Diversification of Wheat-based Cropping System in the Inland Pacific Northwest Using Winter Pea and Fall Seeded Forage Crops

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Abstract

The dryland production region of the Inland Pacific Northwest (IPNW) is dominated by wheat-based cropping systems. Unusually wet springs and early hot summer weather can negatively impact spring planted crops and these conditions are predicted to become more frequent and intense with climate change. A possible solution is to diversify the existing cropping system by incorporating additional fall seeded crops to cope with unique challenges in the different agroecological regions of the IPNW. Due to cold winters and lack of summer precipitation or access to irrigation, there are very few crop options that can be incorporated into the existing cropping system. Winter pea and forage crops were explored as options for crops that can be grown in the dryland IPNW. Three separate field studies were conducted at each Genesee, ID and St. John, WA during the 2017 to 2021 growing seasons. In the first study, winter pea and fall or spring seeded forage crops were incorporated in place of traditional spring crops or fallow depending on the location and were compared to the standard cropping system for both regions. Inclusion of alternative crops in the rotation at Genesee did not impact the yield of any subsequent crops in the rotations. At St. John, there was a 16 and 12% reduction in winter wheat yield when fallow was replaced with winter pea and spring forage mix, respectively. While the soil moisture content was comparable with that measured under similar crops at Genesee, there was significantly less moisture in the plots with winter pea or spring forage mix compared to fallow at St. John, which ultimately reduced the yield of winter wheat following these alternative crops. Economic analyses of incorporating winter pea and forage mix increased the total net returns of the 3-year rotation by 46 and 62% at Genesee and 66 and 77% at St. John, respectively, compared to the standard rotation at each location. There also was a significant reduction in the use of pesticides and fertilizers.

To complement the rotation study, small scale plots were established to examine best management practices for winter pea production, as well as explore different winter forage crops mixes. The winter pea study included two commercial winter pea cultivars grown with three seeding dates, four seeding rates (65, 87, 108 and 130 seeds m^{-2}), and with and without starter fertilizer. Early seeding of winter pea with a seeding rate of 107 to 130 seeds m^{-2} produced the highest yields at both locations. At Genesee, there was an average reduction of 210 kg ha^{-1} in yield for each week seeding was delayed between the end of September and late October/early November. Application of phosphorus and sulfur starter fertilizers did not have an impact on stand establishment or yield.

In the forage mixture study, different mixtures of winter barley, winter oat, winter pea, crimson clover, balansa clover and radish were evaluated for establishment, forage yield and forage quality. The cultivars of barley, oat and pea utilized were all originally developed for forage production. Fall seeded forage crops evaluated at Genesee and St. John produced an average of 3,995 kg ha^{-1} and 2,832 kg ha^{-1} of dry matter, respectively, and had acceptable forage quality. The crimson clover, balansa clover and radish had very poor or no establishment at either location. In contrast, winter barley and winter pea had the best establishment in the mixtures at Genesee, while winter oat and winter pea were the prominent crops at St. John. The mixture of winter barley and winter pea producing 5,890 kg ha^{-1} at Genesee and the mixture of winter oat and winter pea producing 3,269 kg ha^{-1} at St. John had the highest dry matter production. Spring planted crops in the high precipitation region and fallow in the intermediate precipitation region of the IPNW were successfully replaced by winter peas and forage crops. The results from these studies highlight the benefits of using winter pea and forage crops in IPNW rotations as well as practices that can improve the productivity of both crops. Integration of these fall seeded options will help to develop a more resilient and sustainable cropping system for the intermediate and high precipitation region of the IPNW.

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Dedication

I would like to dedicate this work to my parents, Mr. Madhusudan Baskota, and Mrs. Punnyashila Poudyal Baskota; my beloved wife, Karuna Nepal; and my brother, Sangit Baskota for their continuous love and support throughout this journey. You all have been there with me during all the ups and downs in my life. Without you all and your sacrifices, I would not have been successful.

Table of Contents

Abstract ii

Acknowledgments v

Dedication vi

Table of Contents vii

List of Tables ix

List of Figures xiii

Chapter 1: Literature Review 1

- Overview of the Inland Pacific Northwest 1
- Cropping systems in the IPNW 2
- Climate change impacts in the IPNW 3
- Strategies to improve cropping system resilience to climatic variability 4
- Alternative crops to diversify the existing cropping system in the IPNW 7
- Winter pea 10
- Cover crops 14
- Objectives 21
- References 23

Chapter 2: Integrating winter pea and forage crops into wheat-based cropping systems in the Inland Pacific Northwest 40

- Introduction 40
- Materials and Methods 43
- Results 52
- Discussion 84
- Conclusion 92
- References 93

Chapter 3: Optimizing Winter Pea Production in the Inland Pacific Northwest 101

- Introduction 101

Materials and Methods 104

Results 108

Discussion 125

Conclusion 131

References 132

Chapter 4: Evaluation of fall-seeded forage crop mixtures in the Inland Pacific Northwest 136

