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Ecological Refugia as a Precision Conservation Practice in Agricultural Systems

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Abstract.

Current global agriculture fails to meet the basic food needs of approximately 700 million people. At the same time, our food system is responsible for catastrophic losses of biodiversity. Precision conservation solutions offer the potential to optimize production and conservation goals. Transforming low-producing areas on farm fields into ecological refugia may provide patch habitat and ecosystem services in fragmented agricultural landscapes. Ecological refugia were assessed in three precision agriculture farming systems in Montana for their capacity to support biodiversity, enhance beneficial ecosystem services and increase food production. Plant diversity declined significantly with distance from naturally occurring refugia (p-value < 0.1) and insignificantly from a newly created refuge (p-value = 0.87). Non-native plant species richness was highest in the crop field and lowest in refugia, indicating that ecological refugia host native plant diversity and are not sources of weedy species. Insect diversity declined significantly with distance from refugia for all refugia (p-value < 0.0001). Two fields with refugia had a higher abundance of beneficial insects (p-value < 0.05), while a control field without a refuge had a significantly higher abundance of pest insects (p-value < 0.05). Seed trap data indicated that a mix of seed predation services and disservices varied with refugia presence in addition to farm management practices. Lastly, crop yield declined significantly with distance from a naturally occurring refugia (p-value < 0.0001) and increased with distance from a created refuge (p-value < 0.0001). A random forest model that included yield data, a distance from refuge matrix, and a suite of remote sensing variables such as topography, normalized difference vegetation index, precipitation, and soil characteristics indicated that distance from refuge was the most important positive predictor of yield. Including distance from refuge in the model improved the r-squared value from 0.56 to 0.70 and reduced root mean square error by 104.2 kilograms. Future research will assess the feasibility of implementing ecological refugia as a precision conservation practice to enhance biodiversity and maintain yields in agricultural landscapes.

Keywords.
Precision conservation, agricultural biodiversity, sustainable agriculture, ecosystem services, patch habitat, agroecosystems

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Introduction

Current global agriculture fails to meet the basic food needs of nearly 700 million people (FAO, 2021). At the same time, conversion of land for agriculture is responsible for catastrophic losses of biodiversity (IPCC, 2022). As we encroach on multiple planetary boundaries and navigate a variety of global crises, agricultural solutions must become increasingly multi-objective (Ahmed et al., 2021). Thus, when considered alone, singular objectives such as food security, farm input reduction, and biodiversity conservation are not sufficient to address the complex problems inherent in food systems. However, novel applications of precision agriculture technology can widen the scope of yield-centric agriculture to encompass all the interrelated economic, social, and ecological components of agroecosystems. For example, precision agroecology aims to transform food systems by synthesizing technology and traditional knowledge in a way that informs and empowers farmers as decision-makers (Duff et al., 2022). Like precision agriculture, precision conservation should be site-specific, data-intensive, and farmer-led. Furthermore, it advances a multi-objective approach that optimizes conservation and food production outcomes. The effects of on-farm conservation can be quantified using combine-mounted yield sensors and remote sensing data to map yield, net return, biodiversity patterns and ecosystem services. While precision conservation has been defined an emerging approach to conserve natural resources using spatial technologies (Berry et al., 2005), precision conservation under the agricultural umbrella involves planning for or maintaining on-farm biodiversity, managing for beneficial ecosystem services and quantifying tradeoffs of on-farm conservation with consistent probability for farmers (Figure 1). By providing the data and tools to quantify economic and ecological tradeoffs in agroecosystems, precision conservation offers a management strategy that benefits production and natural systems alike.

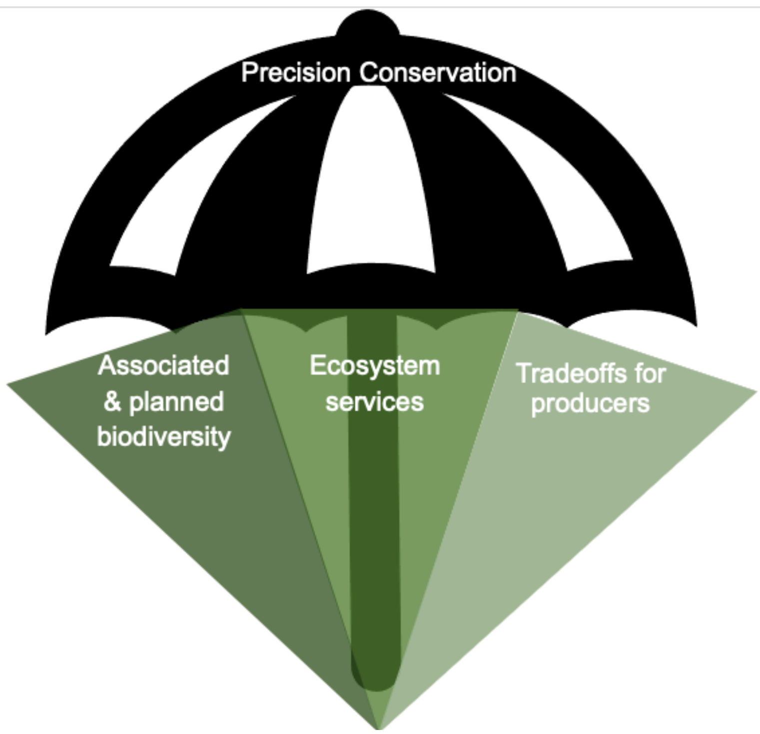


Figure 1. Beneath the agricultural umbrella, precision conservation consists of three components: planning for or maintaining on-farm biodiversity, managing for beneficial ecosystem services and quantifying tradeoffs of on-farm conservation for farmers.

