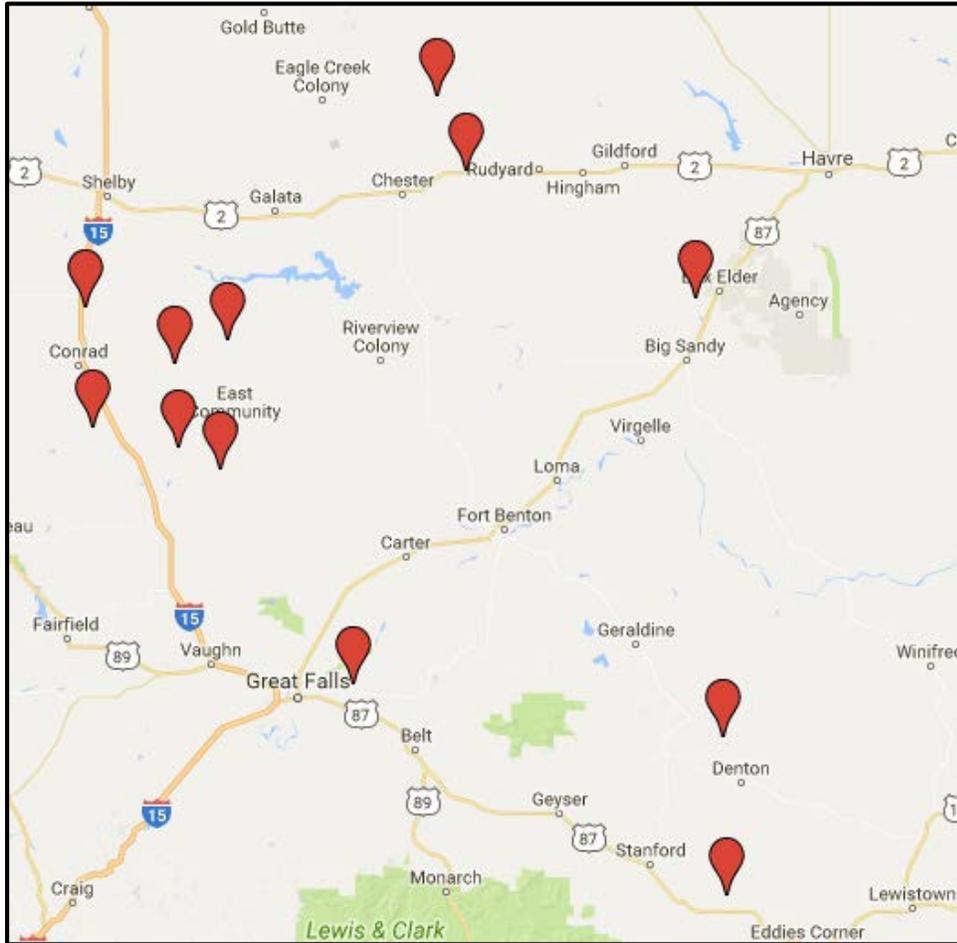


Figure 1. Locations of 12 sites where adjacent field comparisons of overwintering wheat stem sawfly and braconid parasitoid numbers were collected. Each site had a flowering field (pulse or cover crop) adjacent to a field of growing wheat and a fallow wheat field adjacent to a field of growing wheat.

Emergence Barrels

Materials and Methods. Crop residue was placed inside of barrel liners which had a black contractor bag around it to block light. Lids were made by gluing plastic jars to poster board. Barrels were left in the light from the 29th of May to the 9th of July, and insects were collected daily to be weighed and measured. Pre-emergence stubble samples were collected as the plant material used in emergence barrels. Postharvest stubble samples were collected to process stems. There were 7.5 m of stubble were collected for each comparison. Comparisons between numbers emerged were made using a Chi-square or Fisher's exact test. Trap captures were compared using *t* - tests.

Results. There were 12 fields from 2015 that were collected for initial counts of parasitoids (Table 1) and wheat stem sawflies (Table 2) in emergence barrels. At Site 1 there were a significantly greater number of parasitoids in wheat adjacent to fallow, but a significantly greater number of wheat stem sawflies

next to the cover crop. At Site 3 there were a small number of parasitoids next to the cover crop only and there were no wheat stem sawflies in either field. At Site 7 there were only 3 parasitoids and these were adjacent to the cover crop, but there were a significantly greater number of wheat stem sawflies next to the cover crop and none next to fallow. At Site 8 there were a significantly greater number of wheat stem sawflies and parasitoids next to the cover crop. At Site 9 the numbers of parasitoids adjacent to the two fields were not different but there were a greater number of wheat stem sawflies adjacent to fallow. Finally, at Site 10 there were a significantly greater number of parasitoids adjacent to chickpea and the number of wheat stem sawflies was not different between the two fields.

Table 1. The number of parasitoids that emerged from 2015 wheat residue collected adjacent to cover crop or pulse field and the number that emerged from wheat residue collected adjacent to a matched 2015 fallow field.

SAWFLIES							
Site	Comparison	Fallow	Flowers	Expected Fa	Expected FL	Value	P
1	Cover Crop	15	35	25	25	8	0.0047
2	Peas	0	0	n/a	n/a	n/a	n/a
3	Cover Crop	0	0	n/a	n/a	n/a	n/a
4	Peas	1	0	0.5	0.5	1	0.3173
5	Cover Crop	1	0	0.5	0.5	1	0.3173
6	Peas	0	0	n/a	n/a	n/a	n/a
7	Cover Crop	0	40	20	20	40	<0.0001
8	Cover Crop	30	88	59	59	28.508	<0.0001
9	Cover Crop	27	2	14.5	14.5	21.552	<0.0001
10	Chickpea	12	13	12.5	12.5	0.04	0.8145
11	Peas	1	0	0.5	0.5	1	0.3173
12	Peas	0	5	2.5	2.5	5	0.21> X >0.091

Table 2. The number of wheat stem sawflies that emerged from 2015 wheat residue collected adjacent to cover crop or pulse field and the number that emerged from wheat residue collected adjacent to a matched 2015 fallow field.

PARASITOIDS							
Site	Comparison	Fallow	Flowers	Expected Fa	Expected FL	Value	P
1	Cover Crop	32	9	20.5	20.5	12.902	0.0003
2	Peas	0	6	3	3	6	0.091
3	Cover Crop	0	7	3.5	3.5	7	0.091> X >0.038
4	Peas	0	1	0.5	0.5	1	0.3173
5	Cover Crop	2	1	1.5	1.5	0.333	0.5637
6	Peas	2	1	1.5	1.5	0.333	0.5637
7	Cover Crop	0	3	1.5	1.5	3	0.0833
8	Cover Crop	5	75	40	40	61.25	<0.0001
9	Cover Crop	20	12	16	16	2	0.225
10	Chickpea	2	22	12	12	16.667	<0.0001
11	Peas	6	2	4	4	2	0.304
12	Peas	5	2	3.5	3.5	1.286	0.500> X >0.304

Trapping at Field Interface

Materials and Methods. Traps were deployed at the beginning of wheat stem sawfly flight period and removed just prior to harvest. Rebel Yellow sticky traps from Great Lakes IPM were used for trapping. Counts of trapped wheat stem sawfly, *Bracon cephi*, and *B. lissogaster* were made weekly. Observations began on June 20th, 2016, and continued until the wheat was harvested. The last observation was made August 4th, 2016.

Results. Monitoring in the growing 2016 crop indicated that there were 2 fields with a greater number of wheat stem sawflies at the wheat - cover crop interface and a field with a greater number of wheat stem sawflies at the wheat - chickpea interface. There was one field that had greater capture of parasitoids at the cover crop - wheat interface, while the number of wheat stem sawflies was not different between the cover crop - wheat interface and the fallow interface (Table 3).

Table 3. The number of wheat stem sawflies and parasitoids trapped at cover crop or chickpea – wheat interface during the 2016 growing season.

SAWFLIES							
Site	Comparison	Fallow	S.E.	Flower	S.E.	t value	P
A	Cover Crop	7.0	± 0.9	17.2	± 2.4	4.1	0.002
B	Cover Crop	3.3	± 1.0	35.3	± 15.2	2.1	0.065
C	Cover Crop	7.2	± 1.4	32.9	± 7.3	3.5	0.006
D	Chickpea	33.3	± 4.4	48.3	± 3.6	2.6	0.023

PARASITIDS							
Site	Comparison	Fallow	S.E.	Flower	S.E.	t value	P
B	Cover Crop	0.7	± 0.3	12.3	± 5.0	2.3	0.002

Final Metrics

- Total additional grants received: 3
- Total additional grants in progress: 3
- Number of partnerships formed (private and public sector): 4-public
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: 1
- Jobs created: 2 graduate research assistants

Expenditures

- Total Personnel: \$42,429.04
- Total Operations: \$2,030.96

Weed Imaging/Pulse Crop Herbicide subproject of the Agriculture MREDI project

- 1) **41W217 – Principal Investigator:** Prashant Jha; Email: pjha@montana.edu
PULSE CROP HERBICIDE EVALUATION

List the accomplishments of the project in quantitative and qualitative terms

1. New Weed Control Options in Pulse Crops

Weed control has been a major challenge for pulse producers in Montana and other Northern Great Plain states. There are limited chemical weed control options labeled for use in pulse crops. This research funded by the MRDEI grant allowed us to develop new and innovative herbicide solutions for weed control in pea, lentil, and chickpea for enhanced adoption of pulse crops grown in rotation with wheat. Pulse crop tolerance and weed control in response to fall-applied, soil-residual herbicides were examined during 2015 to 2016 at four different field locations across Montana: Huntley; Havre;

Moccasin; and Sidney. These sites were selected to represent the diversity in soil and environment across the pulse growing region in the state. Plots were established between September 5 and 15, 2015 after wheat harvest under no-till conditions.

At each location, treatments were arranged in a split-plot design with four replications. Whole plots comprised of herbicide treatments, while subplots comprised of pulse crop species (pea, lentil, or chickpea). Weedy and weed-free plots were included in each replicate at each trial location for comparison, and weed-free plots were kept clean by hand weeding as and when needed. Each herbicide treatment alone or in combination was applied at the recommended fall-use rate(s) in fallow and twice that rate, except metribuzin and pendimethalin treatments in which the high rates were within the labeled rate range. Herbicide treatments were applied between September 5 and 15, 2015 using a CO₂-pressurized backpack sprayer calibrated to deliver 10 GPA of spray solution at 40 PSI. The pulse crops viz., dry pea, lentil, and chickpea were planted into the fall herbicide-treated plots in wheat stubble using a no-till planter in the subsequent spring (2016).

In summary, Sencor (4 or 8 oz/a), Valor (3 or 6 oz/a), Anthem Flex (3.64 or 7.28 oz/a), Prowl + Outlook (16 or 32 + 18 or 36 oz/a), Spartan Charge (6 or 12 oz/a), Authority MTZ (8 or 16 oz/a) applied the previous fall had no significant visual injury ($\leq 8\%$ early-season) or yield reductions in dry pea and chickpea. Although Spartan Charge or Authority MTZ caused unacceptable crop injury and yield reductions in lentil, fall-applied Sencor, Anthem flex, Prowl + Outlook, and Valor applied at both high or low rates were safe to lentil and improved lentil grain yields. Sencor or Anthem Flex at the high rate and Valor, Spartan Charge, or Authority MTZ even at the low rate applied in the fall, provided 75 to 99% end-season control of kochia and Russian-thistle. These fall-applied, soil-residual herbicide programs with optimum crop safety will broaden the herbicide tools available for effective weed control in pulse crops.

Soil-residual herbicides are important components of IWM programs and offer several benefits, including reducing the selection pressure for resistance development to foliar-applied POST herbicides. Growers can potentially incorporate these fall, soil-residual herbicide programs (multiple sites of action) into their current weed control programs for managing glyphosate-resistant kochia and Russian-thistle seed banks in wheat-pulse rotations in the semi-arid environments of Montana. The tested fall herbicide programs will enhance the weed control options and reduce uncertainties in crop injury from some of these herbicides when used PRE (spring) in pulse crops. This research will also facilitate registration of relatively new products such as Zidua or Anthem Flex for weed control in pulse crops in Montana, with the ultimate goal of enhancing the adoption of pulse crops in wheat-based rotations in this region.