Introduction 136

Materials and Methods 141

Results 144

Discussion 165

Conclusion 171

References 172

Chapter 5: Summary and Conclusion 178

Appendix A 181

Appendix B 185

Appendix C 187

Appendix D 196

Appendix E 211

Appendix F 213

List of Tables

Table 1.1. Winter pea cultivar development in the Inland Pacific Northwest. 14
Table 2.1. Crop rotations and sequence of each rotation at Genesee and St. John from 2017 to 2021.46
Table 2.2. Planting and harvest dates of different crops in different rotations at Genesee and St. John from 2017 to 2021.. 48
Table 2.3: Total nitrogen applied to individual plots at Genesee and St. John at planting. 48
Table 2.4. Preplant soil characteristics of the top 30 cm of soil at Genesee, ID from 2017 to 2021... 54
Table 2.5. Preplant soil characteristics of top 30 cm of soil at St. John, WA from 2017 to 2021. 55
Table 2.6. Mean monthly maximum and minimum temperature and total monthly precipitation for Genesee, ID for the growing seasons from 2017 to 2021 57
Table 2.7. Mean monthly maximum and minimum temperature and total monthly precipitation for St. John, WA for the growing seasons from 2017 to 2021. 58
Table 2.8. Yield of all crops in three different rotations at Genesee from 2017 to 2021. 61
Table 2.9. Yield of all crops in three different rotations at St. John in four years from 2017 to 2021.62
Table 2.10. Yield of crops in incremental and business as usual rotation summarized over four years from 2017 to 2021 at Genesee.. 63
Table 2.11. Yield of crops in aspirational and business as usual rotation summarized over four years from 2017 to 2021 at Genesee.. 63
Table 2.12. Yield of crops in all rotations summarized over four years from 2017 to 2021 at St. John. 63
Table 2.13. Dry weight of the winter forage crop harvested at different dates at Genesee from 2017 to 2021.. 68
Table 2.14. Dry weight of the spring forage crop harvested at different dates at St. John from 2017 to 2021.. 68
Table 2.15. Forage quality of winter forage mixes harvested at different dates at Genesee from 2017 to 2021.. 69
Table 2.16. Forage quality of spring forage mixes harvested at different dates at St. John from 2017 to 2021.. 70
Table 2.17. Forage quality of individual crops from the winter forage mix sampled during the last harvest at Genesee during 2018 to 2021.. 71
Table 2.18. Forage quality of individual crops from the spring forage mix sampled during the last harvest at St. John during 2018 to 2021. 73

Table 2.19. Total returns, total annual cost, and total net return for individual crops in incremental, aspirational, and business-as-usual rotations at Genesee using a land area of 1,012 ha. 81

Table 2.20. Total returns, total annual cost, and total net return for individual crops in incremental, aspirational and business-as-usual rotations at St. John using a land area of 1,012 ha................ 82

Table 2.21. Summary of total net returns, quantity of inputs and percentage change from the business-as-usual rotation for incremental and aspirational crop rotations at Genesee using a land area of 1,012 ha. 83

Table 2.22. Summary of total net returns, quantity of inputs and percentage change from the business-as-usual rotation for incremental and aspirational crop rotations at St. John using a land area of 1,012 ha. 83

Table 3.1. Planting dates for winter pea from 2017 to 2019 at Genesee, ID and St. John, WA. 105

Table 3.2. Harvest dates for winter pea from 2018 to 2020 at Genesee and St. John. 107

Table 3.3. Soil characteristics of top 30 cm of soil at Genesee, ID and St. John, WA during three growing seasons from 2017 to 2020. 108

Table 3.4. Mean monthly temperature and total monthly precipitation for Genesee, ID for the growing season from 2017 to 2020.. 110

Table 3.5. Mean monthly maximum and minimum temperature and total monthly precipitation for St. John, WA for the growing season from 2017 to 2020. 111

Table 3.6. Main effects of year, planting date, fertilizer application, seeding rate and cultivar on plant population, vine length and canopy height of winter pea at Genesee, ID and St. John, WA from 2018-2020.. 114

Table 3.7. Main effects of year, planting date, fertilizer application, seeding rate and cultivar on 1,000 seed weight and grain protein content at Genesee, ID and St. John, WA from 2018-2020. 119

Table 3.8. Economic analysis for winter peas seeded at different seeding rates from 2018 to 2020 at Genesee.. 123

Table 3.9. Economic analysis for winter peas seeded at different seeding rates from 2018 to 2020 at St. John.. 124

Table 4.1. Seeding rates (seeds m^{-2}) for the forage crop species planted at Genesee and St. John... 142

Table 4.2. Planting and harvest dates for forage crops at Genesee and St. John from 2018 to 2021.143

Table 4.3. Fresh weight biomass production for all treatments at three different sampling times at Genesee, ID averaged over 2019 to 2021.. 150

Table 4.4. Fresh weight biomass production for all treatments at three different sampling times at St. John, WA averaged from 2019 and 2021.. 151

Table 4.5. Dry matter production for all treatments at three different sampling times at Genesee, ID averaged from 2019 to 2021. 154
Table 4.6. Dry matter production for all treatments at three different sampling times at St. John, WA averaged from 2019 and 2021.. 155
Table 4.7. Forage quality parameters for fifteen different treatments at Genesee, ID averaged across three years from 2019 to 2021.. 160
Table 4.8. Forage quality parameters for fifteen different treatments at St. John. WA averaged across two years from 2019 and 2021. 161
Table 4.9. Average net return per hectare for various forage crop mixtures from 2019 to 2021 at Genesee.. 163
Table 4.10. Average net return per hectare for various forage crop mixtures in 2019 and 2021 at St John.. 164
Table 4.11. Alfalfa guidelines (domestic livestock use and not more than 10% grass) (USDA Hay Quality Designation Guidelines). 169
Table A.1. Summary of application of pesticides to each crop in all rotations along with the application rate as well as price of each chemical. 182
Table A.2. Assumption of field operations and number of each field operation performed for each crop in the rotations... 183
Table A.3. List of Power Units and Machinery Values, Years of Life, Width and Speed of Operations. 184
Table A.4. Assumptions of interest rates, fuel prices and labor rates used for the economic analyses. 184
Table B.1. Analysis of variance (sources were similar crops in different rotations) and p-values of crop growth parameters at Genesee from 2018 to 2021. 185
Table B.2. Analysis of variance (sources were similar crops in different rotations) and p-values of crop growth parameters at St. John from 2018 to 2021... 185
Table B.3. Analysis of variance (sources were harvest dates and crops) and p-values of forage yield and forage nutritive values of winter forage mixes at Genesee from 2018 to 2021. 186
Table B.4. Analysis of variance (sources were harvest dates and crops) and p-values of forage yield and forage nutritive value of spring forage mixes at St. John from 2018 to 2021.......................... 186
Table C.1. Plant height or vine length of crops in the rotation at Genesee, ID from 2017 to 2021. . 187
Table C.2. Plant height or vine length of crops in the rotation at St. John, WA from 2017 to 2021. 188
Table C.3. Grain protein of all crops in three different rotations at Genesee from 2017 to 2021..... 189
Table C.4. Grain protein of all crops in three different rotations at St. John from 2017 to 2021. 190