Studies of biodiversity in farmland fragments have traditionally focused on remnant habitats such as buffer zones, pollinator strips and roadside margins (Cousins & Eriksson,2008; Schulte et al., 2017). However, assessing the potential for uncropped patches, or ecological refugia, to host biodiversity in agricultural landscapes provides a new lens for on-farm conservation studies. Ecological refugia may naturally occur on farms due to topographical features that make them too difficult to cultivate, such as low-lying areas or marginal lands. These types of on-farm patch habitats offer potential to harbor on-farm biodiversity and provide ecosystem services across fragmented agricultural landscapes (Cousins, 2006; Martin et al., 2020). For instance, beneficial ecosystem services on farms are provided by insects, birds and small mammals and include pollination, pest predation, and weed seed predation (Kremen, 2005; Swinton et al., 2007). Therefore, intentionally transforming low-producing areas into ecological refugia may provide associated ecosystem services that benefit farmers and enhance local diversity. Landscape and land cover heterogeneity are a means of generating biodiversity, where different natural cover types and crops provide different habitats and resources for more species (Fahrig et al., 2011; Landis, 2017). Contrary to common assumptions, biodiverse farms are not necessarily less productive. In fact, farms with higher plant diversity are associated with increased pest predators, reduced weed density, enhanced nutrient cycling and increased soil fertility (Garbach et al., 2017; Isaacs et al., 2009; Power et al., 2010). Accompanying agronomic benefits may result in lower input costs, higher crop nutrient content, and maintained or increased crop yields (Tscharntke et al., 2005; Zuo & Zhang, 2007). However, the tradeoffs of incorporating on-farm biodiversity could include increased pest habitat, increased weed density, and yield reduction (Karp et al., 2018). While the benefits of multi-function agricultural biodiversity, habitat management and stacked ecosystem services have been generally demonstrated (Fiedler et al., 2008; Gurr et al., 2003), the difficulty of quantifying site-specific tradeoffs makes it challenging for farmers to manage for on-farm biodiversity at the appropriate scale without compromising yield (Kremen, 2005; Tscharntke et al., 2005).

Fortunately, precision agriculture technology provides site-specific data which can be used as an on-farm conservation tool to optimize ecosystem services and manage tradeoffs in agricultural systems (Basso & Antle, 2020). Profit mapping is a promising precision conservation practice that is employed at the field and farm scale. Profit mapping enables farmers to identify low-producing areas in their fields that can be taken out of production to save time and money while simultaneously creating habitat in the agricultural ecosystem (Capmourteres et al., 2018). This application highlights the dual capability of spatial analysis to facilitate precision agriculture and precision conservation objectives. Profit maps are a practical management tool for farmers to evaluate economic and ecological tradeoffs on their farms by visualizing where precision conservation might increase both on-farm biodiversity and net return. Moving forward, precision agriculture and remote sensing data will prove increasingly vital to the optimization of agricultural production and conservation efforts at all scales (Duru et al., 2015; Gabriel et al., 2010). The goal of this study was to use precision agriculture data to assess ecological refugia at the field scale for their capacity to support biodiversity, enhance beneficial ecosystem services and maintain or increase yields in agroecosystems.

Methods

Ecological refugia were identified on three precision agriculture farms in dryland wheat production in Montana. The selected refugia varied in both their size and years of establishment. Ranging from less than 1 hectare, to nearly 20 hectares, ecological refugia were located in fields as small as 31 hectares and as large as 114 hectares (Table 1). Two of the selected refugia were naturally occurring, uncropped areas that farmers considered too difficult to cultivate and had no history of cultivation. The third refuge was a low-producing area that the farmer opted to remove from production and convert to habitat by planting it with a native seed mix in 2018 (Table 1). To characterize the refugia's capacity to host plant diversity, insect diversity, seed predators and impact yield, field surveys were conducted in the summers of 2020 and 2021. A radial web design consisting of six transects was established in the center of the refugia and extended 100 meters towards the crop field. A sampling web was replicated in an adjacent field without a refuge as a control on each farm (Figure 2).

Table 1. Field and ecological refuge size in hectares of selected sites for ecological refugia assessment on three farms.

Farm	Farm 1	Farm 2	Farm 3
Field with Refuge Area (ha)	31.02	63.23	113.52
Refuge Area (ha)	0.86	18.57	0.16
Refuge Type	naturally occurring	naturally occurring	created

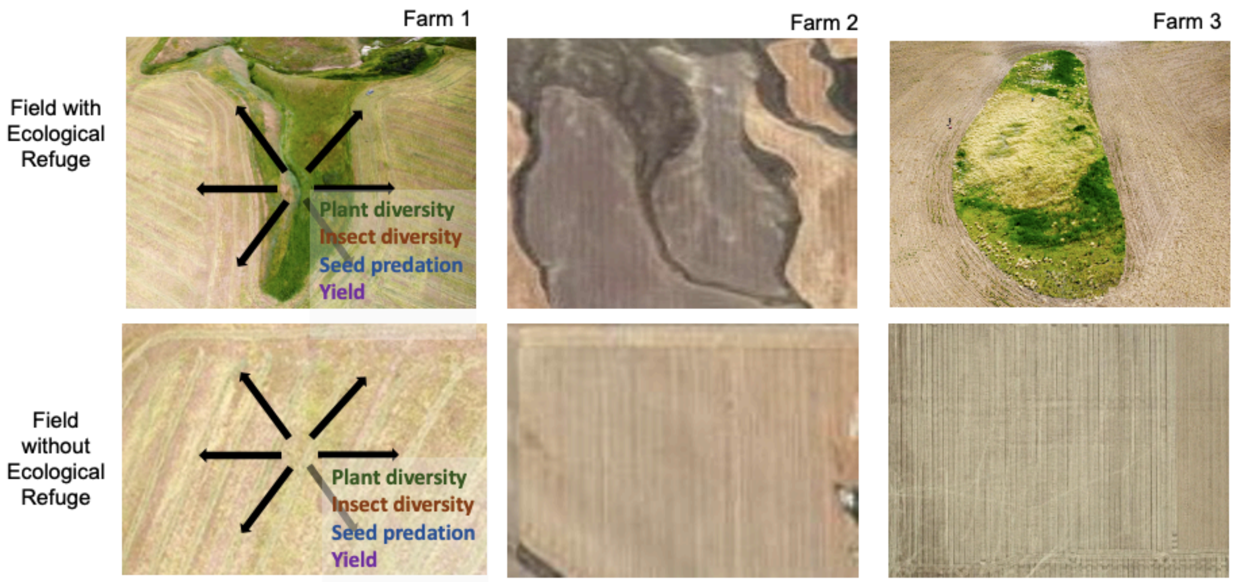


Figure 2. Field surveys of plant and insect diversity, seed predation, and their impact on yield were assessed on three farms with and without ecological refugia in Montana.