We focused on dissemination of results obtained from this research to Montana clientele. Findings and recommendations were presented during MSU Research Center Field Days, MABA, and winter grower meetings across Montana. The findings of this research will be available to the growers through extension publications as "*Montana Guide*" and "*MSU Research Bulletin*". A research article was written and has been accepted for publication in *Agronomy Journal*. Based on the results obtained from this project, we were able to initiate collaborative work with chemical industry and Montana Pulse Commodity groups for prioritizing pulse weed control research and registration of new herbicides and optimizing application timing for weed control in pulse crops (pea, lentil, and chickpea). This research will significantly contribute to increased adoption and sustainable production of pulse crops in Montana.

2. *Light Activated Sensor Controlled (LASC) WeedSeeker Sprayer for Precision Weed Control*

During this grant period, we built a tractor-mounted 30-foot spot sprayer fitted with 30 WeedSeeker units. This technology will be tested during summer of 2017 in grower fields across Montana. The precision sensor units are fitted with TeeJet 6502 flat-fan nozzles spaced 12" apart, calibrated to deliver 20 gal/acre of herbicide spray solution. A pull-type sprayer will be used with a 300 gallon tank. The LASC spot sprayer will be compared for weed control with a conventional broadcast sprayer calibrated to deliver the same volume of herbicide spray mixture.



Figure 1: WeedSeeker sprayer with 30 LASC units for precision (site-specific spot spray) weed control in chemical fallow (2016).

Based on our field evaluations (2015-2017) of LASC technology in no-till fallow and post-harvest wheat stubble, weed control efficacy with LASC sprayer was consistent with the conventional broadcast sprayer. LASC sprayer reduced the herbicide (plus adjuvant) usage by 55 to 70% of the amounts (depending on weed density) used with a conventional broadcast sprayer. The herbicide savings were mainly due to savings in the spray volume using LASC sprayer vs. broadcast application. Based on results from the field research in 2015-2016, use of LASC sprayer reduced herbicide costs per acre by up to 70% compared with the conventional broadcast application for the herbicide programs tested in chemical-fallow/wheat stubble. This technology has proven accuracy in weed detection/sensitivity and spot spray (weed heights from 1 to 8 inches) at operating speeds of 10-12 mph. *This technology can potentially bring million dollars' worth of savings in chemical use in 3.4 million acres of fallow every year in Montana and will reduce the pesticide load for environment-friendly and sustainable agriculture in the state.*



Figure 2. A chem-fallow field sprayed with Roundup using the 30-foot tractor-mounted WeedSeeker sprayer in the spring of 2017. Excellent weed control 10 days after application; the only survivor in this field is a Roundup Ready Alfalfa plant. There was 66% savings in the spray volume with this spot sprayer technology in this field.

The weed science program at the MSU-SARC, Huntley established a long-term collaboration with Dr. Joseph Shaw (MSU Optics, Department of Electrical Engineering) on the hyperspectral imaging (MREDI subproject) to detect herbicide-resistant weeds in-crop (*report presented by Dr. Shaw*). The initial milestones achieved from that project was used to leverage more grant funding to further expand this technology for use in UAVs designed with hyperspectral camera to detect and develop herbicide-resistant weed maps in crop fields for site-specific weed management and herbicide resistance mitigation.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

Educational Activities

- Demonstration of WeedSeeker technology for site-specific weed control in fallow. CCA tour, Southern Ag. research Center, Huntley, MT, August 7, 2017
- Presentation on hyperspectral imaging to detect herbicide-resistant weeds in-crop. Weed Science Society of America Annual Meeting, February 6-9, 2017.
- Presentation on advanced optical sensor-based hyperspectral imaging and spot spray technologies for precision weed control. Malt Barley and Sugar beet Symposium, Billings, MT, January 10-11, 2017.
- Presentation on mitigating herbicide carryover and introducing new weed control options in pulse crops in Montana. CHS Grower Meeting, Malta, MT, January 9, 2017.
- Presentation on precision weed control technologies in Montana agriculture. MSU-Extension Crop and Pest Management Convention, Bozeman, MT, January 3, 2017.
- Presentation and demonstration on precision weed control technologies, MSU-SARC, Field Day, Huntley, MT, June 28, 2016.
- Presentation on weed control options for herbicide resistance management in pulse crops in eastern MT, MSU Eastern Agricultural Research Center Field Day, Sidney MT, June 24, 2016.
- Presentation on fall-applied soil residual herbicides in wheat stubble and rotational crop safety and weed control in pulse crops, Northern Agricultural Research Center Field Day DRC-NARC, Havre, MT, June 22, 2016.
- Presentation on management of glyphosate-resistant weeds in wheat-pulse rotation, Divide County Crop Improvement Meeting, Crosby, ND, December, 2016.

Media Contribution

Precision agriculture and site-specific weed management using optical sensors and hyperspectral imaging. Montana Ag Live– Broadcasted by Montana PBS Live TV Show (1 hour). October 16, 2016.

Final Metrics

- Total additional grants received
 - Private industry (BASF, FMC, and Bayer CropScience) funds were obtained (\$25,000) to conduct trials to facilitate registration of new herbicides for weed control in pulse crops.
- Total additional grants in progress
 - PI: P. Jha and Co-PI: Joseph Shaw recently (May 2017) submitted a proposal for possible funding (\$325,000) through USDA-NIFA to further enhance the research on hyperspectral imaging to detect herbicide-resistant weeds in-crop (wheat, barley, sugar beet, soybean, and corn).

- To further enhance the weed control work in pulse crops in Montana, a grant proposal was submitted in the amount of \$37,500 to US Dry Pea and Lentil Council in spring 2017.
- Number of partnerships formed (private and public sector)
 - The MREDI grant allowed a long-term collaborative relationship between the MSU College of Agriculture, Weed Science program at SARC, Huntley and College of Engineering, MSU Optics Center, Bozeman.
 - Broadened partnership with Ag. Industries including BASF, Bayer Crop Science, FMC Corporation, NWB Sensors, Inc., Triangle-Ag Services, and Resonon, Inc.
 - Broadened partnership with state agricultural commodity boards including MT Grain Growers Association, MT Agri-Business Association, MT Wheat and Barley Committee, Montana Pulse Grower Association, and US Dry Pea and Lentil Council.
 - New partnerships with Montana Precision Ag and Drone industry to further enhance research and commercialization of site-specific weed management technologies.
- Number of new Montana businesses created - With the recent expansion of pulse crop acreage in Montana (~1.2 million acres), there will be an increased demand for new Montana Agri-Business in private and public sector to:
 - Develop management guidelines for problematic weeds in pulses including herbicide-resistant biotypes.
 - Screen candidate herbicides for use in pulses.
 - Generate data to support the registration of new herbicide products for pulses through the Minor Use Label expansion program and Regional IR-4 programs.
 - Collaborate with MSU pulse crop breeders to improve the tolerance of pulse crop varieties to herbicides and to generate data to support herbicide registration.
- Patents awarded or in progress
 - Provisional patent applied in Nov. 2016: "*Discrimination of herbicide-resistant weeds with hyperspectral imaging*," J. A. Shaw, P. Jha, P. W. Nugent, A. Donelick, B. Scherrer, and V. Kumar; submitted 29 Nov. 2016 (U.S. Provisional Appl. No. 62/428,090).
- Commercial products developed
 - The WeedSeeker technology is likely to be commercialized for use in chemical fallow and for postharvest weed control in Montana. Growers are interested in adopting this precision weed control technology on their farm fields for herbicide cost savings and environmental sustainability.
 - New pulse herbicide products are likely to be commercialized following IR-4, EPA approvals.
 - Hyperspectral imaging sensors on hand-held devices and UAVs for detection of herbicide-resistant weeds in crop fields will be commercialized in the near future in partnership with local MT Drone- and Optics-based companies.
- Jobs created – the following people were supported by this grant at MSU:
 - Dr. Vipin Kumar – Postdoctoral research associate
 - Mr. Shane Leland – Research technician
 - Mr. Charlemagne A. Lim – Ph.D. student
- Peer-Reviewed Publications
 - P. Jha and V. Kumar. 2017. Pulse Crop Tolerance and Weed Control with Fall-Applied Soil-Residual Herbicides. *Agronomy Journal* (Accepted, July 2017).
 - J. A. Shaw, P. W. Nugent, A. Donelick, B. Scherrer, P. Jha, and V. Kumar, Discrimination of herbicide-resistant weed with hyperspectral imaging. *Journal of Applied Remote Sensing* (submitted July 2017).

Expenditures

- Total Personnel: \$41,431.36
- Total Operations: \$10,318.64
- Total Equipment: \$15,000.00

2) 41W216 – Principal Investigator: Joseph Shaw; Email: jshaw@montana.edu PRECISION WEED CONTROL USING ADVANCED OPTICS AND SENSOR-BASED TECHNOLOGIES

List the accomplishments of the project in quantitative and qualitative terms

Milestones

- 1) December 31, 2015 - initial agricultural data collection and analysis complete.
- 2) April 1, 2016 Weed sensor system ready for deployment on spray boom.
- 3) September 30, 2016 All in-field data collection complete.
- 4) December 31, 2016 Submit proposal with industry partner for technology commercialization.
- 5) June 30, 2017 Finish imaging systems and algorithms.

Overview

The objectives of this subproject were to develop spectral imaging systems for identifying weeds for improving the economic efficiency of Montana grain farmers. Although the original concept was to design a system for use on a spray boom, at the encouragement of our weed scientist collaborators, this quickly evolved into a more challenging and economically significant effort to distinguish between herbicide-resistant and herbicide-susceptible weeds. All milestones were met, with the primary difference that measurements were made of resistant and susceptible weeds in greenhouse and outdoor field environments with the imaging system mounted on a tripod instead of on a spray boom.

The work reported here was performed by a group led by Dr. Joseph Shaw in the MSU College of Engineering, specializing in the development of optical remote sensing technology and methods. We worked in direct collaboration with a group from the MSU College of Agriculture, headed by Dr. Prashant Jha at the Southern Agricultural Research Center (SARC).

Our research began with indoor greenhouse experiments designed to assess if there were spectral reflectance signatures in the visible and near-infrared spectral range that could be used to distinguish between resistant and susceptible weeds. The measurements were made with a compact hyperspectral imager manufactured by Resonon, Inc. of Bozeman, Montana. This imager recorded images of reflected light in 240 contiguous channels in the 400-900 nm spectral range, providing spectral resolution of 2.1 nm. The hyperspectral imager recorded three-dimensional “image cubes,” with two spatial dimensions like a conventional image and a third spectral dimension. Each frame recorded by a conventional 2-D camera contained 640 spatial pixels on one side and 240 spectral pixels on the other side. By scanning the camera across a scene, multiple frames were combined to create a 3D image cube that can be thought of as multiple images of the same scene, with each image being recorded in a different narrow spectral band. In other words, the image cube contained an image in which each pixel contained a complete and continuous spectrum. Rather than a conventional 3-color red-green-blue (RGB) image, this images contained 240 contiguous color bands.

Figures 1 and 2 contain photographs from the early indoor experiments conducted in the fall of 2015, showing the hyperspectral imager and scanner mounted on a tripod, with the imager viewing potted plants grown by

Dr. Jha's group at the SARC in Huntley, Montana. These plants were measured under artificial lights, as well as natural light on sunny and cloudy days.



Figure 1. Tripod-mounted hyperspectral Imaging System and computer-controlled scanner.



Figure 2. Example of the plants measured in the greenhouse experiments.

In the summer of 2016 we moved outdoors to measure potted weeds set near and within crops. The weeds were still grown and maintained in pots to avoid unintentionally spreading herbicide-resistant weeds outdoors. Example photographs of the summer 2016 experiments is shown in Figure 3.



Figure 3. Tripod-mounted hyperspectral imager recording spectral images of potted weeds and crops.

Machine learning algorithms were developed to identify the various weed and crop species based on their reflectance spectra. Weeds and crops have similar spectra, so the algorithms had to be trained to analyze subtle spectral features such as spectral peaks and gradients. With this information, we were able to automatically generate scene-classification images such as Figure 4. This figure identifies herbicide-resistant kochia in blue, susceptible kochia in red, and spring wheat in green. In this image, taken under diffuse lighting, five of the six kochia plants were correctly classified.