Table C.5. Thousand seed weight of all crops in three different rotations at Genesee from 2017 to 2021. 191
Table C.6. Thousand seed weight of all crops in three different rotations at St. John from 2017 to 2021. 192
Table C.7: Test weight and flour qualities of winter wheat in three different rotations at Genesee from 2017 to 2021.. 193
Table C.8: Test weight and flour qualities of spring wheat in two different rotations at Genesee from 2017 to 2021.. 193
Table C.9: Test weight and flour qualities of winter wheat in three different rotations at St. John from 2017 to 2021.. 194
Table C.10: Test weight and flour qualities of spring wheat in three different rotations at St. John from 2017 to 2021.. 195
Table E.1. Analysis of variance (Sources: Y- Year, P-Planting date, F-Fertilization, R-Seeding rate, and C- Cultivar) including F-value and level of significance of winter pea growth, yield and quality parameters at Genesee, ID from 2018 to 2020... 211
Table E.2. Analysis of variance (Sources: Y- Year, P-Planting date, F-Fertilization, R-Seeding rate, and C- Cultivar) including F-value and level of significance of winter pea growth, yield and quality parameters at St. John, WA from 2017 to 2020. 212
Table F.1. Analysis of variance including F-value and level of significance of yield and quality of winter forage mixes at Genesee, ID from 2019 to 2021... 213
Table F.2. Analysis of variance including F-value and level of significance of yield and quality of winter forage mixes at St. John, WA from 2019 and 2021.. 213

List of Figures

Figure 2.1. Example plot layout of the study at Genesee in 2018/2019.. 47
Figure 2.2. Plant population of individual components in the winter forage mix at Genesee from 2017 to 2021.. 66
Figure 2.3. Plant population of individual components in the spring forage mix at St. John from 2017 to 2021.. 66
Figure 2.4. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019. 75
Figure 2.5. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020. 76
Figure 2.6. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021. 77
Figure 3.1. Grain yield of winter pea planted at Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location. 116
Figure 3.2. Grain yield of winter pea planted at three different planting times in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location... 116
Figure 3.3. Grain yield of winter pea planted with or without application of 23 kg ha^{-1} of phosphorus and sulfur in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location; ns indicates non-significant... 117
Figure 3.4. Grain yield of winter pea planted at various seeding rates in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location. 117
Figure 3.5. Daily precipitation during growing season and average volumetric water content at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm) at Genesee and St. John from 2018

to 2020. (A-Genesee, 2018; B-Genesee, 2019; C-Genesee, 2020; D- St. John, 2018; E- St. John, 2019; and F- St. John, 2020) in late September planted winter peas. 121

Figure 4.1. Total number of plants per m^2 for all treatments at Genesee pooled over three years at Genesee, ID from 2019 to 2021 [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at $P = 0.05$. 146

Figure 4.2. Total number of plants per m^2 for all treatments at Genesee pooled over two years at St. John in 2019 and 2021 [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at $P = 0.05$. 147

Figure 4.3. Forage fresh weight across three years at Genesee and two years at St. John and summarized fresh weight from 2019 to 2021. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at $P = 0.05$. 149

Figure 4.4. Forage dry weight across three years at Genesee and two years at St. John and summarized dry weight from 2019 to 2021. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at $P = 0.05$. 153

Figure 4.5. Comparison of dry matter production of mixtures when individual crops are either present or absent in the mixtures or monocropping at Genesee, ID from 2019 to 2021. WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish. Bars followed by different letters for a crop are statistically different using Fisher's LSD at $P = 0.05$. 156

Figure 4.6. Comparison of dry matter production of mixtures when individual crops are either present or absent in the mixtures or monocropping at St. John, WA from 2019 and 2021. [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters for a crop are statistically different using Fisher's LSD at $P = 0.05$... 157

Figure 4.7. Dry matter yield comparing the treatment based on the number of crop types in the mixture at Genesee, ID and St. John, WA from 2019 to 2021. Bars followed by different letters for a crop are statistically different using Fisher's LSD at $P = 0.05$.. 158

Figure D.1. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019. 196

Figure D.2. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020. 197

Figure D.3. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021. 198

Figure D.4. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019............. 199

Figure D.5. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020............. 200

Figure D.6. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021............. 201

Figure D.7. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019............ 202

Figure D.8. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020............ 203

Figure D.9. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021............ 204

Figure D.10. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019. 205

Figure D.11. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020. 206
Figure D.12. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021. 207
Figure D.13. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019. 208
Figure D.14. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020. 209
Figure D.15. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021. 210