Vegetative diversity and plant species percent cover were assessed in the field using ocular estimates for 60 0.25-meter squared sampling frames at ten-meter intervals along each transect. Insect abundance and diversity were evaluated using sweep net sampling along the same sampling webs in 20-meter intervals from the center of the refuge. Insect specimens were collected and stored within their 20-meter segment groupings, frozen, and subsequently identified in the lab. Plant and insect diversity were calculated using the Shannon-Weaver index from the vegan: Community Ecology Package in R Studio (Version 1.1.453 – © 2009-2018 RStudio, Inc.). Bayesian Kriging interpolation of sampled points was used to predict where higher plant diversity would occur in the rest of the refuge and crop field. Linear regression was used to assess the relationship between both plant and insect diversity and distance from refuge. Insect samples were classified by order of Araneae, Diptera, Coleoptera, Hemiptera, Hymenoptera, Odonata, Orthoptera and Lepidoptera. Then, insect orders were classified into general categories of beneficial or detrimental insects based on their associations with ecosystem services and disservices such as weed control, pest control, nutrient cycling or crop damage and yield reduction (Altieri, Nicholls & Fritz, 2005; Moonen & Barberi, 2008). A pairwise comparison of insect abundance in each order by field type was used to compare whether fields with or without refugia hosted higher beneficial and pest insect abundance.

$$Shannon - Weaver\ Diversity\ = -\sum_{i=1}^{S} \rho_i \ log_b \ \rho i$$

To assess the beneficial ecosystem service of seed predation, 30 seed traps were set at 20-meter intervals on each sampling web. To test seed selection preference, each seed trap was set with two weed and two crop species and left in the field for two weeks before collection and analysis.

Lastly, to evaluate the effect of refugia on crop production, yield data from a combine-mounted monitor was split into 20-meter buffer zones around the refuge and analyzed with a linear regression where yield was a function of distance from refuge.

Linear Regression = Yield ~ *f* {Distance from Refuge}

Subsequently, two random forest models were built using yield data and a suite of remote sensing variables such as topography, normalized difference vegetation index, precipitation, and soil characteristics. Using a QGIS analysis tool, a distance matrix was created to calculate the distance between the refuge and every point surrounding it, thus creating distance from refuge as an explanatory variable. The only difference between the models was that Model 2 included distance from refuge as a variable.

Model 1 = Yield ~ *f* {Elevation, Slope, Aspect, East Aspect, North Aspect, Topographic Position Index, NDVI, Average Daily Minimum Temperature, Average Daily Maximum Temperature, Soil Percent Clay, Soil Organic Carbon, Mean Annual Precipitation 2019-2020}

Model 2 = Yield ~ *f* {Elevation + Slope + Aspect + East Aspect + North Aspect + Topographic Position Index + NDVI + Average Daily Minimum Temperature + Average Daily Maximum Temperature + Soil Percent Clay + Soil Organic Carbon + Mean Annual Precipitation 2019-2020 + Distance from Refuge}

Variable importance plots were used to rank the relative importance of each explanatory variable in the random forest models. Variable importance plots quantified the mean decrease in accuracy if a particular variable was removed from the random forest model. R-squared values indicated the proportion of observed variability in yield that each model was able to explain. The root mean square error (RMSE) was calculated to quantify the reduction in error received from incorporating distance from refuge in the model. RMSE was calculated between observed yield and the predicted yields from Models 1 and 2 using the following equation:

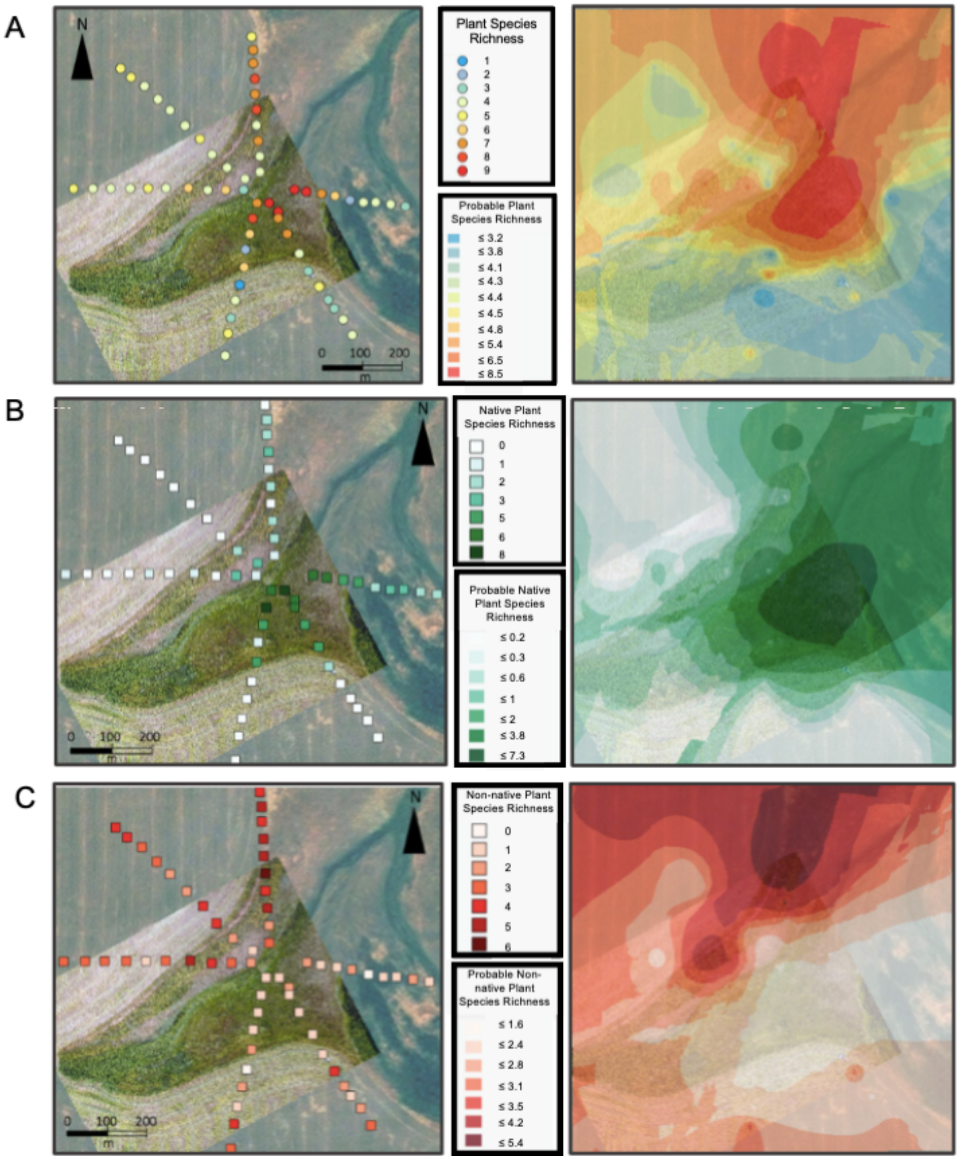
$$RMSE = \sqrt{mean(Observed\ Yield - Predicted\ Yield)^2}$$