In November 2016 we filed a provisional patent application for this method of identifying herbicide-resistant weeds using hyperspectral imaging. An invited talk was given at the Montana Grain Growers annual convention in Great Falls, MT, and a peer-reviewed journal paper has been submitted to the *Journal of Applied Remote Sensing*.

In the last weeks of the MREDI project during early summer 2017, we made repeated measurements of the growing plants to assess the variability that might occur as a function of growth phase. These measurements were made again in a greenhouse at the SARC in Huntley, MT (see Figure 5).

Images were also recorded of a larger number of plants so that we could begin assessing the variability of the spectral signatures with plant sample. Images were also taken of plants with varying levels of herbicide resistance. A proposal has been submitted to the USDA for follow-on research designed to address the important questions of how robust the spectral signatures are with plant growth phase, level of herbicide-resistance and plant sample.

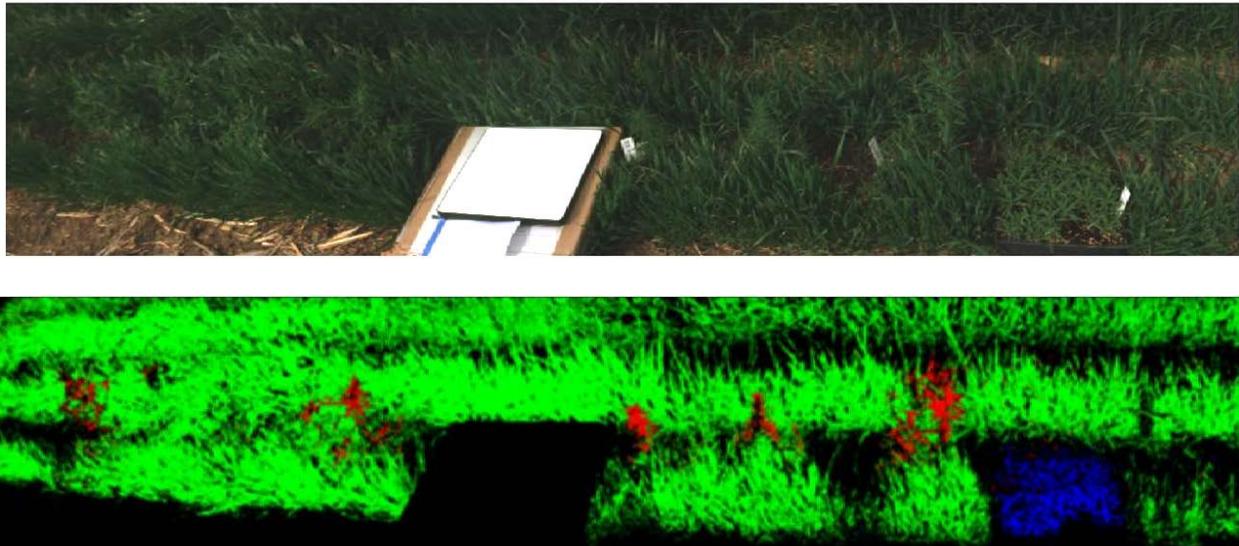


Figure 4. (top) RGB image showing potted weeds set among crops, with a white reflectance calibration panel at the center; (bottom) classification image produced by automated smart algorithm, identifying winter wheat as green, kochia as red, and dicamba-resistant kochia as blue.



Figure 5. Tripod-mounted hyperspectral imager recording spectra of multiple plants at multiple growth phases.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

The most lasting benefit of this MREDI research project was the establishment of a new collaborative relationship between agriculture/weed science and engineering, specifically between the Southern Agricultural Research Center in the MSU College of Agriculture and the Optical Remote Sensor Laboratory in the Electrical and Computer Engineering Department. This new partnership provides a rich combination of expertise in weed science and sensor technology, which has numerous potential benefits to the Montana agricultural community. The first of these benefits is that this research has shown great promise for this collaboration to increase the capability of Montana researchers to solve practical problems in detecting weeds and distinguishing between herbicide-resistant and herbicide-susceptible weeds, which has potentially very large economic impact in Montana.

We also developed a broadened partnership with Montana photonics companies, specifically in this case NWB Sensors, Inc., and Resonon, Inc., both of Bozeman, MT. Resonon is a manufacturer of hyperspectral imaging systems and will experience market growth as this technology is found to offer practical benefits in agricultural applications. NWB Sensors is a relatively new company, who because of this MREDI project have developed expanded interest and capabilities in agricultural sensing. At the end of this report section, there is a segment that reports the results of a commercialization study done by NWB Sensors, Inc., which adds greatly to the value this project provides to the people of Montana.

Finally, through this project the Optical Remote Sensor Laboratory at MSU acquired new capacity for drone-based spectral imaging. This provides a critical middle option between the conventional options

of ground-based and airplane-based optical imaging, which will open up numerous new opportunities in applications ranging from agriculture to ecology. This also connected the MSU sensor researchers with the rapidly growing industry in Montana that is providing drones and drone services.

Final Metrics

- Total additional grants received:
 - SBIR from the USDA to NWB Sensors, Inc. (Bozeman, MT).
- Total additional grants in progress:
 - “Hyperspectral imaging: A remote-scouting IPM tool for early detection of herbicide-resistant weed in-crop,” submitted to USDA in May 2017 by P. Jha and J. A. Shaw for \$200k (direct follow-on to the MREDI Agricultural hyperspectral remote sensing subproject).
 - “CREWS: Convergent research on environmental water,” Multiple investigators throughout the MUS with Shaw, to be submitted July 2017 for \$24M (Shaw’s portion builds on drone-based spectral imaging capabilities established in the MREDI AG and Optics projects).
- Number of partnerships formed (private and public sector):
 - MSU College of Agriculture and College of Engineering, specifically SARC and ORSL
 - Broadened partnership with Montana photonics companies, specifically NWB Sensors, Inc. and Resonon, Inc.
 - New partnerships between the rapidly growing Montana photonics industry and the also-rapidly growing drone industry.
- Number of new Montana businesses created:
 - NWB Sensors, Inc. has existed in Bozeman, MT since 2008, but became more solidly established through the MREDI effort and added capabilities in agricultural imaging. This is a particularly appropriate direction, given that the two company founders both grew up in Montana agricultural regions.
- Patents awarded or in progress:
 - Provisional patent applied for in Nov. 2016: “Discrimination of herbicide-resistant weeds with hyperspectral imaging,” J. A. Shaw, P. W. Nugent, A. Donelick, and B. Scherrer, submitted 29 Nov. 2016 (U.S. Provisional Appl. No. 62/428,090).
- Commercial products developed:
 - As part of this MREDI effort, NWB Sensors, Inc. (Bozeman, MT) performed a market study and determined that, while many research groups are exploring hyperspectral imaging applications in agriculture worldwide, ours would be perhaps the first to reach the commercial market. Furthermore, they showed that there is a demand for not only an imaging system or service, but also for a data base of hyperspectral data for different weed species and variations. This points the way for an immediate joint public-private collaboration that could place Montana companies at the forefront of a worldwide market.
 - This MREDI effort also provided a new potential market for the newly released drone-capable hyperspectral imaging systems sold by Resonon, Inc. (Bozeman, MT) and drones sold by a variety of Montana companies.
- Jobs created:
 - The engineering portion of this MREDI effort supported the following people at MSU:
 - 1 faculty member (Dr. Joseph Shaw – subproject director, supported with partial summer salary)

- 1 Research Engineer for part of the project
- 1 PhD student
- 1 MS student for part of the project
- This MREDI effort also helped generate the following new jobs in Montana companies:
 - 4 full-time professional jobs at NWB Sensors, Inc. in Bozeman, MT.
 - 1 full-time temporary professional job conducting market analysis at NWB Sensors, Inc.
- 1 new full-time professional engineering position at Resonon, Inc., in Bozeman, MT.

Expenditures

- Total Personnel: \$51,355.41
- Total Operations: \$49,423.63
- Total Equipment: \$44,690.96

Commercialization study by NWB Sensors, Inc.

Summary of MREDI Business Outcomes

The MREDI program has provided opportunities to NWB Sensors, Inc. that may not have existed without this program. Funding through the MREDI program has allowed NWB Sensors to explore additional avenues of work and areas into which we could expand. As part of this work we have been able to add one full-time and one half-time employee, thus going from 2 to 3.5 employees nearly doubling the size of our business. In addition to these benefits, the work conducted through the MREDI program has led to both new business contacts and a better understanding of the precision agriculture industry, largely through our conversations with Montana farmers and MSU agricultural researchers.

Although at the end of this commercialization study NWB Sensors, Inc. has not elected to establish a license for the herbicide-resistant weed detection technology, we are continuing to explore future experimental and commercialization opportunities with MSU researchers. If an appropriate program were identified, NWB Sensors, Inc. would be interesting in establishing a license and commercializing this technology.

Overview

The occurrence of herbicide resistant weeds is a worldwide problem caused by ability of weed species to readily mutate and adapt to a constant genetic selection pressure. This has been enabled by the widespread use of herbicides without the appropriate accompanying management practices. Rapid identification of herbicide resistant weeds would change the nature of weed management by reducing the time between suspecting a resistant weed to knowledge of its resistance.

The Precision Agriculture Market

The global precision agriculture market was estimated at 3.2 billion (USD) in 2015 and is forecasted for rapid growth, with an expected market size between of 10.2 billion (USD) and 11.5 billion (USD) by 2025, demonstrating a growth rate near 13%. This market is significantly outpacing the global economic growth rate near 3.5%. Within this market the weed mapping technology fits into many aspects of the industry, but fits best in the crop scouting applications that account for approximately 10% of the total market.

In the United States, the adoption of precision agricultural methods has been slow, but steadily growing. Currently, more than 60% of the cropped land is maintained using at least one precision agricultural technology, most prominently auto-steer. Of the farmers surveyed during this study, this trend was roughly supported, with 66% using at least one precision agriculture technique, with many implementing crop scouting techniques.

Market Need

Farms of any size would benefit from having the ability to rapidly identify herbicide-resistant weeds, though the most appropriate market for a product providing rapid identification would be farm service level that support multiple farms. This is due to a number of factors, including the cost of the system, the number of times it might be used in a season, and the need for consistent measurements, all of which are not appropriate for individual farmers.

During the interviews, Montana farmers were asked, "On a scale from 1 (no concern) to 5 (highest concern), what is your level of concern for herbicide-resistant weeds in your crop?" All responses were 3 or higher, with an average of 4.3. One farmer went as far as to say he's "scared to death of resistant weeds." Of those interviewed, over half had some experience with resistant weeds on their lands, mostly managed by changing to a different herbicide.

During interviews, they were also asked, "If a technology existed to discern between resistant and non-resistant weeds, would you work with your local coop or agronomist to do additional scouting for definitive resistant identification?" Every farmer polled answered Yes. When pressed for more information, the stage at which they would start working with local coops was dependent on when weeds started to rob yields. One precise response stated that if 1-5 bushels/acre (approximately \$4.00 to \$20.00 / acre) were being robbed, that would be enough to pursue outside assistance.

Existing Solutions

Currently, herbicide resistance/sensitivity testing is a time-consuming process involving harvesting the weeds suspected of being resistant, letting these weeds go to seed, collecting the seeds, growing new weeds from seeds, and finally testing these new weeds for their level of herbicide resistance before information can be sent back to the farmer. This lag time, 3-4 months or more, between collection and knowledge of resistance forces reactive measures to be taken with insufficient (and occasionally inaccurate) information. For example, not managing a population of resistant weeds allows them to go to seed and spread their resistance, making the problem larger during the next growing season, and potentially reducing the yield in the current season. On the other hand, aggressively managing a population of non-herbicide-resistant weeds using herbicides with a different site of action or manual technique adds cost that need not be incurred if the weeds would be taken care of with herbicide application later in the year or during the next year and the suspected resistance was due to poor spraying or suboptimal conditions present during spraying.