Chapter 1: Literature Review

Overview of the Inland Pacific Northwest

The Inland Pacific Northwest (IPNW) represents the dryland region of the Pacific Northwest comprised of northern Idaho, southeastern Washington and northeastern Oregon. The IPNW has a semi-arid, Mediterranean climate with cool and moist winters along with warm and dry summers. The average winter temperature in December and January within the IPNW is -1.1°C with minimum as low as -10°C, while the summer maximum temperatures range from 20 to 35°C (Schillinger et al., 2010). There is an elevation gradient across the region with lower elevations and warmer conditions in the western portion of the IPNW and higher elevations along with comparatively cooler conditions in the east. About 70% of the total precipitation in the IPNW occurs between the months of October and March with very little precipitation from July through September (Schillinger et al., 2010). Similar to temperature, there is a strong gradient of mean annual precipitation in the IPNW. The annual precipitation ranges from 25 cm in the west (Central Washington) to more than 50 cm in the east (Northern Idaho) (Papendick, 1996). The dryer regions in the west have sandy soil with low organic matter while eastern Washington and northern Idaho have soil with higher organic matter and relatively high clay content (Schillinger et al., 2010; McClellan et al., 2012). Soils in the IPNW are characterized as Mollisols and Alfisols in northern Idaho while in the central Washington, it is characterized as Aridisols (Papendick, 1996). Localized regions also have soils classified as Entisols, Andisols, and Inceptisols (USDA, 1999). The topography of the region is quite unique. The western part of the region has relatively flat land when compared to the steep hills in the eastern region (Kruger, 2017) with some slopes as steep as 45 degrees.

Cropping systems in the IPNW

The IPNW is considered an important winter wheat (*Triticum aestivum*) producing region in the USA. In 2022, among the 2.35 million ha of crop land in the IPNW, winter wheat was harvested from 672,000 ha in Washington, 280,731 ha in Oregon and 123,145 ha in Idaho (USDA-NASS, 2021). Apart from winter wheat, other crops like spring wheat, barley (*Hordeum vulgare*), spring pea (*Pisum sativum*), chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), canola (*Brassica napus*) and mustard (*Brassica juncea*) are used in the cropping system. Depending on the annual precipitation in the IPNW, 2- to 3-year rotations may be utilized. Based on climatic and edaphic factors, the IPNW region itself is divided into three different agroecological classes (AEC), namely the crop fallow region, transitional region, and annual cropping region (Huggins et al., 2014).

The crop fallow region represents the western part of the IPNW with annual precipitation of about 25 cm. More than 40% of the land in this region is fallow each year (Kruger et al., 2017). It has a typical two-year crop rotation with winter wheat and mechanical annual fallow. Annual fallow is used to allow soils to recharge with water and for there to be adequate soil moisture for crop establishment in the fall. However, in this drier region of the IPNW, mechanical tillage and low precipitation makes the soil vulnerable to wind erosion. This AEC is characterized by poor soil health and lower productivity compared to others along with limited soil moisture, annual weed pressure and intense tillage (Kirby et al., 2017a).

The transitional cropping region has higher precipitation than the crop fallow region, but 10 to 40% of the land is fallowed each year (Kruger et al., 2017). The annual precipitation in this cropping region is about 35 cm and a typical rotation is either a 2-year rotation with winter wheat and fallow or a 3-year rotation with winter wheat, spring wheat and fallow.

However, some farmers also grow yellow mustard, winter and spring canola, and dry spring pea in some localized regions. Annual cropping is occasionally practiced when there is adequate precipitation using one of the spring broadleaf crops mentioned (Schillinger et al., 2010). Comparatively, there is less fallowing in this region than the crop fallow region. Crop productivity is higher and there is less erosion when compared to the crop fallow region. However, both wind and water erosion can be problematic in the transitional cropping region (Kirby et al., 2017a).

The annual cropping region is the wettest region of the IPNW with more than 50 cm annual precipitation. Fallow is used on less than 10% of the agricultural land in this region (Kruger et al., 2017). The cropping system in this region is often a 3-year rotation with winter wheat, spring wheat and a spring broadleaf. With the availability of higher precipitation, there is higher diversification of crops and greater productivity compared to other AECs (Huggins et al., 2015). Some of the challenges within this region are steep slopes, water erosion, winter annual weed pressure, and cold and wet spring conditions that can delay or prevent planting in the spring (Kirby et al., 2017a).

Climate change impacts in the IPNW

Like many other regions of the world, climate change will likely alter the AECs within the IPNW in the coming years. There has been a great deal of seasonal variability in the IPNW over the years. From 1901 to 2012, the mean annual temperature increased by 0.6 to 0.8℃ (Abatzoglou et al., 2014) and it is projected to increase by an additional 3.3 to 5.6℃ by the end of the 21st century (Antle et al., 2013). Another projection shows an increase in annual temperature by 2.7℃ by 2069 (Stöckle et al., 2018). Along with the increased temperature, Abatzoglou et al. (2014) have projected wetter springs and dryer summers in the coming years.

These projected changes in the climate will directly impact agriculture in the IPNW. Warmer winter temperatures will result in a longer freeze free season leading to increased winter runoff and reduced snowpack, and warmer springs will result in early plant maturity. Crops in the summer might be affected by heat stress, high evapotranspiration, and increased drought stress due to warmer and drier conditions. High precipitation in the spring could delay spring planting or result in more land being left fallow due to prevented planting (Pan and Borrelli, 2015). Land use is likely to change following shifts in temperature and rainfall patterns. The size of the annual cropping region will decrease with portions being converted to the transitional cropping region while part of transitional cropping region will become a crop fallow system (Kaur et al, 2017).

Crop productivity would be significantly impacted due to climate change by the end of this century (Stöckle et al., 2010). A reduction in yield of cereals and alternative crops would be observed as the summer becomes increasingly drier and warmer (Kruger et al., 2017). Conversely, there are projections that the yield of small grains in the region could increase due to increased atmospheric carbon dioxide and agronomic adaptation (Stöckle et al., 2010). Estimates suggest a significant increase in winter wheat production by 2090. However, these projections were based on average annual temperatures and do not account for extreme climatic events which will result in reduction of the productivity of crops (Tubiello et al., 2002).