Finally, a multiple linear regression was used to characterize the relationship between each modeled variable and the yield response. Variable inflation factor and model residuals were checked to ensure that the model did not violate any assumptions of normality or independence. AIC selection criterion was used to select the model of best fit, as follows:

Model 3 = Yield ~ *f* {Elevation + Topographic Position Index + East Aspect + NDVI + Average Daily Minimum Temperature + Soil Percent Clay + Soil Organic Carbon + Distance from Refuge}

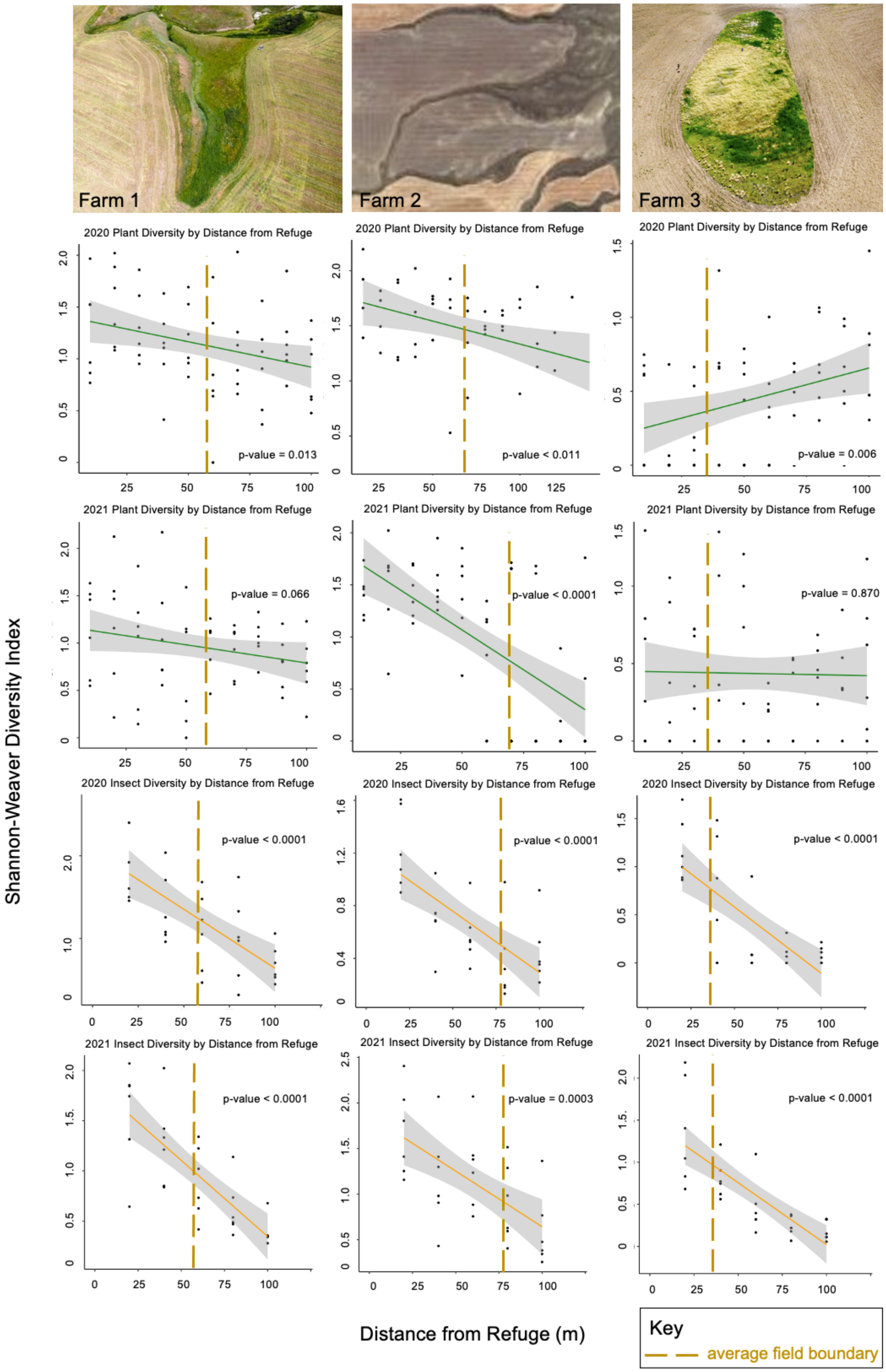
Results

As proof of concept that small patch refugia host biodiversity, a Bayesian Kriging interpolation of sampled plant species indicated that plant diversity was likely to be higher in the refuge than in the crop field (Figure 3A). With higher plant diversity in and around the ecological refuge, we would expect beneficial ecosystem services such as pollination or pest predation to also occur. However, not all biodiversity is beneficial. To decipher between desirable and undesirable on-farm biodiversity, plant diversity was separated into native and non-native diversity for analysis. A Bayesian Kriging interpolation indicated that native species are likely to have higher species richness in the refuge while non-native species are likely to have higher species richness in the crop field. This suggests that refugia are sources of native plant diversity and not sources of weeds in crop fields. (Figure 3B & 3C)



(Figure 3).A) Despite its small size, the ecological refuge hosted higher plant species richness than the crop field. B) Native species have higher species richness in the refuge. C) Non-native species have higher species richness in the crop field and are less likely to occur in the ecological refuge. This suggests that refugia are sources of native plant diversity and not sources of weeds in crop fields.