Proof of Concept

The technology developed under the MREDI project at MSU demonstrated optical detection methods to distinguish between herbicide-resistant and herbicide-susceptible weeds using hyperspectral imagers. The project focused on the identification of glyphosate- and dicamba-resistant kochia biotypes from Montana. These weeds pose an economically significant problem for Montana growers. MSU

researchers demonstrated that in controlled (greenhouse) tests, machine-learning based classifiers could distinguish dicamba-resistant and glyphosate-resistant kochia from the susceptible kochia. These classifiers used hyperspectral reflectance data to exploit the reflectance differences that exist between susceptible and resistant weeds. Independent verification was conducted by NWB Sensors, Inc. using a limited set of the data from kochia collected under controlled lighting conditions. In these tests, the dicamba-resistant kochia were correctly identified 98% of the time, susceptible kochia were correctly identified 92% of the time, and glyphosate-resistant kochia were identified 94% of the time.

Proposed Technology

Moving away from the controlled environment into outdoor testing has shown mixed results. It is currently believed that these difficulties arise from variations in natural lighting that cause difficulties determining the spectral reflectance of the plants. During overcast conditions and controlled lighting, MSU researchers showed classification was possible. Therefore, for this commercialization study it was assumed the sensor would have a controlled light source that moved the study away from outdoor, boom-mounted sensors to an embodiment of the technology as a handheld hyperspectral sensor, such as a leaf-clip spectrometer.

The proposed system is to use a hyperspectral sensor to measure the reflectance spectrum of a weed that is suspected to be herbicide resistant. This technology is general enough that any hyperspectral sensor with accurate calibration would work in identifying problem weeds; however, a recommended sensor would be sold along with the processing service. After the spectrum is obtained, it would be compared to a database of spectra to determine if the weed of interest is herbicide resistant or not. If a weed tested herbicide resistant, then further tests could be done to determine the level of resistance as a confirmation and to provide feedback into the database, though this is not information that directly affects the farmer. The early identification provides actionable information to the farmer, allowing them to address the situation by management techniques appropriate to the farmer, the field, and the crop. Targeted aggressive management techniques can remove the resistant weed population from the seedbank, and prevent future infestation.

An individual farm service provider would travel to a farm containing suspected herbicide-resistant weeds. They would use a handheld hyperspectral sensor with an integrated leaf clip to test the weeds. The sensor would pass data to a smartphone via Bluetooth, where the spectra would be analyzed either on the device itself or in the cloud, and after analysis a determination of resistance would be returned to the user as to whether the weed was resistant or not and a confidence of both the quality of the measurement and the quality of the analysis. Multiple weeds could be measured in a short time, and with these results the farmer would have actionable information as to how the weeds would need to be managed. The data collected would be added to the database to give more accurate data as to the natural variation of the weed species, both resistant and nonresistant, which will improve future detection. Weeds that are not confidently categorized may need to be remeasured, or they may represent a new type of resistance/phenotype and would be sampled by the service provider and sent for further analysis. After further analysis, the database would be updated with results, continually improving the detection.

Benefits Over Existing Solutions

While the current method of herbicide dosing tests in a control laboratory is highly accurate, it is time consuming and requires human intervention at nearly every stage. The proposed technology using

hyperspectral data to determine herbicide resistance significantly reduces the time necessary to make a judgement on whether a weed is herbicide resistant and limits the human element to data collection, which given an appropriate sensor design is highly repeatable. No other technology currently available can make these types of rapid identifications, and while biological based rapid sampling is being developed, it is not yet available. The approach of using hyperspectral data to determining herbicide resistance has been shown in scientific literature, but in terms of real world application it is a game changer. Furthermore, even in the literature, success is limited to small samples of specific weeds and has not been generalized beyond a small region of the country and to a single weed species.

Competitors

Utilizing hyperspectral sensing (either imaging or non-imaging) for herbicide resistance detection is a technology that, in addition to the work at MSU, is being pursued by multiple institutions worldwide. However much of this success has been in controlled settings and none of these technologies have seen commercialization. Therefore, if commercialized, this technology will be one of the first solutions on the market.

Necessary Development

Future development entails building a database of weed-resistant spectra across multiple species across multiple regions. This scale of data collection will require collaboration. Potential collaborators include USDA-ARS that have offices nationwide and have done research in using hyperspectral data to determine herbicide resistance. The larger the database, in terms of spectra and variation, both within a weed species and across different species, the more accurate the determination of herbicide resistance will become. Initial work has shown within a single species that using modern classification techniques on small sample sizes, that an accuracy greater than 90% is obtainable. To be readily adapted, it has been suggested an accuracy >99% will need to be obtained, as many of these weeds can spread rapidly across a field and severely affect crop yields if they are not appropriately managed.

The short-term goal of this technology is to develop a database and, more importantly, the associated detection model in which common modes of herbicide resistance are detected >99% of the time in all weeds included in the database. This level of accuracy is achieved by having a database in which the reflectance spectra of both herbicide resistant and non-herbicide resistant weeds and the natural variation of said spectra under different conditions (stage of growth, water deprivation, heat stress, pest stress, etc.) is well known. Once this type of variation is quantitatively determined, the database can be expanded to include other types of vegetation, such as agricultural crops (which can be measured alongside of weeds during data collection). The database at this level becomes a commodity that can be licensed. Potential licensing can be agricultural drone mapping companies, research institutions, companies designing specialized cameras, etc.

Film Production for the Agriculture MREDI Grant

41W218 – Organizer: Eric Hyyppa; Email: eric_hyyppa@montanapbs.org

List the accomplishments of the project in quantitative and qualitative terms

Please view the complete video production regarding the Ag MREDI grant at:

<http://www.pbs.org/video/2365867692/>

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: None
- Number of partnerships formed (private and public sector): None
- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: None

Expenditures

- Total Personnel: \$9,716.19
- Total Operations: \$7,284.81
- Total Equipment: \$7,999.00

Economic analysis subproject of the Agriculture MREDI project

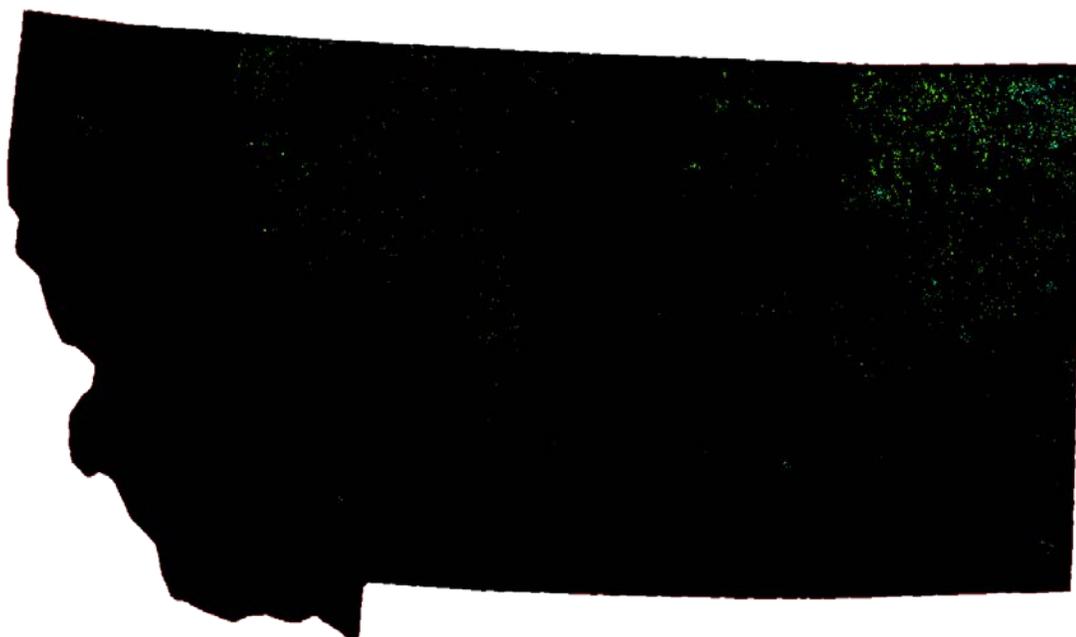
41W219 – Principal Investigator: Anton Bekkerman; Email: anton.bekkerman@montana.edu

Progress towards milestones

Rapidly, Montana has become the largest producer of pulse crops in the United States and an important participant in global pulse crop markets. Continuing growth of this agricultural sector in the state is important for at least two reasons. First, it represents an opportunity for Montana agricultural producers to diversify their production portfolio and lower their exposure to market risk. For example, many Montana producers have been able to leverage their pulse crop production to lessen the adverse economic impacts of recent weak global wheat markets. Second, the development of Montana pulse markets has provided an economically-effective incentive for producers to convert summer fallow land—which has consistently been shown to not be a sustainable long-term production system—to more efficient use.

However, while the transition to more intensive cropping systems has been significant in some parts of the state, large portions of productive agricultural land remains in the traditional wheat–fallow rotation. For example, Figure 1 shows changes in planted pulse crop acres between 2007 and 2016. The data indicate that the majority of the growth has occurred in northeast Montana, while conversion in large portions of central and northern Montana still remains fairly slow. To a large extent, this is due to the fact that there has been little research investment and a very short time period—relative to Montana's wheat sector—to develop improved pulse crop varieties, management systems, and knowledge transfer mechanisms that can help Montana's farmers to transition in an economically effective manner.

(a) Pulse Acres, 2007



(b) Pulse Acres, 2016



Figure 1. Planted Pulse Acres in Montana, 2007 and 2016

Source: USDA National Agricultural Statistical Service, CropScape (Cropland Data Layer)

While one of the primary goals of this MREDI project is to overcome these challenges and expedite Montana's producers' ability to transition to more intensive cropping systems, it is important to measure the extent to which the state's agricultural sector could benefit from these efforts. Moreover, in developing these measures, it is critical to acknowledge and account for issues such as capacity constraints in the state's

grain handling and transportation infrastructure, productivity of newly converted land, and lack of rail infrastructure to ship pulse crops to non-traditional markets.

This report provides a summary of the approaches and methods used to estimate state-level economic impacts resulting from increasing conversion of fallow land into pulse crop production. Specifically, I focus on measuring the additional value that farmers could gain by moving away from wheat–fallow systems, and aggregating that value to the state level to provide a big-picture perspective of Montana's production agriculture sector. Intentionally, the analysis only focuses on profits realized by those directly involved in the production of those crops. While these estimates do not capture all of the potential additional economic activity through various multiplier effects and related sector growth, they are more accurate because they are not distorted by potentially poorly estimated economic multipliers (a common concern when conducting macroeconomic impact studies). Thus, the estimates in this study represent a lower bound of economic effects that are likely as a result of increased pulse crop production in lieu of summer fallow.

Under conditions that most realistically represent the current and short-term future state of Montana's production and marketing landscapes, I estimate that if land conversion continues at its most recently observed pace (approximately 4–5% per year), five-year direct additional value to Montana's production agriculture sector are estimated to be just under \$3 million. However, developing improved pulse crop varieties, improving methods for better management techniques for more intensified cropping systems, and transferring new knowledge to producers—all objectives of this MREDI project—are likely to increase farmers' willingness to more quickly convert fallow acres into more productive uses. If a 10% annual conversion rate is assumed for a five-year period—not inconceivable given recent trends and likely outcomes of more intensive research efforts—cumulative state-level additional returns to farmers are estimated to be nearly \$5.2 million.

Methods and Data

The general modeling approach is to consider the additional net value that an acre of land would provide to a typical Montana farmer if that acre was to be used for pea or lentil production rather than fallow. Then, determine the aggregate state-level added value by modeling the transition of fallow acres to intensified pulse producing acres. It is important to note that this type of analysis has certain advantages and disadvantages.

The primary advantage is that the methodology provides information about actual farm-level profits, rather than simply looking at sales revenues. Analyses that consider only revenues are likely to overestimate the community and state-level impacts because only the *net* revenues are salient. That is, producers will make decisions based on whether the benefits of intensifying agricultural land use exceed the costs. Moreover, indirect benefits at the community and state levels will only occur if farmers increase their *disposable* income, which can then be used to increase economic activity and trigger multiplier effects.

The main disadvantage of using an aggregated farm-level measure is that it likely represents a lower-bound of potential community and state-level impacts. Other types of impact studies consider macroeconomic, market-level effects and implement numerous estimates of economic multipliers across various economic sectors to provide a total impact value. However, these analyses can be highly sensitive to economic multiplier assumptions and interactions among economic sectors. For Montana, a literature review resulted in very few, often dated multiplier and sector dynamics estimates, implying that results from a macroeconomic impact analysis may be at high risk of highly over- or under-valuing economics effects. As such, the decision was made to provide a more conservative but likely much more accurate analysis using farm-level information.