Strategies to improve cropping system resilience to climatic variability

Several cropping system management strategies could be adopted to address climate change issues in the IPNW. These could include using new cultivars with improved resistance to abiotic stresses (Howden et al., 2007). Conservation of soil water with crop residue management (Tao et al., 2017) and reduced tillage (Bista et al., 2017) are also highly important to deal with the eminent dry summer conditions likely to occur in the IPNW in the future. Diversification of the cropping system with integration of alternate crops and other farming activities like inclusion of livestock is another option (Howden et al., 2007; Lin 2011). Some of these alternative crops might include more fall seeded crops like winter pea and winter lentils (Chen et al., 2012) as well as winter cover crops (Lavergne et al., 2021) or forage crops. Establishment of crops in the fall avoids potential wet planting conditions in the spring and fall seeded crops would mature earlier than spring planted counterparts, avoiding the hottest and drier conditions in the summer.

Improving soil health with an integrated approach is one method to mitigate climate change problems (Veni et al., 2020). The USDA-NRCS describes soil health as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans”. Soil health in the IPNW has been deteriorating due to intensive tillage operation with reduction in soil organic matter, reduction in soil microbial diversity and their associated activity and soil erosion. The decline in soil health also can be attributed to intensive cereal crop production with little to no rotation, continuous use of nitrogen fertilizer and limited or untimely precipitation (Awale et al, 2017). Improving soil health is vital and can be achieved by further expansion of minimum or reduced tillage, crop diversification and intensification, and crop residue management. Intensive tillage operations in the field can cause accelerated soil erosion, loss of organic matter, reduced soil structure and lower rates of water infiltration (Bista et al., 2017). Minimum or reduced tillage will increase crop residue on the soil surface and improve soil structure leading to decreased soil loss from erosion and improving the soil physical, chemical and biological characteristics (Bista et al., 2017; Tao et al., 2017).

The crop fallow and transitional cropping regions have low residue in the soil due to lower productivity and less intensive cropping than the annual cropping region. Conversely, the annual cropping region has high crop residue which can become challenging to manage (Tao et al., 2017). In the region of high residue production, mowing the residue is an easy solution but might be unpopular with growers with additional field operation. Sizing the straw at harvest and cutting the straw shorter is a more efficient mechanism of residue management (Siemens and Wilkins, 2006). Another solution is to diversify the crop rotation with crops like peas, lentils, canola, etc. that help reduce the amount of crop residue with increased rate of residue decomposition. Legumes have higher decomposition compared to cereals (Ntonta et al., 2022). While in the transitional and crop fallow region of the IPNW, intensification and diversification of the cropping system will help increase residue biomass and increase soil and water conservation (Schillinger et al., 1999; Gollany et al., 2013; Young et al., 2015). Crop residue management would be a mitigation strategy to deal with the impact of climate change in the agriculture sector (Haas et al. 2022).

The dynamics of weed, insect and disease incidence are important concerns in all agriculture production systems as improper management of these factors significantly reduces crop productivity (Walker, 1983). Climate change will likely affect the distribution, virulence, vigor, and impact of weeds, diseases, and insects (Patterson et al., 1999). Being a dominantly wheat-based cropping region, annual grassy weeds are a serious problem in the IPNW (Young et al., 1996). Additionally, shift from intensive tillage to reduced tillage or direct seeding has drastically changed weed density and composition (Thorne et al., 2007) and created the need to develop new weed control strategies (Dentzman and Burke, 2021). Continuous use of chemicals to control weeds while adopting reduced tillage operations has increased herbicide resistance in the region (Dentzman and Burke, 2021). With the shifting climate, weeds might mature earlier, and this will impact the competition dynamics with the crop species (Burke et al., 2017). Disease and insect management are also critically important for IPNW agriculture. However, the effect of climate change on disease and pest incidence and severity is very unpredictable. Timing of pest incidence, change in the composition of pathogens and insects, length of life cycles of these pathogens and pest can change due to the changing climate and management of these pests could be challenging (Kirby et al., 2017b; Eigenbrode et al., 2017). Regular monitoring is required to predict the impact of these pest and adoption of proper integrated techniques to control weeds, insect and disease is thus needed to minimize the impact of climate change on crop productivity. Increasing the diversity of crops in the cropping system helps break the weed, disease and insect pest cycle in the field (Sharma et al., 2021).

Alternative crops to diversify the existing cropping system in the IPNW

Due to the lack of moisture availability and climatic pattern, there are few crop options available for growers in the region. Additionally, warm season crops cannot be effectively grown in the higher rainfall region due to lack of heat units. Regardless of the precipitation, winter wheat is the major crop in all cropping regions and is the only crop grown in most of the crop fallow region. Winter cereals, spring cereals, spring grain legumes and canola are common components of the cropping system. However, other crops like winter peas, spring and fall planted cover crops or forage crops, triticale, safflower, camelina, and mustard, are some options that have been tested in some parts of the IPNW and could be incorporated in the dryland crop rotations (Kirby et al., 2017a; Schillinger, 2020).