Second, a linear regression of diversity as a function of distance from refuge demonstrated that not only do refugia host biodiversity, but that diversity carries into the surrounding agroecosystem. Plant diversity declined significantly with distance from refugia for naturally occurring refugia on Farms 1 and 2 in both years (p-value 0.13 and p-value = 0.011)., but diversity did not decrease abruptly at the crop field boundary (Figure 4). However, plant diversity on Farm 3 increased significantly with distance from the refuge in 2020 (p-value = 0.006) and decreased insignificantly in 2021 (p-value = 0.87) (Figure 4). The nonconforming diversity trends for Farm 3 emphasize the important role of ecosystem structure in supporting ecosystem function for on-farm refugia, as this refuge is by far the youngest, least established, and least diverse of the three refugia. Insect diversity declined significantly with distance from refuge for all refugia in all years (p-value < 0.0005) (Figure 4).



(Figure 4). Plant and insect diversity trends with distance from ecological refuge (100 meters) into the crop field for three on-farm refugia in 2020 and 2021.

Third, further analysis was required to make distinctions between beneficial and pest insects. A pairwise comparison indicated that the field with a naturally occurring refugia on Farm 1 had significantly higher abundance of insects from the orders Hymenoptera, Araneae and Odonata which are associated with beneficial ecosystem services such as pollination by native bees and pest predation by wasps, spiders, and dragonflies (p-value < 0.05) (Figure 5A). On Farm 2, the field with a refuge had a higher abundance of insects from the orders Diptera and Hymenoptera, which are typically associated with beneficial ecosystem services such as pollination by hoverflies and pest predation by native wasps (p-value < 0.001). Furthermore, the field without a refuge on Farm 2 had a significantly higher abundance of insects from the orders Orthoptera and Hemiptera, which are commonly associated with disservices like yield-reduction by grasshoppers and aphids (p-value < 0.05). (Figure 5B). The field with a refuge on Farm 3 had a significantly higher abundance of insects from the order Coleoptera, which are associated with beneficial ecosystem services provided by beetles such as weed seed predation and nutrient cycling. However, the same field had a significantly higher abundance of insects from the orders Orthoptera and Hemiptera, which are commonly associated with yield-reducing pest insects like grasshoppers and aphids (Orthoptera and Hemiptera). (Figure 5C). Again, the mixed results of Farm 3 indicate the difference between the well-established refugia on Farm 1 and 2 and the newly created refugia on Farm 3 in their ability to host beneficial biodiversity and associated ecosystem services.

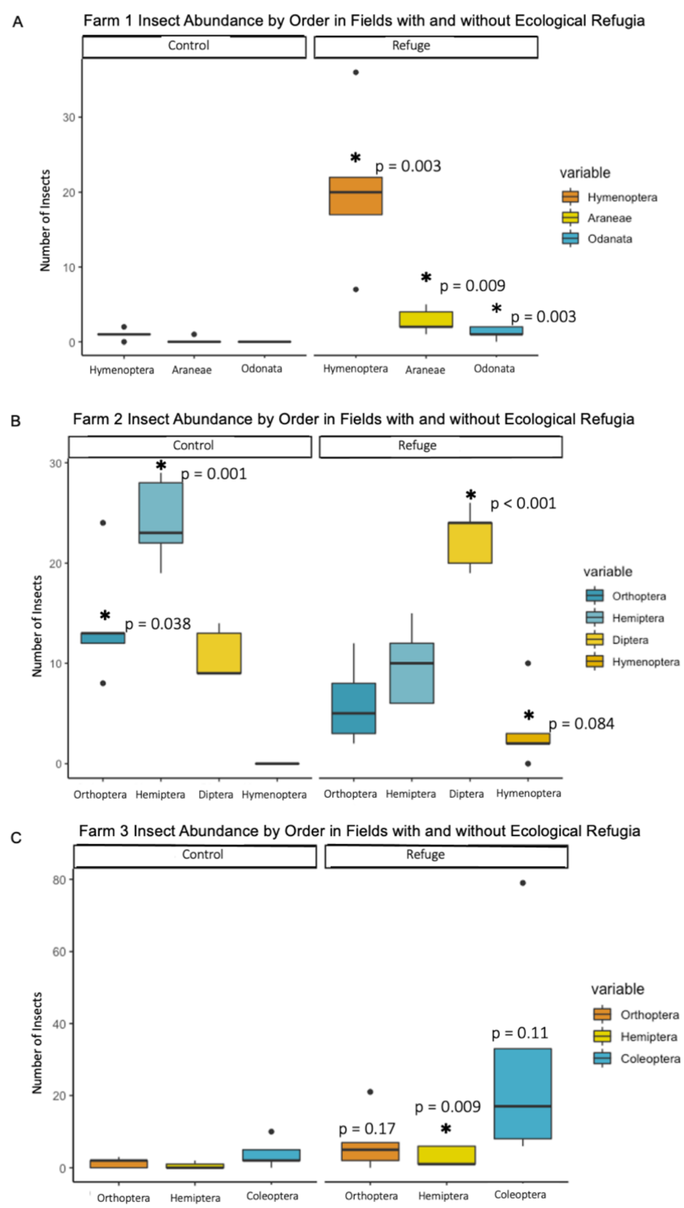


Figure 5. A) On Farm 1, the field with a refuge had a significantly higher abundance of pollinators like native bees (Hymenoptera) and pest predators like spiders and dragonflies (Araneae and Odonata) than the field without a refuge. B) On Farm 2, the field with a refuge had a significantly higher abundance of pollinators like hoverflies (Diptera) and pest predators like native wasps (Hymenoptera), and the control field had a higher abundance of yield-reducing pests like grasshoppers and aphids (Orthoptera and Hemiptera). C) On Farm 3, the field with a refuge had a significantly higher abundance of beetles (Coleoptera) than the control field, which provide services such as weed seed predation and nutrient cycling. However, the same field had a higher abundance of grasshoppers and aphids (Orthoptera and Hemiptera), which are typically associated with yield-reduction.