Farm Budget Analysis

The foundation of the analysis is based on assessing farm-level differences in net returns between a traditional wheat–fallow cropping system and more intensified systems that rotate wheat with pea or lentil crops. Cost of production and net returns budgets for a representative farmer across different cropping systems can be used to make these comparisons. The data required for creating these budgets require estimates of a representative producer's variable costs (those that depend on the operations that occur within a production period), fixed costs (those that occur regardless of a producer's specific production decisions, including ownership and depreciation), and market revenues.

For non-irrigated cropping systems—which characterize the majority of wheat and pulse production in Montana—budgets require information about input costs for operating equipment; labor requirements; seed, fertilizer, and other chemical costs; ownership and repair costs; crop insurance expenses; crop yields; and market prices. Because, as shown in Figure 2, the majority of fallow acres in Montana are primarily located in regions where winter wheat production is predominant, this analysis compares production budgets for a typical winter wheat–fallow operation and an operation that rotates winter wheat with a pulse crop. Furthermore, all operations are assumed to use conventional non-irrigated production and farm management methods, with chemical fallow. Table 1 presents a summary of the inputs used to characterize a typical operation and sources for estimating the most recent cost values. For winter wheat and fallow operations, costs were verified using information from focus group meetings with Montana wheat producers (Bekkerman and Fuller, 2016).



Figure 2. Fallow Acres in Montana, 2016

Source: USDA National Agricultural Statistical Service, CropScape (Cropland Data Layer)

The intent of this budget is to characterize a "typical" Montana producer. While actual producers may be more or less efficient, the "typical" producer is intended to represent an average baseline case. All of the farm-level analysis is completed on a per acre basis, which provides more generalizable insights and comparisons. While there could certainly be some economies of scale for larger operations, the manner

in which these potential savings will affect production costs are likely to be idiosyncratic across operations and are difficult to capture and generalize.

In developing the budget analysis, several assumptions were made to more accurately characterize production and marketing decisions of modern Montana farming operations. For crops for which federally-subsidized crop insurance is available—either the Revenue Protection or average production history (APH) policy—producers were assumed to purchase the insurance product at a 70% coverage. These insurance products and coverage level represents the modal policies purchased by Montana producers.

A full budget is available on request. The total per acre costs for each of the crops of interest are as follows:

Winter wheat: \$175.47 / acre

Peas: \$220.39 / acre

Lentils: \$183.46 / acre

Fallow: \$62.72 / acre

Revenue Calculation and Price Constraint Considerations

The cost of production budget provides only half of the profit equation. The revenue side is determined by a combination of market prices and yields observed for each crop produced in a particular system (wheat–fallow or wheat–pulse).

To determine wheat and pulse crop yields that are likely to be observed in the next five years—the period of analysis—I collect historical yield information (40 years for winter wheat and 12 years for peas and lentils) from the USDA National Agricultural Statistical Survey data. To improve the accuracy of the analysis, the data are collected to represent three USDA-defined agricultural statistical districts in Montana: northeast, central, and north-central.

Next, I follow the detrending approach of Goodwin and Ker (1998) to ensure that the historical yields are adjusted for differences in technological advancements across time (e.g., to be able to compare 1976 yields to 2016 yields after accounting for the fact that machinery and wheat breeding techniques has advanced substantially since 1976). Specifically, I first regress each of the yields and indices on a time trend variable and then use the regression residuals to estimate the detrended yields. This method allows for all yield and index values to be normalized to the 2016 level.

Table 1: Variables in Cost of Production Analysis

Operation	Variables	Budget category	Units	Data Source(s)	Notes
Tractors	180 HP	VC, FC		NDSU; U. Idaho	For sprayer only
	340 HP	VC, FC		NDSU; U. Idaho	All other pulled equipment
Seeding	Air seeder	VC, FC		NDSU; U. Idaho	
	Roller	VC, FC		NDSU; U. Idaho	
	Seed, pea	VC	lb	NDSU	
	Seed, lentil	VC	lb	NDSU	
	Seed, winter wheat	VC	lb	NDSU; U. Idaho	
Fertilizer	Nitrogen	VC	lb	NDSU; U. Idaho; S. Dakota	
	Phosphorous	VC	lb	NDSU; U. Idaho; S. Dakota	
	Potassium	VC	lb	NDSU; U. Idaho; S. Dakota	
	Sulphur	VC	lb	NDSU; U. Idaho; S. Dakota	
Spraying	Sprayer	VC, FC		NDSU; U. Idaho	
Chemicals	Glyphosate	VC	oz	NDSU; U. Idaho; S. Dakota	
	2-4,D	VC	oz	NDSU; U. Idaho; S. Dakota	
	AMS	VC	oz	NDSU; U. Idaho; S. Dakota	
Custom labor	Urea	VC	lb	NDSU; U. Idaho	
	Application	VC	acre	NDSU	
Harvest	Combine	VC, FC		NDSU; U. Idaho	
	Truck, tandem axle	VC, FC		NDSU; U. Idaho	
	Truck, single axle	VC, FC		NDSU; U. Idaho	
	Truck, pickup	VC, FC		NDSU; U. Idaho	
Fuel	Diesel	VC	gal	NDSU; U. Idaho	Includes lubrication costs
Crop insurance	APH or RP	VC		USDA RMA	
Other	Operating interest	VC		NDSU; U. Idaho	5.50% of VC
	Miscellaneous	VC		NDSU; U. Idaho	
	Land opportunity cost	FC	acre	USDA NASS	Rental rate

Abbreviations: VC refers to variable costs; FC is fixed costs (ownership, repairs, depreciation); NDSU is the North Dakota State University's Enterprise Budget and Custom Rate Survey data for the western North Dakota production region; U. Idaho is the University of Idaho's Enterprise Budget, Estimates for the northern Idaho region; USDA RMA is the USDA Risk Management Agency; USDA NASS is the USDA National Agricultural Statistics Service. Full citations are in the References section.

These normalized wheat, pea, and lentil yields are then used to determine the average yield for all three crops, and a "potential" yield for peas and lentils. The potential yield is calculated as the average yield plus one standard deviation, representing advances that are likely to be influenced by the research conducted as part of this MREDI project. Table 2 summarizes these yield values.

Table 2: Average and Potential Yields, in Pounds Per Acre

	Wheat	Peas		Lentils	
	<i>Average</i>	<i>Average</i>	<i>High</i>	<i>Average</i>	<i>High</i>
Yields (lbs)					
<i>Northeast region</i>	2705	1790	1902	1337	1437
<i>North central region</i>	2885	1557	1732	1082	1225
<i>Central region</i>	2780	1348	1498	807	865

Lastly, in calculating revenues from wheat following a pulse crop, yields are assumed to be 7% lower than winter wheat yields in wheat–fallow systems (see Miller et al., 2015). The yield reduction is primarily due to decreased water availability in more intensive cropping systems.

The pricing component of the revenue calculation requires several additional considerations. In a typical market analysis of production returns, it would be reasonable to obtain projected prices from sources such as the Long-term Projections Report published by USDA Office of Chief Economist and U.S. Baseline Projections published by the Food and Agricultural Policy Research Institute (FAPRI). These national prices can then be adjusted using a historical basis for Montana production regions to obtain a local projection. Specifically, the five-year average projected price (using an average of the most recent 2017 USDA and FAPRI estimates) is \$4.82 per bushel, with a –\$0.60 per bushel basis adjustment for Montana (Bekkerman, Brester, and Taylor, 2016). For peas and lentils, the projected prices are \$0.13 per pound and \$0.27 per pound, respectively. Montana is the largest pulse crop producer in the United States, and, therefore, no basis adjustment is made because the projected prices likely account for price formation in major production regions. It is important to note that despite wheat and pulse crops representing two of Montana's most important agricultural products, Montana and the United States account for a very small proportion of total global production of these crops. Therefore, using the USDA and FAPRI price projections is appropriate, because those prices largely reflect global market conditions and are unlikely to alter substantially in response to production and grain handling changes in Montana.

In Montana's rapidly changing grain marketing landscape, however, these typical price projections are not sufficient. This is due to the "growing pains" that are likely to occur in a marketing environment in which the grain handling infrastructure was historically designed to handle mostly wheat–fallow cropping systems, but must now handle more intensive grain production. That is, for over 80 years, Montana's grain handling and grain transportation system has operated in production landscapes in which farmers typically grow wheat every other year and have sufficient on-farm storage to have the option to keep much of their produced wheat from delivery. In the last decade, however, a rapidly increasing amount of fallow land has now been used to produce crops in addition to the existing wheat production. This has resulted in placing pressure on grain handling facilities and the transportation infrastructure to:

- Handle significantly higher volumes of products.
- Respond to higher labor demand to provide more handling services (in areas where the labor supply may be relatively low).
- Provide more off-farm storage (because farmers may not have sufficient on-farm storage or may choose not store pulse crops).
- Face increased demand to quickly move pulse crops, which can oxidize and lose favorable aesthetic characteristics that are demanded in retail consumer markets.
- Increase logistical capacity to ship pulse crops to destinations that have not been traditional terminals for wheat (such as shipping pulses south to processing facilities in the Midwest and to export facilities to South America).

For example, Figure 3 shows the current active grain handling facilities in Montana (data are from the Montana Wheat and Barley Committee, 2017). The size of each elevator location (indicated by a circle) represents the relative storage capacity at that location and green circles represent those that accept peas, lentils, and/or other pulse crops. The figure makes evident that despite the growth in pulse production in Montana, there are still many more elevators that do not accept pulse crops, even in the northeast part of the state. In fact, only 34% of elevators in Montana handle pulse crops. Moreover, an average elevator that accepts pulse crops has an average capacity of 563,909 bushels, while an average elevator that specializes in wheat handling has a capacity of 773,307. On aggregate, out of the total available capacity at active Montana elevators, 29% of that capacity represents elevators that accept pulse crops while 71% of capacity specializes in wheat.

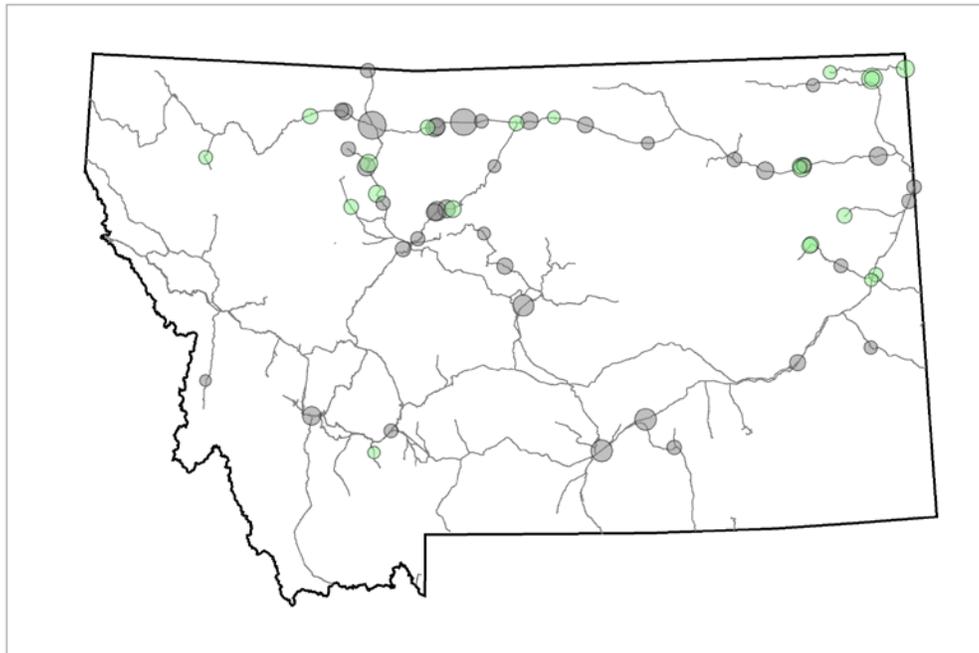


Figure 3. Montana Grain Handling Facilities

Notes: Circles indicate facility locations and the circle size indicates relative storage capacity. Green circles are facilities that accept pulse crops.