Oilseeds crop like safflower, camelina, and yellow mustard have been grown in the region with mixed success. Safflower is well adapted to the dryland agriculture system with deep tap root system reaching up to 3 m, enabling it to extract water from deeper in the profile (Petrie et al., 2010) and is a heat and drought tolerant crop (Kephart et al., 1990). Better yield response for winter wheat has been observed following safflower in a three-year rotation (winter wheat – safflower – fallow) compared to a three-year rotation of winter wheat - spring wheat -fallow and a two-year rotation of winter wheat – fallow in Ritzville, WA, a summer fallow-winter wheat region (Schillinger et al., 2016). Safflower has multiple uses including animal feed and oil from the plant have numerous industrial uses (Meka et al., 2007). However, the resulting crop residue is low, safflower is less water efficient compared to wheat and other alternative crops in the region, and lack competitiveness with weeds (Petrie et al., 2010; Kirby et al., 2017a).

Yellow mustard is adapted to the hot, dry and dryland conditions of the IPNW region and can use nutrients from deeper in the soil profile (Kirby et al., 2017a). Yellow mustard establishes easily and is highly competitive with weeds and has higher yield potential compared to spring canola (Kirby et al., 2017a). In a study at Moscow and Genesee, ID, yellow mustard was shown to improve the yield for the subsequent wheat crop compared to spring cereals (Guy and Karow, 2009). Yellow mustard has a deep tap root system that can break up compaction layers in the soil and can extract water from deeper soil depths; however, this crop has relatively high-water use, cannot tolerate frost damage, and is susceptible to carryover of certain herbicides (Brown et al., 2005; Kirby et al., 2017a). Similarly, camelina also has tolerance to drought and stress (Kirby et a., 2017a). Spring camelina is more commonly grown, but camelina can be grown as a winter crop and has winter hardiness (Kirby et al., 2017a). In addition, camelina has excellent tolerance to cold as well as hot and dry condition (Ehrensing and Guy, 2008; Hulbert et al., 2012; Kirby et al., 2017a). However, camelina is difficult to establish as it requires shallow planting and crust free soil after planting for sufficient emergence and does not have any herbicide labelled for weed control (Kirby et al., 2017a).

Aside from more commonly grown wheat and barley, another small grain grown in the region is triticale. Triticale is usually grown as animal feed as it is highly nutritious (Zhu, 2018) and does not have any reports of winter kill in the IPNW (Schillinger, 2020). Triticale is less susceptible to diseases and pests and provides excellent competition for weeds (Kirby et al., 2017a). Triticale also has higher yield potential than does wheat regardless of growing conditions (Bassu et al., 2011). In the low precipitation region of the IPNW, winter triticale produced higher grain yield using less water and provided better winter water storage efficiency compared to winter wheat (Schillinger, 2020). Additionally, winter triticale produces higher root and shoot biomass than wheat, which will potentially improve soil health and protect soil from erosion (Kirby et al., 2017a). However, the price of triticale in the market is not competitive with wheat (Kirby et al., 2017a; Schillinger, 2020). Another issue is that there have been concerns among growers that triticale may retain some inherent dormancy and pose a contamination risk for subsequent cereal crops, but there is not currently scientific evidence to support this concern (Schillinger, 2020).

Sunflower is drought tolerant (Norwood, 1999) and can be grown in dryland agriculture settings. This crop can extract water and nutrients from deeper depths due to its extensive root systems (Stone et al., 2001). While sunflowers do not have the best drought tolerance, they have acceptable yield when other crops are heavily impacted by drought (Robinson, 1978). Although it has attributes compatible with dryland management, water depletion for subsequent crops in the rotation may be problematic (Jones, 1984; Hattlendorf et al., 1988).

Additionally, sunflower production is significantly impacted by temperature and growing degree days and if planted late, the yield and oil yield is reduced (Kaleem et al., 2011).

Although these crops can potentially be grown in the region, limited market access and lower prices for these crops pose a challenge to growers. Additionally, the yield of these crops is highly variable across years and might not be economically attractive to the growers (Schillinger, 2020). In addition, spring crops discussed above are subject to damage due to heat stress during flowering and grain filling stages (Schillinger, 2020) and do not provide much ground cover during the winter months, exposing the soil to erosion (Kirby et al., 2017a). Winter pea and fall planted forage crops could be excellent options to incorporate into the intermediate and high precipitation region of the IPNW as there may be marketing opportunities for these crops and variable spring seeding conditions could be avoided.

Winter pea

Pea, a member of the *Fabaceae* family, is an annual cool season crop that was domesticated about 10,000 years ago (Mikić, 2012). Pea is one of the most cultivated legumes along with soybean, groundnut, and beans (Husle, 1994). The origin of peas can be tracked back to Abyssinia and Afghanistan and spread around the regions of Europe and Asia (Cousin, 1997). Domestication of peas occurred in the Near East before 7,000 to 6,000 BC with evidence of well-preserved carbonized pea discovered in northern Iraq and southeast Turkey (Zohary and Hopf, 1973). Peas are adapted to a wide range of climatic conditions, ranging from semiarid to temperate maritime climates (Karkanis et al., 2016). Raveneau et al. (2011) reported the minimum temperature required to germinate peas to be -1.1°C and the optimum temperature for pea growth to be 20°C. Temperatures between 28 to 31°C after flowering significantly reduces the yield of peas (Jeuffroy et al., 1990). If planted in compacted soil, the productivity will be negatively impacted (Vocanson and Jeuffroy, 2008). Winter peas are adapted to the dryland production system where winter wheat is usually grown (McGee et al., 2017). While peas can be grown in a wide range of soil types, they perform best on light textured, well drained and fertile soil (Hartmann et al., 1988; Elzebroek and Wind, 2008). Water-logged conditions are not suitable, therefore heavy, and poorly drained soils should be avoided (Endres and Kandel, 2021). Furthermore, saturated soil conditions along with cool weather favors Pythium root rot and cause yield reduction (Kalil et al., 2020).