Fourth, moving from biodiversity analysis into ecosystem service assessment, seed predators provide mixed services to farmers. Seed trap data indicated that seed predators equally selected between the two crop seeds, common wheat (*Triticum aestivum*) and Arvika green pea (*Pisum sativum*). However, for weed seeds, seed predators largely preferred field pennycress over wild oat. Seed predators provide a beneficial service of weed suppression by eating weed seeds and a disservice of reducing crop yield by eating newly planted seeds. Therefore, weed seed predation of field pennycress and wild oats was classified as a beneficial service to famers, while crop seed predation of wheat and peas was considered a disservice to farmers. Farm 1 received two beneficial services as weed seed predation was higher and crop seed predation was lower in the field with a refuge than in the control field (Figure 6). However, the opposite trends occurred on Farm 2, which received two disservices of higher crop seed predation and lower weed seed predation in the field with a refuge (Figure 6). The field with a refuge on Farm 3 received mixed services as it had higher weed seed predation and higher crop seed predation (Figure 6). Overall, crop seed predation was higher than weed seed predation on all three farms but weed seed predation was higher on organic farms than the conventional farm. Therefore, the value of seed predators will depend on the degree of weed suppression they provide to farmers and weed seed predator effectiveness is seemingly impacted by farm management practices.

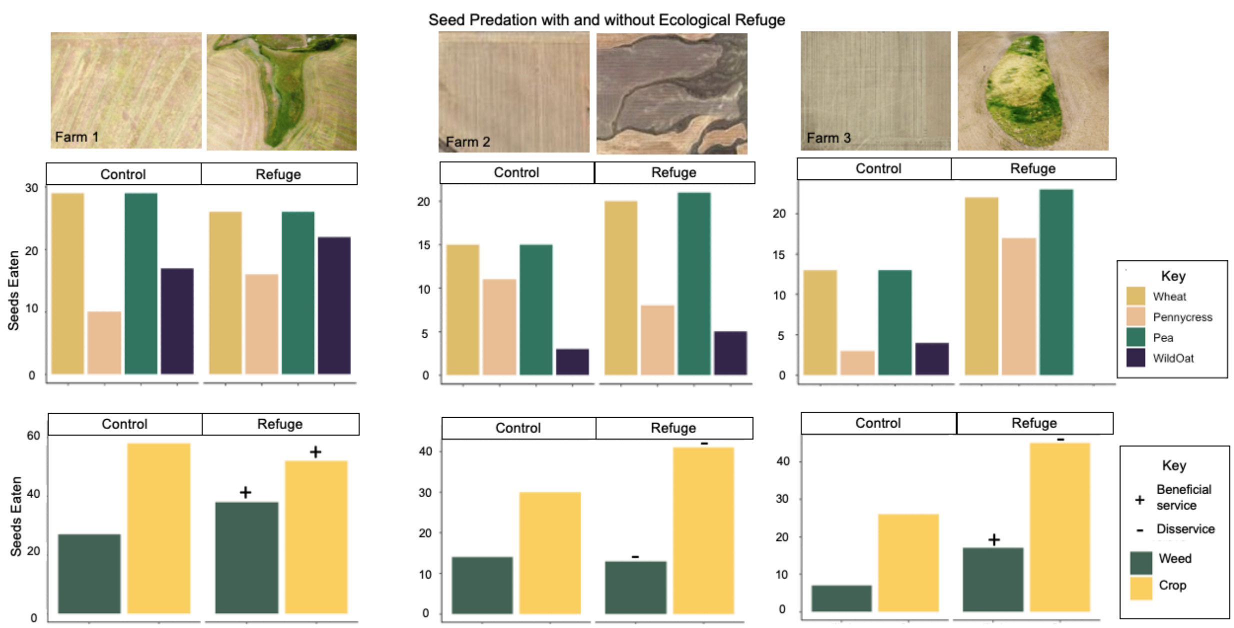


Figure 6. Crop and weed seed predators provide beneficial seed predation services on Farm 1, disservices on Farm 2 and a mix of services on Farm 3.

Finally, the relationship was characterized between ecological refugia, associated biodiversity, ecosystem services and their impact on crop yield. Yield maps from combine-mounted sensor data from Farm 1 indicated a significant decline in crop yield with increasing distance from the refuge (p-value < 0.0001) (Figure 7). Yield decreased approximately 80.1 kilograms with every 20 meters from the edge of the refuge. However, the opposite trend occurred on Farm 3, as yield significantly increased with distance (p-value < 0.0001) (Figure 7). In this case, yield increased about 40 kilograms with every 20 meters from the refuge. As noted previously, the length of time required to establish native plant species and associated ecosystem services may explain the difference in yield trends seen in the well-established, naturally occurring refugia on Farm 1 versus the newly created refuge on Farm 3.

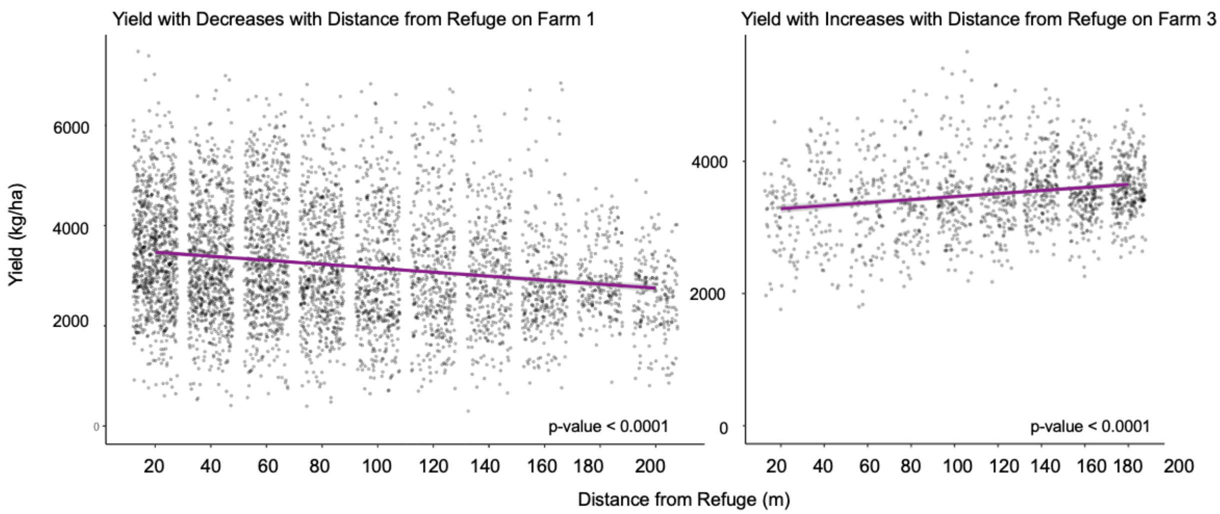


Figure 7. Yield significantly declined with distance from refuge on Farm 1 but significantly decreased with distance from refuge on Farm 3.