Figure 3 provides suggestive evidence that despite the growth in pulse crop production, Montana's grain handling industry is still adapting and may still be capacity-constrained in response to the growth in supply. Another issue facing Montana's pulse handling and transportation industry is the fact that, historically, the demand for Montana's grain has been from either Pacific Northwest export facilities or processing and distribution facilities in the Great Lakes region. While a large portion of Montana peas and lentils also heads west to be exported to Asia and India, there has been increasing demand for peas in the U.S. Midwest region, where many pet food processing facilities are located, and for lentils in Central and South America (personal communication, pulse merchandiser at Viterra USA).

Figure 4 shows a map of the U.S. rail infrastructure. The rail lines through much of Montana and western North Dakota—the primary pulse production regions—have no north–south routes, and the only major north–south thoroughway does not occur until Minnesota. This requires significant additional shipping costs on the part of the grain handler, which are likely to be passed down by grain elevators to farmers in the form of lower price bids.

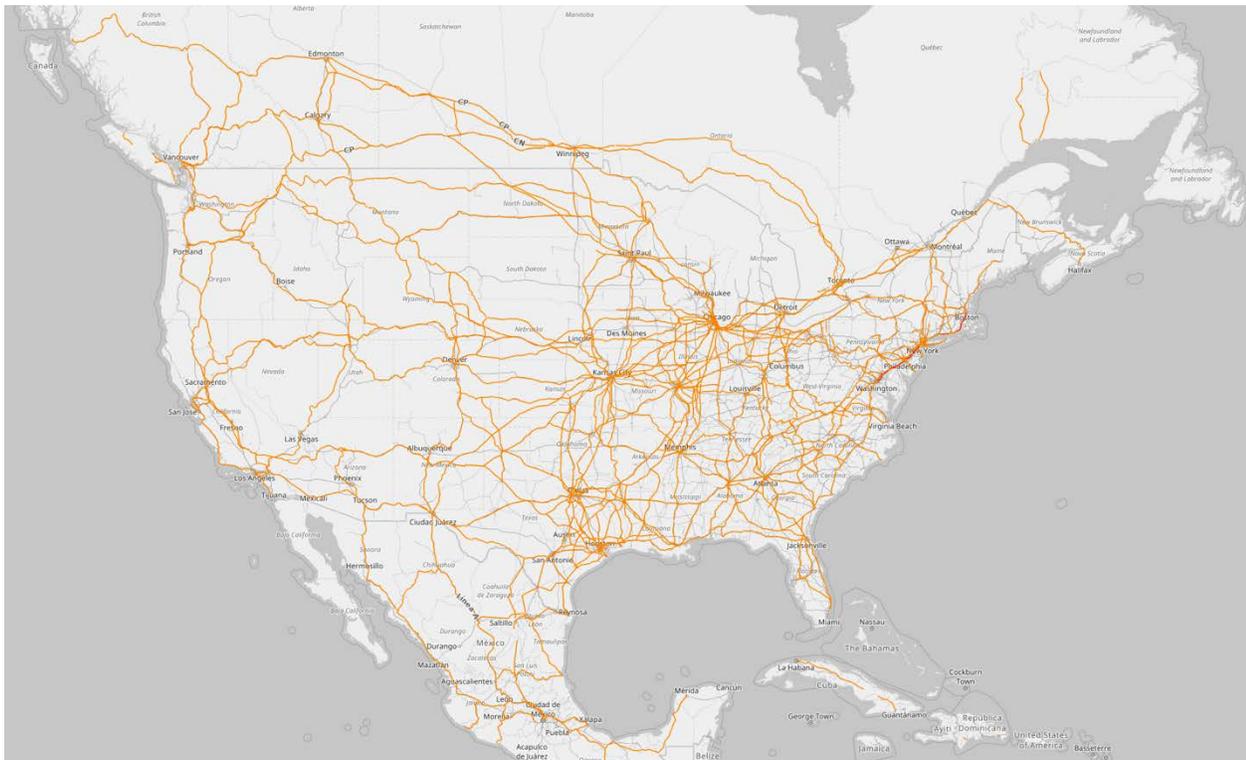


Figure 4. U.S. Rail Infrastructure Map

Source: OpenRailWayMap.org

These issues are expected to result in responses by those in the grain handling sector, and manifest through price dynamics. Specifically, grain elevators can alter the prices they offer to producers in order to increase or decrease the quantities of both wheat and pulse crops delivered to the location and/or to pass through additional costs or cost-savings. For example, if at harvest, the deliveries to an elevator begin to exceed the facility's capacity, they can lower their bids to reduce the demand for their grain handling services. Moreover, it is likely that the reduction will occur for *both* wheat and pulse prices because elevators typically handle both crops.

To empirically measure the extent to which Montana's grain handling may be constrained and whether prices have been impacted, I use historical daily basis wheat data for four Montana regions—northeast, north-central, Golden Triangle, and southeast—between 1998 and 2016. Using an event-study regression analysis, I estimate monthly basis values before and after 2009, which is when the major increase in pulse production began occur in Montana. The model controls for differences in location, seasonality, and differences across years.

Figure 5 shows a visual representation of the regression results for the four regions. The figure shows that there was a clear reduction in wheat basis (and, thus, prices paid to farmers) after the major expansion in pulse production. That is, relative to basis *prior* to the major pulse expansion, elevators offered lower basis bids after the expansion. On average, wheat basis decreased by an estimated 26%, with much of the decrease occurring at harvest time when there is the greatest influx of pulse crops. As the supply of pulse crops wanes throughout the marketing year, wheat basis returns to its historical normal levels.

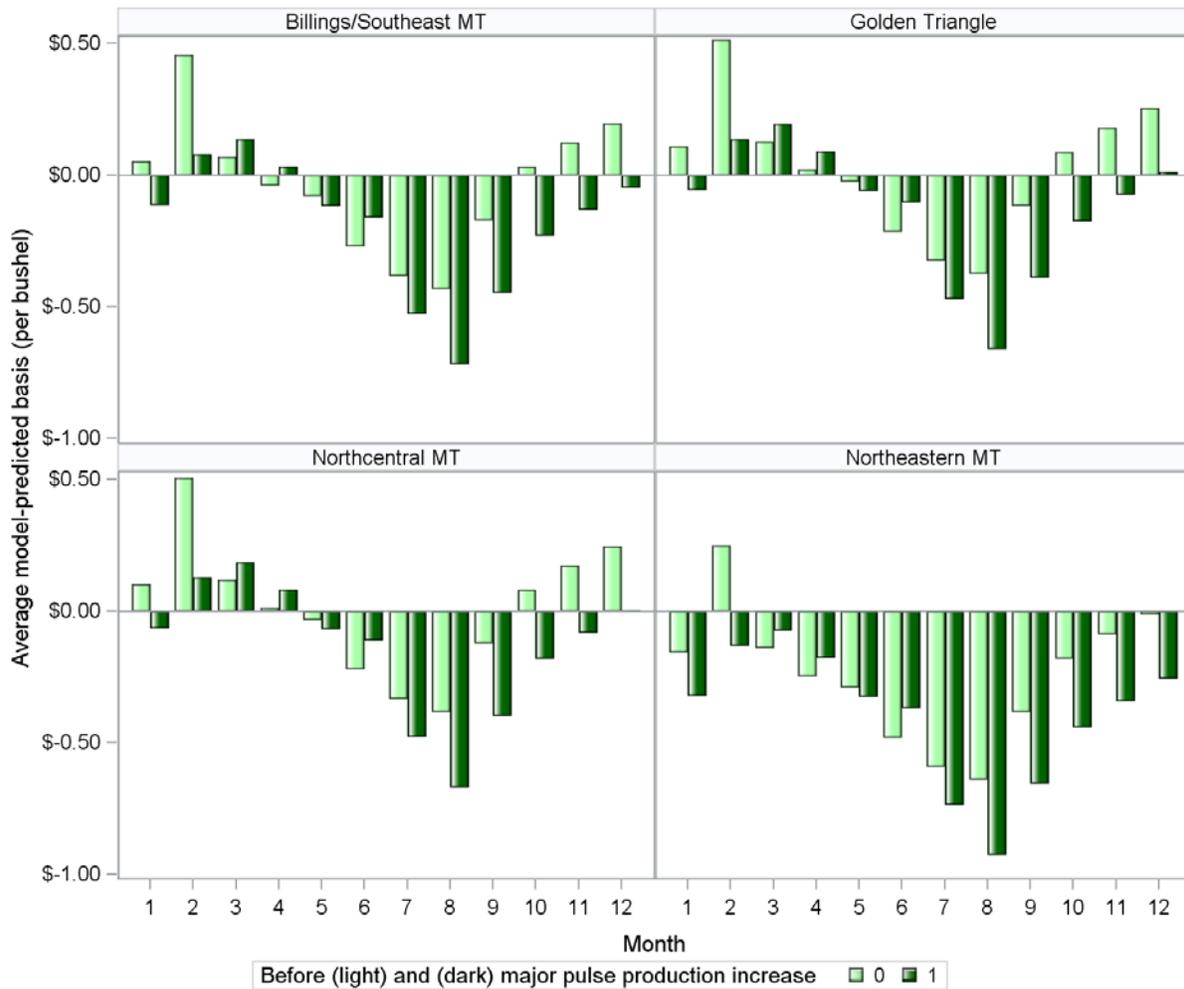


Figure 5. Estimation Results of Basis Regression Model

The results of the empirical analysis indicate that when evaluating farm-level returns from pulse production and marketing and aggregating to the state level, it is necessary to account for price reductions when calculating revenues. However, it is also important to note that as the industry continues to develop and the grain handling and marketing infrastructure expands, prices for both wheat and pulse crops are likely to strengthen. While it is difficult to know how quickly this expansion will occur, it is also useful to examine the potential returns in an environment that is not constrained by the capacity and transportation limitations.

Finally, the net returns are projected for the period 2017–2021. In order to ensure that the time-value of money is appropriately accounted for before comparing returns from alternative cropping systems, I calculate five-year discounted net present value (NPV) for each system's net return. The five-year NPV helps capture potential forgone longer-run opportunities that a producer would have if they were not able to invest revenues across the five-year period. For example, if a farmer chooses one production approach and earns an additional \$1 relative to an alternative production system, then the farmer can invest that extra dollar and earn interest. The producer who was not able to earn the additional \$1 would not have the choice to invest it. The discount rate used to calculate the NPV is 1.84%, which is the 2016 five-year U.S. treasury bill yield rate. This characterizes a risk-free investment that can be made by any producer.

State-level Land Conversion and Aggregated Net Returns Estimation

After calculating farm-level net returns for a representative acre of land under alternative cropping systems, state-level net returns can be calculated by aggregating returns on converted acres. In performing the aggregation, there are three issues that needed to be considered and addressed:

- How many fallow acres should be assumed to enter production annually?
- When fallow acres enter, what proportion are likely to be allocated to pea production and to lentil production?
- Should the overall productivity of a new converted acre be assumed to be the same as the overall productivity of a previously converted acre?

First, to determine the likely entry of new fallow acres into agricultural production, I look to historical conversion data. Records from the 1997 and 2012 USDA Censuses of Agriculture indicate that between those years, there was a 37.9% decrease in summer fallow acres in Montana. Annualizing this fifteen-year change suggests that an average annual reduction in fallow acres is approximately 2.5%. Because the 2017 Agricultural Census has not yet been completed, more recent information can be gleaned by using satellite imagery published by the USDA National Agricultural Statistical Service, CropScape (Cropland Data Layer). These data indicate that in Montana between 2012 and 2016, fallow acres decreased by 9.1%, or a 2.3% annualized rate of decrease.

It important to also note that in recent years, there is suggestive evidence that fallow acre conversion may be increasing. For example, from 2015 to 2016, 9.7% of fallow acres entered production. Moreover, the number of acres that can be enrolled into the Conservation Reserve Program has been continually lowered over the past decade and is now at a maximum ceiling of 24 million acres nationwide. This implies that farmers may be unable to enroll idle acres into the program. Lastly, the combination of rapid entry of acres into pulse production in Montana (see Figure 1 above), relatively high pulse price with respect to wheat prices, and continued research and improvements in pulse varieties and production techniques, may suggest that future fallow land conversion may be more rapid than observed in the past. As such, I use a 5% annual land conversion rate as a benchmark for the next five years, 3% as a lower bound (representing historical trends), and 10% as a potential upper bound.