Peas are high in nutrients and have many uses including as animal feed, human consumption, cover crops, and green manure (Pavek, 2012). Immature green peas are consumed directly or can be stored by freezing or canning while dry peas are used for soups and other dishes (Karkanis et al., 2016). Peas are highly nutritious and contain high protein content, minerals, carbohydrates, and fiber (Gueguen and Barbot, 1988; Świątecka et al., 2010; Dahl et al., 2012; Karkanis et al., 2016). Peas contain about 14 to 31% crude protein among which 15 to 25% are albumins, 49 to 70% are globulins, 11% are glutelin, and 5% are prolamin (Chakraborty et al., 1979; Alonso et al., 2000; Alonso et al., 2001; Cai et al, 2002; Tzitzikas et al., 2006; Guleria et al., 2009). In addition, peas contain 86 to 87% total digestible nutrients and compared to soybeans have a lower concentration of trypsin inhibitors, a protein that reduces the biological activity of trypsin and makes it unavailable to bind with other proteins for the digestion process, making pea an ideal feed for livestock (Endres and Kandel, 2021).

Pea production in the IPNW has been reported as early as 1915 in the eastern Palouse region (Freeman, 1943). Records show that Austrian winter pea was used as a green manure or cover crop in the region in 1932 (Slinkard and Murray, 1979). The Austrian winter pea cultivar Fenn was the first release for the IPNW region (Murray and Slinkard, 1973) (Table

1.1). The reported area planted to winter pea in the IPNW is not distinguished from spring pea. In 2021, 27,500 and 11,330 ha of land was used for dry edible pea production in Washington and Idaho, respectively (USDA-NASS, 2021). However, most of this land is currently in spring pea production.

Winter pea has several advantages over spring legumes, especially spring pea. Winter pea typically outyields spring peas by as much as 300% (McGee et al., 2017). Additionally, winter pea produces higher above and below ground biomass, resulting in improved ground cover compared to spring pea (Chen et al., 2006). Winter pea also has better weed competitiveness as well as early flowering and maturity compared to spring pea (Vocanson and Jeuffory, 2008). Winter pea also provides soil cover during winter months, reducing soil erosion. Winter pea can assist in reducing weed, disease, and pest incidence in subsequent cereal crops (McGee et al., 2017). Winter pea is a relatively low input crop and can fix atmospheric nitrogen in symbiosis with *Rhizobium leguminosarum* (McGee et al., 2017). Koenig (2013) estimated that 23 kg ha^{-1} of residual nitrogen will be available to a subsequent cereal crop with 2800 kg ha^{-1}grain production of winter pea. Pea has better water use efficiency compared to other legumes with higher biomass production in semiarid dryland conditions (Biederbeck and Bouman, 1994) and uses less water than winter wheat in similar dryland condition (Schillinger, 2020).

Good winter hardiness is a key trait on any fall crop intended for production in the IPNW. In winter pea, winter hardiness is a combination of three distinct factors including acclimation, tolerance and avoidance (McGee et al., 2017). Winter peas acclimate in the autumn as the temperature lowers, photoperiod shortens and quality of light changes (McGee et al., 2017). This acclimatization can be related to accumulation of sugar in roots, stems, and leaves. Cysteine and methionine production by peas is related to the frost tolerance in peas (Legrand et al., 2013). Furthermore, a delay in shift from vegetative to reproductive phase helps winter peas avoid harsh winter conditions (McGee et al., 2017). In addition, the growth habit of winter peas with short internodes is also related with winter hardiness (Markarian and Andersen, 1966; Andersen and Markarian, 1968; Huggins and Pan, 1991).

Guy (2016) has highlighted the suitability of winter pea in the all the AECs of the IPNW and it is considered an excellent crop for rotation with cereals. Due to larger seed size compared to cereal crops, winter pea can be planted as deep as 15 cm below the soil surface, which is beneficial to reach stored water in the crop fallow region (Schillinger, 2020). Vocanson and Jeuffory (2008) also suggest that winter peas are less vulnerable to abiotic stresses compared to spring peas.

Both public and private pea breeding programs in the IPNW are continually developing superior cultivar of winter pea that are well adapted to the region with food grade quality, and with improved winter hardiness for food, feed and forage uses. All winter pea varieties developed before 2017 were grown for either animal feed or forage and cover crop purposes. In 2009, there was a change in regulation which resulted in categorization of peas based on characteristics rather than the time when they are planted (USDA-GIPSA, 2009). Therefore, since 2018 at least six cultivars of winter peas were developed that meet the criteria to be sold into the food market (Table 1.1). Food grade peas have a clear seed coat and hilum, white flowers, larger seed size, and better palatability than previous cultivars. The food grade winter peas can get a premium as high as 50% compared to feed or forage grade peas (McPhee and Muehlbauer, 2007; McGee and McPhee, 2012).

Table 1.1. Winter pea cultivar development in the Inland Pacific Northwest.

Varieties	Released Year	Type	Developed by
Fenn	1972	Austrian	Idaho AES†
Melrose	1977	Austrian	Idaho AES
Glacier	1984	Austrian	Idaho AES
Granger	1996	Austrian	USDA-ARS, Washington AES
Whistler	2005	Feed	ProGene LLC
Specter	2006	Feed	USDA-ARS, Washington AES
Windham	2006	Feed	USDA-ARS, Washington AES
Icicle	2011	Forage	ProGene LLC
Lynx	2012	Forage	USDA-ARS, Washington AES
Koyote	2014	Food/split pea	ProGene LLC
Blaze	2017	Feed	ProGene LLC
Keystone	2018	Food	ProGene LLC
Vail	2019	Food	ProGene LLC
Goldenwood	2019	Split pea/ingredient	ProGene LLC
Mica	2022	Food	USDA-ARS, Washington AES
Dint	2022	Food	USDA-ARS, Washington AES
Klondike	2022	Food	USDA-ARS, Washington AES