After building two random forest models with and without distance from refuge as an explanatory variable, the variables were ranked using variable importance plots. The x-axis quantified the decrease in accuracy a model would experience if a particular variable was removed from the model. Variable importance plots indicated that distance from refuge was by far the highest ranked explanatory variable in the model, although linear regression was subsequently modeled to characterize whether the direction of the relationship between yield and distance from refuge was positive or negative (Figure 8). In addition, R-squared values were calculated for each model and compared for their ability to explain the variability observed in yield. Model 1, a random forest model that does not include distance from refuge as an explanatory variable, explained only 57% of the overall variability (R-squared = 0.57). Model 2, a random forest model that did include distance from refuge as a variable, explained 70% of the variability (R-squared = 0.70) model. The vast improvement in R-squared from Model 1 to Model 2 indicates that distance from refuge is an important variable for characterizing yield in this agricultural system.

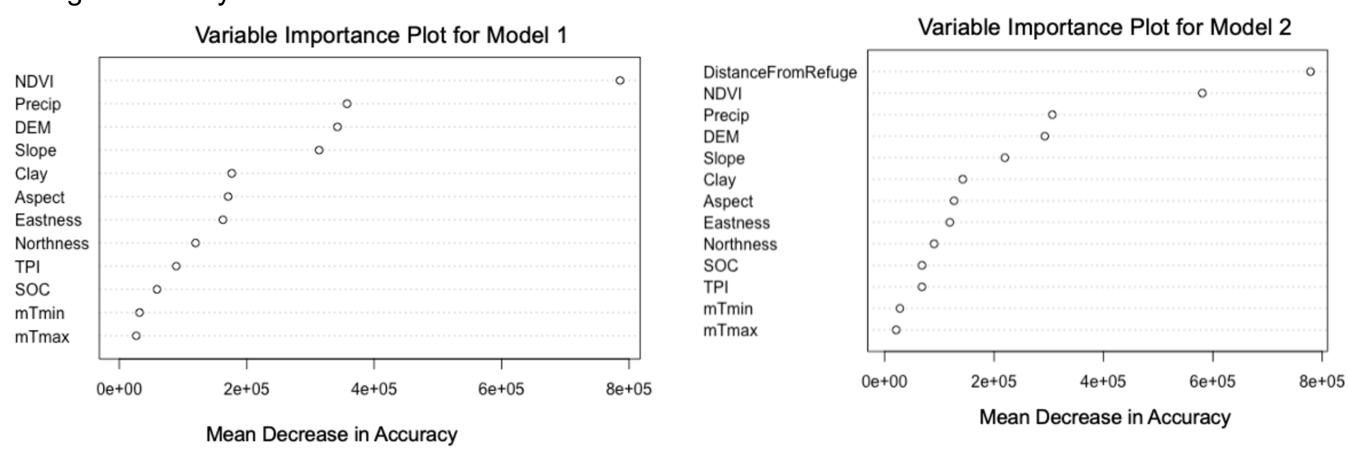


Figure 8. The variable importance plot for Model 1, a random forest model without distance from ecological refuge as a variable, has an R-squared value of 0.57. The variable importance plot from Model 2, a random forest model that includes distance from refuge as a variable, has an R-squared value of 0.70.

To demonstrate model improvement with the inclusion of distance from refuge as a variable, the RMSE was calculated between the two modeled yield responses and the observed yield data (Figure 9). Including distance from refuge as a variable in Model 2 slightly reduced the model error. The RMSE for Model 1 was 579.7 kilograms while the RMSE for Model 2 was only 475.5 kilograms. Therefore, including distance from the refuge in the model reduced the RMSE by 104.2 kilograms.

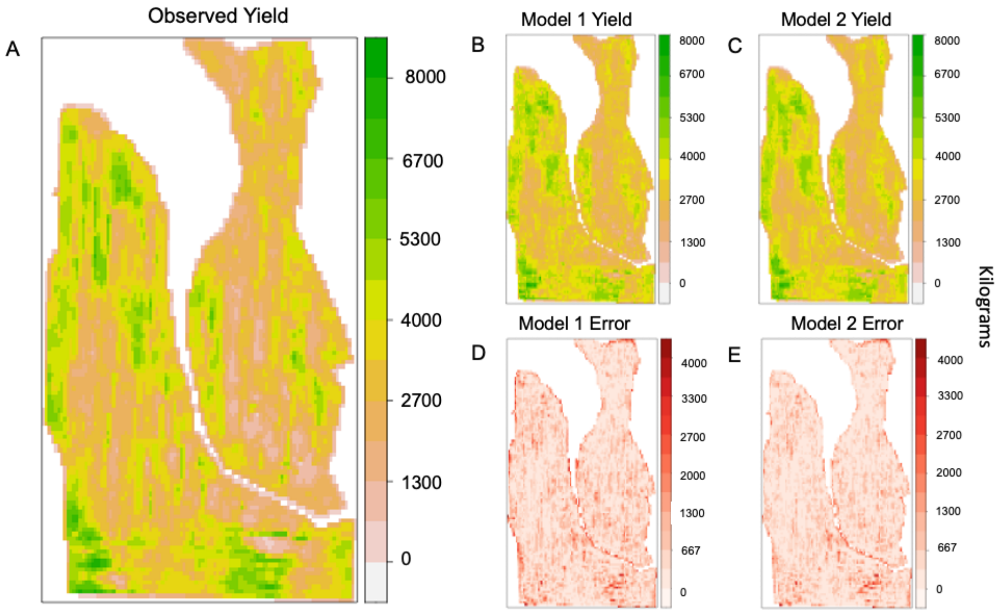


Figure 9. A) Actual yield data in kilograms from combine-mounted sensor in 2020. B) Modeled yield response from Model 1, a random forest model that does not include distance from refuge as a predictor. C) Modeled yield response from Model 2, a random forest model that does include distance from refuge as a predictor. D) The root mean square error between observed and modeled yield from Model 1 was 579.7 kilograms. E) The root mean square error between observed and modeled yield from Model 2 was 475.5 kilograms.