The second consideration is a farmer's decision to allocate converted fallow acres into pea or lentil production. Using historical regional planted acreage data from the USDA National Agricultural Statistical Service, the main pulse production regions tend to allocate approximately 70% of land to pea production and 30% to lentils. Table 3 provides a summary of regional land use in Montana.

Table 3. Summary of Land Allocation, by Agricultural Statistical District

Land	Northeast	Central	North-central
<i>Fallow, 2016 acres</i>	527,658	337,316	2,180,339
<i>Winter wheat, 2016 planted acres</i>	200,453	443,807	1,401,038
<i>All wheat, 2016 planted acres</i>	2,230,498	576,886	2,429,507
<i>Fallow as proportion of all land in wheat, 2016</i>	19.13%	36.90%	47.30%
<i>Historical allocation lentils relative to peas</i>	31.20%	12.90%	31.20%

Notes: Agricultural statistical districts are defined by the USDA.

The last modeling consideration is the treatment of the productivity of additional converted acres. Economic theory suggests that farmers will first convert the most productive acre of land. They will then convert the next most productive acre of land, and so on. This theoretical intuition is reflected in farmers' decisions to convert pulse acres in Montana. For example, Figure 1 shows that between 2007 and 2016, much of the new pulse production has occurred in the northeast portion of the state, where pulse production conditions are most

favorable. In the Golden Triangle, where less moisture has made growing pulse crops less productive, conversion has been slower.

This implies that as additional fallow acres are added into pulse crop production, it is reasonable to expect decreasing marginal returns to those acres. As such, each annual influx of fallow acres into production is expected to have lower potential aggregate state-level returns (i.e., state-level returns are likely to still be positive, but will be less than the returns observed in the preceding year). To model this behavior, I use an inverse distance weighting function based on the percentage of fallow acres remaining in an agricultural region. That is, if 100% of Montana's acres were fallowed, then the first acre to be converted would have the highest productivity after conversion and would receive the highest "productivity" weight. The further fallow acres move from 100%, the lower "productivity" weight they receive. Figure 6 helps visualize the weighting scheme used for aggregating farm-level productivity to the state-level.

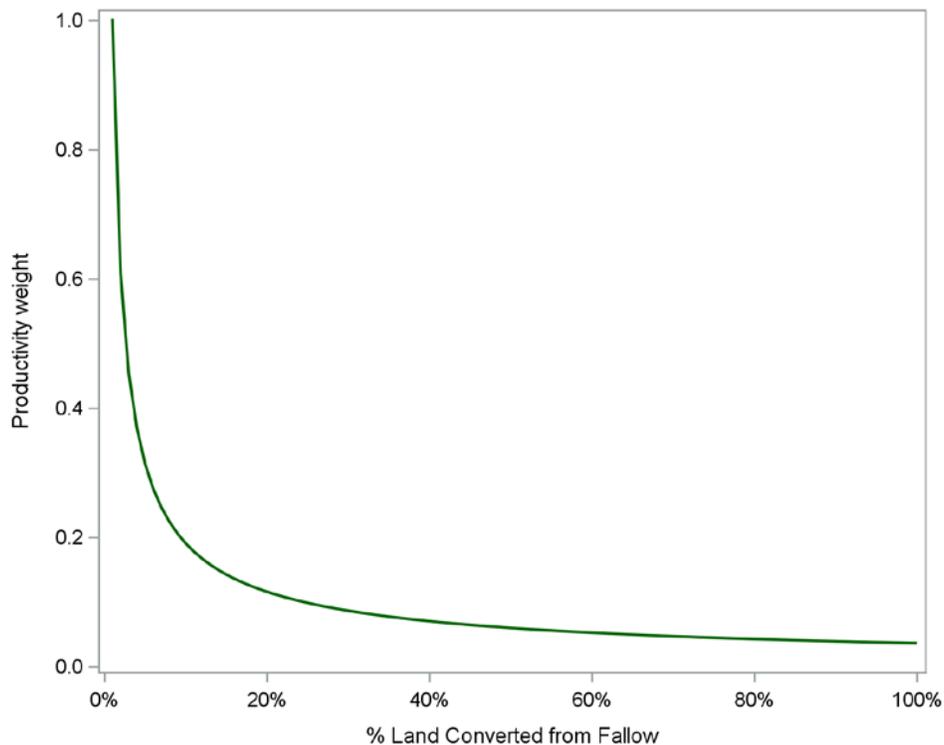


Figure 6. Land Productivity Weighting Function for State-Level Aggregation

Analysis Results

Figures 7–9 provide visual summaries of the economic analysis for projecting aggregate state-level returns to farmers. Again, it is important to note that the figures represent *additional* value that is provided by converting a wheat–fallow cropping system to a wheat–pulse system (not the total return from a wheat–pulse system). Each of the three figures represents impacts associated with the three grain handling and transportation infrastructure constraint conditions. Figure 7 represents the assumption that Montana's grain handling infrastructure is so constrained that both wheat and pulse crop prices are not at their maximum potential. Figure 8 represents the scenario that only wheat prices are lower due to constraints, but that pulse crops prices are at their efficient market levels. And Figure 9 characterizes a scenario that assumes both wheat and pulse crop prices are fully unconstrained by the evolving grain handling infrastructure.

In each figure, the solid green line represents the annual additional state-level value of fallow acres converted to pulse production. These baseline estimates assume a 5% annual land conversion rate. The light green band around the solid line represents value added if fallow land conversion is assumed to be between 3% and 10%

annually. The dark green bars represent cumulative net present added value under the 5% fallow land conversion assumption. That is, each bar represents the sum of value added from the current year and all previous years. The whiskers represent cumulative returns if fallow land conversion is assumed to be between 3% and 10% annually. Lastly, the top panel of each figure represents aggregate returns if pulse crop yields are assumed to remain at historical averages. The bottom panel represents state-level returns to farmers if pulse crop yields are higher as a result, for example, from research associated with this MREDI project.

The fully constrained assumption (Figure 7) provides the most conservative market characterization. Under the average pulse crop yield assumption, state-level added value is between \$256,000 in 2017 and \$160,000 in 2021. If higher land conversion rates are assumed, these returns increase to approximately \$829,000 in 2017 and \$408,311 in 2021. Cumulative five-year returns range between \$629,000 (3% conversion rate) and \$1.84 million (10% conversion rate), with the baseline cumulative returns of \$1.01 million. However, significantly higher returns are expected if pulse crop yields increase as a result of research and increase knowledge transfer. Specifically, even under the most price-constrained market scenario, the baseline five-year cumulative state-level aggregate net returns are estimated to be \$1.64 million, and up to \$2.99 million if fallow conversion is assumed to occur at a 10% annual rate.

Figure 8 shows perhaps the most representative model for Montana's current markets, in which wheat prices are likely constrained but pulse crop prices are becoming less constrained as global and domestic demand has expanded and stabilized significantly. Under the average pulse yield and baseline land conversion assumptions, annual returns range between \$524,000 in 2017 and \$320,000 in 2021. Under these assumptions, cumulative five-year state-level returns are estimated to be \$2.07 million. That is, if land that would have been fallowed was converted to pea and lentil production, aggregate farm-level returns to Montana producers would increase by over \$2 million dollars in a five year period. Under alternative land conversion assumptions, these returns can range between \$1.29 million and \$3.77 million.

Figure 8 also shows that significantly higher additional farm-level returns can be realized if pulse crop yield potential can be improved. Under a baseline land conversion assumption, cumulative five-year returns are estimated to be \$2.82 million. However, developing improved pulse crop varieties, improving methods for better management techniques for more intensified cropping systems, and transferring new knowledge to producers is likely to increase their willingness to more quickly convert fallow acres into more productive uses. If a 10% annual conversion rate is assumed for a five-year period—not inconceivable given recent trends and likely outcomes of more intensive research efforts—cumulative state-level returns to farmers are estimated to be nearly \$5.2 million.

It is again important to note that this cumulative additional value likely represents a lower bound of overall state-wide economic impacts. That is, the value characterizes returns that directly go to agricultural producers. It is likely that as Montana's grain handling and transportation industry continues to adapt to the changing production environment, there will be increased demand for labor and services. Moreover, while some of the additional returns to farmers will be re-invested in their operations, some portion is expected to enter and enhance other economic sectors in the state. As such, associated economic multiplier effects will likely increase the overall economic impacts.

Lastly, Figure 9 shows the results under the assumption that grain handling and transportation constraints are sufficiently low that they do not impact wheat or pulse crop prices. Interestingly, these results do not differ substantially from those in Figure 8. This suggests that even when wheat prices recover, it is unlikely that producers who maintain a wheat–fallow cropping system would outperform those with a pulse crop rotation (conditional, of course, on wheat yields within a pulse system maintaining only a moderate reduction relative to a fallow system and on pulse crop prices remaining relatively stable).

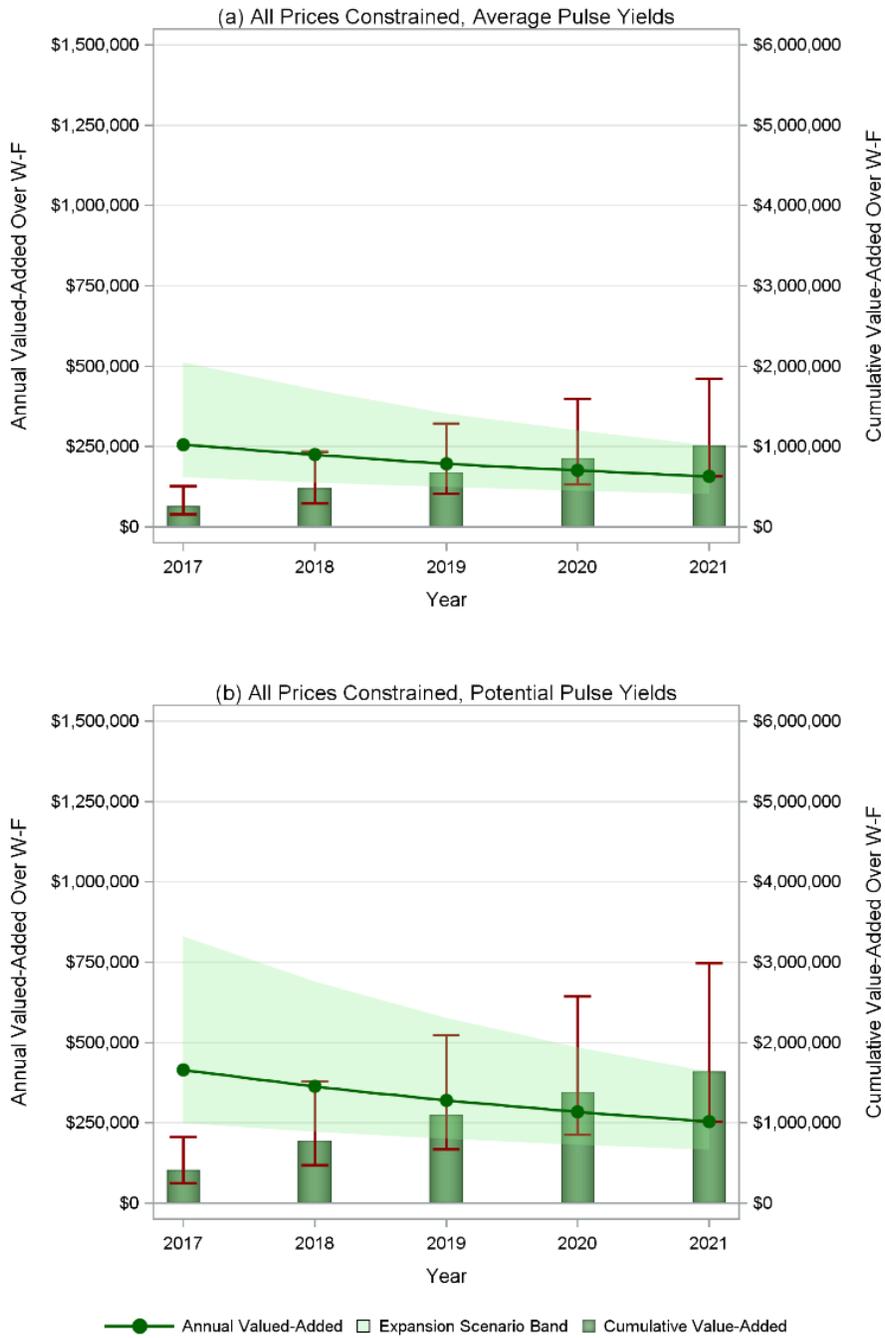


Figure 7. State-level Returns, Constrained Wheat and Pulse Price Assumption

Notes: Green line indicates returns to wheat-pulse cropping systems relative to wheat-fallow under the assumption that there is an annual 5% of fallow land converted to production. The light-green band indicates additional returns if fallow land conversion is assumed to be between 3% and 10% annually. Bars represent cumulative net present value of added value under the 5% fallow land conversion assumption, and whiskers represent cumulative returns if fallow land conversion is assumed between 3% and 10% annually.