Lastly, multiple linear regression was used to characterize the relationship between each modeled variable and the yield response. Regression analysis indicated that yield significantly increased with higher normalized difference vegetation index and soil organic carbon but decreased with higher elevation, eastern aspect, lower average daily minimum temperatures, higher soil clay content and distance from refuge (p-value < 0.0001).

Discussion

While plant diversity trends demonstrated a direct relationship between diversity and distance from refuge on Farms 1 and 2, the results were inconsistent on Farm 3. Furthermore, beneficial and pest insect data were clearly positively related to fields with a refuge on Farms 1 and 2, while Farm 3 showed mixed results. The divergent plant and insect trends on Farm 3 emphasize the important role of ecosystem structure in supporting ecosystem function for on-farm refugia, as this refuge is by far the youngest, smallest, least established, and least diverse of the three refugia. Before recommending that farmers remove land from production to convert into on-farm habitat, further research is needed to understand the amount of time, amount of habitat area and amount of biodiversity needed to provide beneficial ecosystem services in patch habitat. Additionally, mixed results for seed predation services and disservices suggest that seed predator activity may be explained by differences in farm management practices. Farm 1, which hosted two beneficial seed predation services, did not only have the advantage of starting with a diverse, naturally occurring refuge, but was under organic management. The practice of polycropping and lack of chemical inputs on the farm may be another factor in explaining the higher biodiversity and beneficial ecosystem services trends on this organic farm (Sarabi, 2019).

In contrast, Farm 2, received only disservices from seed predators, despite having a large, naturally occurring refuge. These disservices may be explained differences in farm management, as Farm 2 is managed conventionally. Chemical application and monocropping in the field may be responsible for reducing beneficial seed predator activity (Smith, Gross & Robertson, 2008; Snyder, Gómez, & Power, 2020). Farm 3, which had both seed predation services and disservices, was also under organic management. It experienced higher weed seed predation but also higher crop seed predation. The higher amount of crop seed predation may be attributed to the lack of seed and other food sources provided by the small refuge (Letourneau et al., 2011).

Lastly, while precision conservation of on-farm patch habitat is a promising future component of precision agriculture, it is currently fraught with methodological complications and barriers to farmer adoption. At its present state, precision conservation relies on mixed methods of time-consuming field surveys, expensive precision agriculture technology and complicated remote sensing data. Field biodiversity surveys are time and labor intensive and require an advanced level of taxonomic expertise, making it unlikely for farmers to survey for biodiversity on their own farms. Furthermore, precision agriculture technology can be expensive and incompatible with pre-existing farm machinery. Even if obtained, precision agriculture and remote sensing data require specialized knowledge to manage, analyze and apply data effectively. If precision agriculture or precision conservation practices are to become widely adopted, these barriers to adoption must be reduced. The on-farm precision experimentation (OFPE) framework currently provides helpful steps to guide farmers and researchers alike through the data-intensive, adaptive management farming process. (Hegedus, 2022). Moreover, improvements in remote sensing technology specifically aimed at capturing biodiversity could reduce the amount of labor and expertise needed to facilitate biodiversity monitoring on farms. Recently, near-infrared spectroscopy demonstrated accurate plant identification up to the species and subspecies level (Robb et al., 2021). Furthermore, optical insect sensors can now identify and continuously monitor insects in the field using their color, wing to body ratio, and wing beat frequency (FaunaPhotonics®). Continuing improvements of near-infrared spectroscopy and infrared sensors may make it increasingly affordable and possible to accurately quantify on-farm vegetative and insect diversity. This will contribute to a better understanding of on-farm ecosystem services like pollination, pest predation and seed predation. The implications for farmers would be to increase their knowledge of on-farm plant and insect populations, which could enhance their ability to make data-informed management decisions that promote conservation objectives.

Conclusion or Summary

Ecological refugia were assessed for their capacity to support biodiversity, enhance beneficial ecosystem services, and benefit food production on three precision farms in Montana. A combination of field surveys, precision agriculture technology and remote sensing data was used to quantify the tradeoff between the conservation benefits and food production impacts that refugia provide. Plant diversity declined significantly with distance from naturally occurring refugia into the crop field and insignificantly from a newly created refuge. Contrary to common assumptions, native plant species richness was highest in the crop field and lowest in refugia, indicating that ecological refugia are not sources of weedy species but hosts of native plant diversity. Insect diversity declined significantly with distance from refugia for all refugia. In addition, fields with naturally occurring refugia had a higher abundance of beneficial insects while the created refuge and control field without naturally occurring refugia had a significantly higher abundance of pest insects. Seed trap data indicated that beneficial weed seed predation services were higher on organic farms while seed predation disservices were higher on a conventionally managed farm. Lastly, crop yield declined significantly with distance from a naturally occurring refugia and increased with distance from a created refuge. A variable importance plot indicated that distance from refuge is the most importance predictor of yield in a random forest model and incorporating distance from refuge in the model raised the R-squared value from 0.57 to 0.70. Future research will assess the feasibility of implementing ecological refugia as a precision conservation practice to enhance biodiversity and maintain yields in agricultural landscapes.

Validation of ecological refugia as a recommended precision conservation practice requires site-specific evidence that they maintain or increase crop yields, decrease inputs, increase beneficial biodiversity, enhance ecosystem services, and increase farm net return. While precision conservation could be used as a farm management tool in the future, further research must be done to ensure that it become a trusted and useful part of the decision-making process. Future research must clarify the relationship between biodiversity and habitat fragments across multiple scales, test the association between on-farm biodiversity and ecosystem services, and explore ways to reduce barriers to adoption of on-farm technology. Pairing precision agriculture with precision conservation provides a novel opportunity to synthesize conservation and agriculture goals and enact multi-objective agricultural solutions.

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