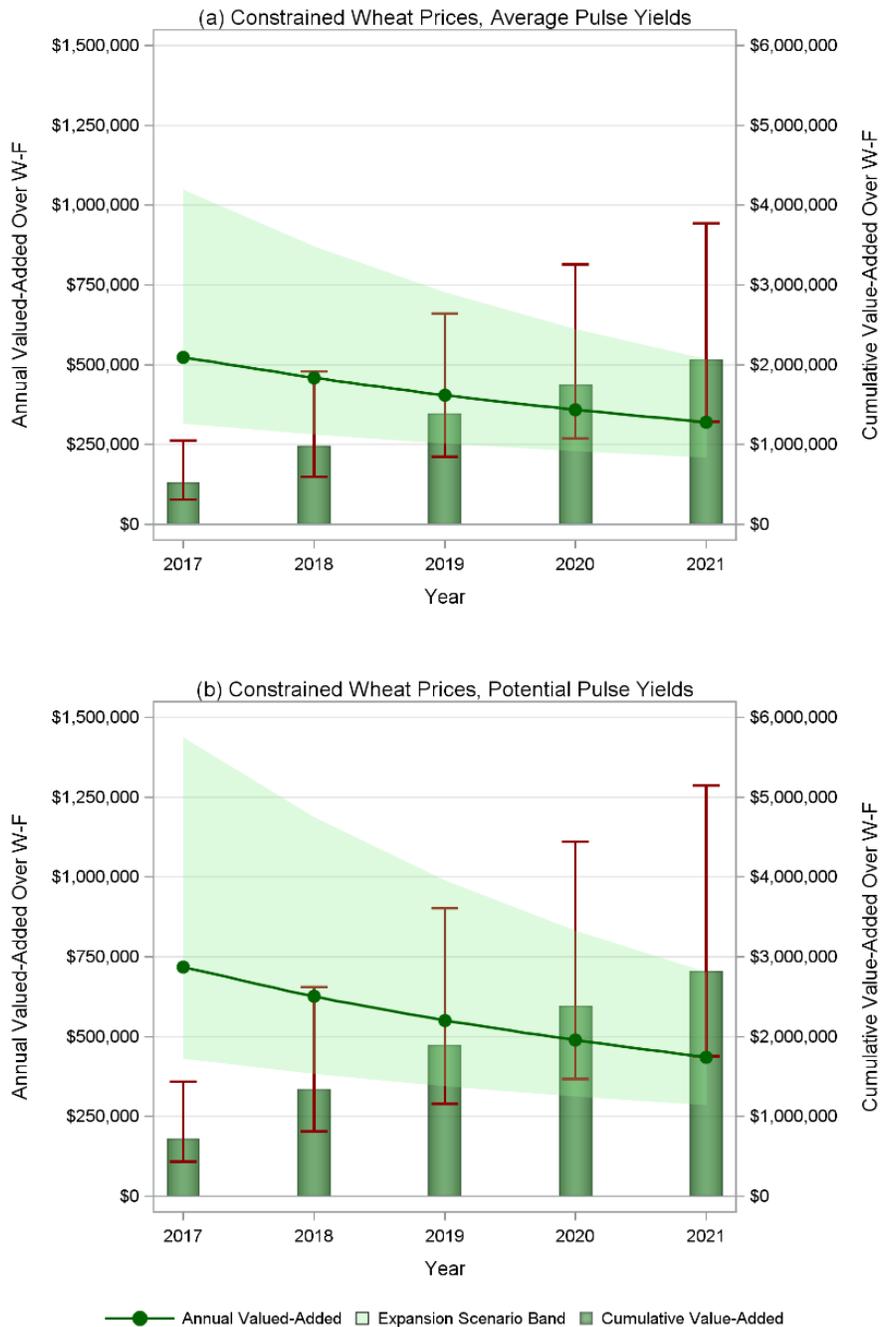


Figure 8. State-level Returns, Constrained Wheat Price Assumption

Notes: Green line indicates returns to wheat-pulse cropping systems relative to wheat-fallow under the assumption that there is an annual 5% of fallow land converted to production. The light-green band indicates additional returns if fallow land conversion is assumed to be between 3% and 10% annually. Bars represent cumulative net present value of added value under the 5% fallow land conversion assumption, and whiskers represent cumulative returns if fallow land conversion is assumed to be between 3% and 10% annually.

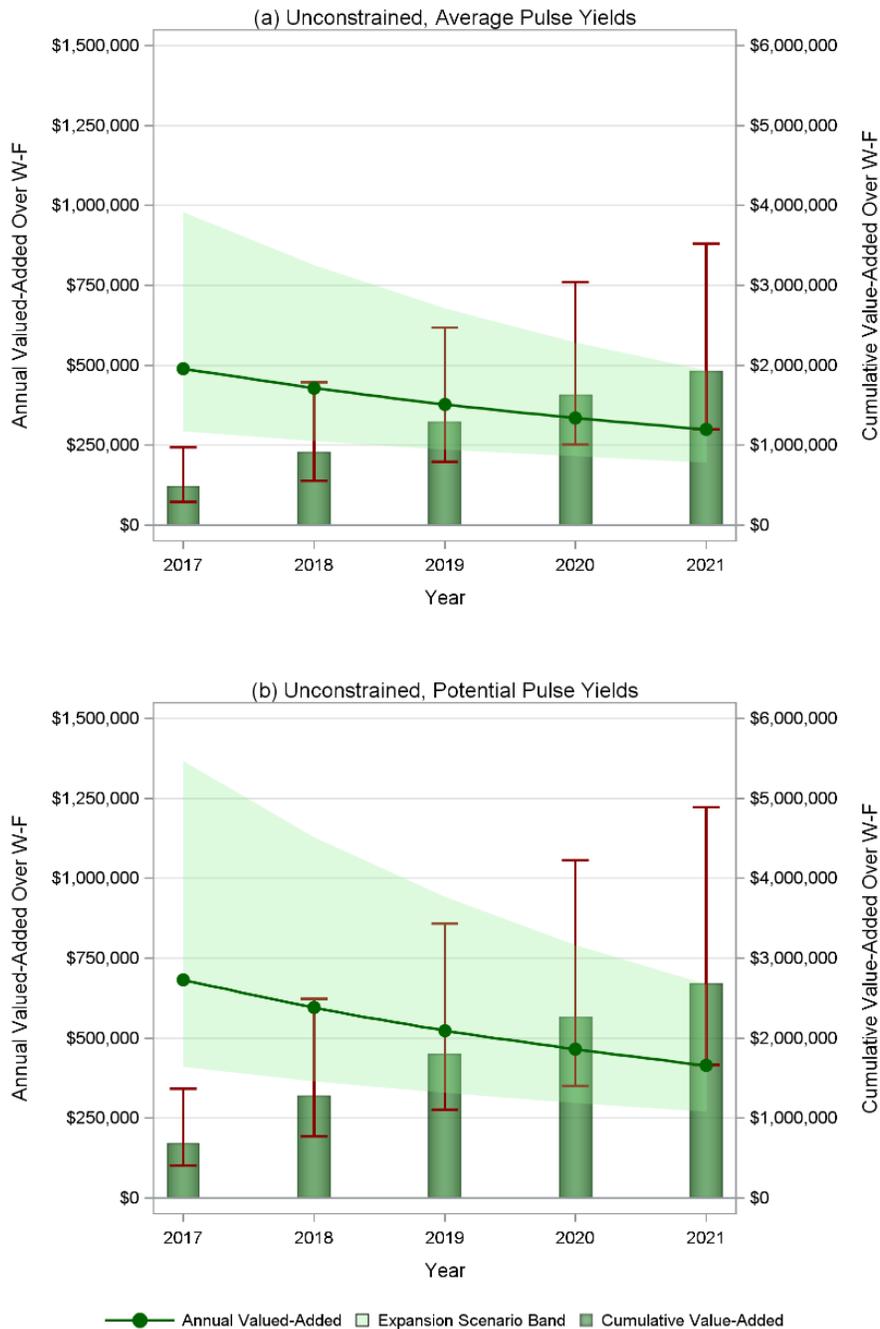


Figure 9. State-level Returns, Unconstrained Price Assumption

Notes: Green line indicates returns to wheat-pulse cropping systems relative to wheat-fallow under the assumption that there is an annual 5% of fallow land converted to production. The light-green band indicates additional returns if fallow land conversion is assumed to be between 3% and 10% annually. Bars represent cumulative net present value of added value under the 5% fallow land conversion assumption, and whiskers represent cumulative returns if fallow land conversion is assumed to be between 3% and 10% annually.

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: None
- Number of partnerships formed (private and public sector): None
- Number of new Montana businesses created: None
- Patents awarded or in progress: NA
- Commercial products developed: NA
- Jobs created: None

Expenditures

- Total Personnel: \$42,527.06
- Total Operations: \$14,060.94

Participatory research network subproject of the Agriculture MREDI project

1) 41W224 – Principal Investigator: George Haynes; Email: haynes@montana.edu

List the accomplishments of the project in quantitative and qualitative terms; compare results with the objectives in the original proposal.

The purpose of this part of the MREDI project was to conduct a farm-level cost:benefit analysis and participatory research assessment. The farm-level cost:benefit analysis used variable costs information supplied by other project participants and survey information on long-term fixed costs. Preliminary results suggest that net benefits (benefits less costs) ranged from \$x.xx to \$x.xx per acre. While it was very early in this experiment to assess long-term fixed costs, collaborators were most concerned about machinery and equipment and data processing requirements; where additional estimated expenditures varied widely from near zero for those who have already made these investments to over \$100,000 for other collaborators.

The participatory research assessment that producers were very satisfied with their collaboration with research faculty at MSU. The seven most important barriers facing these collaborators were the following: Added time to implement variable rate technologies, additional soil testing, handling fertilizer, financial considerations (low prices), equipment costs, technical support, and data processing.

Describe long-term impact (spinoff programs or other indicators) that will result from the project. Provide detail on future activities extending beyond the life of the original MREDI grant.

The project has had important contributions to Extension economics programming. The integration of variable rate technologies into crop budgeting models has changed how these analyses are presented to producers. Any efforts to teach crop budgeting to producers now includes an introduction to utilizing the “big data” provided by the monitoring required to implement variable rate technologies.

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: Haynes, G. W. (2017). Farm and Ranch Management 101 for Native American and Frontier Community Agricultural Producers, submitted to Farm Service Agency, Washington, DC. \$99,000.
- Number of partnerships formed (private and public sector): The results of this work has been presented to Extension Agriculture Agents at the Central Region Ag Update; interviews with the collaborators (Broyles, Merga, Van Dyke, and Woods) and other producers (primary, Doug Weist, Farm Tech, LLC).

- Number of new Montana businesses created: None
- Patents awarded or in progress: None
- Commercial products developed: None
- Jobs created: Graduate student, Tom Woods

Expenditures

- Total Personnel: \$14,887.67
- Total Operations: \$2,606.33

2) 41W223 – Principal Investigator: Colter Ellis; Email: colter.ellis@montana.edu

Project accomplishments and long-term impacts summarized above under Dr. Haynes’.

Final Metrics

- Total additional grants received: None
- Total additional grants in progress: None
- Number of partnerships formed (private and public sector): None
- Number of new Montana businesses created: None
- Patents awarded or in progress: NA
- Commercial products developed: NA
- Jobs created: 1 temporary graduate assistantship

Expenditures

- Total Personnel: \$19,165.17
- Total Operations: \$13,854.83