†AES-Agriculture Experimental Station

Cover crops

A cover crop is defined as a plant that is used primarily to slow erosion, improve soil health, enhance water availability, smother weeds, help control pests and diseases, increase biodiversity, and bring a host of other benefits to a farm (Clark, 2019). Hartwig and Ammon (2002) described cover crops as plants grown during dormant period of the rotation and planted after a cash crop and terminated before planting subsequent cash crop. While popularity has increased in recent years, cover crops are not a new concept. Cover crops have been grown across the world since the early 1900s as a part of a cropping system. Pieters and McKee (1938) reported using cover crops for reducing soil erosion in North Carolina and maintaining soil organic matter in New Jersey in the 1930s. There has been documentation of the use vetch, rye or oats as cover crops in the orchards in the Pacific Northwest in the early 20th century (Morris, 1913).

There have been numerous reported benefits of cover crops across the world in various agroclimatic conditions. Improving soil infiltration, scavenging of nutrients, increasing soil organic matter, improving the water holding capacity of the soil, retaining of nutrients for subsequent crops and improving the overall property of soil (Fageria et al., 2005; Steenworth and Belina, 2008; Duncan et al., 2022) are few of the numerous benefits. Additionally, with the use of crops containing fibrous roots, soil erosion can be significantly reduced (De Baets et al., 2011). There is also increased ground cover, nitrogen uptake, nitrogen fixation, C/N ratio and residue quality with the use of cover crops (Ramirez-Garcia et al., 2015). Use of crops like pea, clover and rye help reduce the leaching rate by 80% compared to fallow plots (Kaye et al., 2019).

Apart from improving physical and chemical properties of soil, use of cover crops has additional biological benefits. Cover cropping is an ecofriendly tool to control weeds. Several experiments have shown that cover crops help suppress weed and reduce weed densities (Osipitan et al., 2018; Nichols et al., 2020; Restuccia et al., 2020), however, other weed management tools such as chemical control or tillage must be integrated to support the suppression provided by cover crops (Fernando and Shrestha, 2023). The biological health of the soil is also improved with the use of cover crops along with an increase in soil enzyme activity and fungal abundance (Thapa et al., 2021). Use of cover crops was shown to increase soil microbial diversity and microbial activity (Kim et al., 2020). As a result of cover crop production, there can be a significant increase in nematode communities, higher organic matter conversion and may improve or maintain soil health (Eshel et al., 2021). Growing cover crops in a no tillage system seemed to reduce production costs compared to a conventional tillage operation with chemical weed control, while significantly reducing the risk of accelerated soil erosion (Jacobs et al., 2022).

Cover crops as forage

In addition to planting cover crops for the advantages listed above, they have also been planted with the intent of using the resulting biomass for animal feed. When used as a forage crop, many of the benefits of cover crops are realized while also realizing an immediate economic return with the sales of hay or grazing livestock (Clark, 2019; Obour et al., 2021). Plastina et al. (2018) has reported a positive net return from cover crops when they were grazed compared to just used as a cover crop. Crops that are used as a cover crop can also be used as part of forage crop mixtures (Hansen et al., 2013), but the nutritive value of the forage crop will differ depending on type of the crop species, management of crops, edaphic condition, climatic condition, and maturity stage of these crops (Moore et al., 2020). Furthermore, use of these crops helps in reducing the overaccumulation of nutrients in the soil by utilizing nutrients already present in the soil and converting them into high quality forage (Martin et al., 2017). Krueger et al. (2012) reported that forage crops can remove residual nitrogen and phosphorus from the soil and produce high quality forage for livestock.

While a single crop can be used as a forage crop, there are multiple crop species that can be planted in mixtures to be used as forage crops. Crops like wheat, annual ryegrass, triticale, sudangrass, forage sorghum, millet, oats, barley, pea, vetch, sunflower, radish, mustard, canola, turnip, clovers, alfalfa, flax, lentils and many more can be used as forage crops. Two important factors in forage production are forage yield and forage quality. Grass crops tend to have high forage yield with rather low forage quality. However, legumes and broadleaves generally have lower forage biomass production but have superior nutritive value compared to grass species (Ball et al., 2001).

Forage nutritive value

Forage nutritive value is the amount of nutrition that can be derived from a feed and the presence or concentration of any toxic compounds that could reduce animal performance or threaten animal health. The quality of the forage along with the amount that animals consume can help to understand and develop a ration plan for animals (Hancock et al., 2014). Forage nutritive value can be measured using various parameters such as acid detergent fiber (ADF), neutral detergent fiber (NDF), crude protein (CP), dry matter digestibility (DDM), dry matter intake (DMI), crude protein (CP), lignin, and relative field value (RFV).

The ADF is comprised of cellulose, lignin, and minerals/silica in a forage sample. ADF is the least digestible component of the sample as higher ADF decreases the digestible energy (Saha et al., 2010). In a forage sample, higher ADF is not favorable. NDF refers to the cell wall components which include cellulose, hemicellulose, lignin, silica, tannins and cutins in a forage sample, representing the total fiber composition of the forage sample (Saha et al., 2010). As NDF in a forage sample increases, the forage quality declines.

DDM and DMI are measures of dry matter in the forage sample and are estimated using ADF and NDF. The DDM is an estimate of the portion of dry matter that is digested by the animal at a specified feed intake. The estimate is made by using the calculations: %DDM = 88.9- [0.779 * %ADF] (Saha et al., 2010). Similarly, DMI is the estimate of total dry matter consumed by the animal. This also cannot be analyzed in the lab and is estimated using the

NDF value: %DMI (of body weight) = 120/NDF. As NDF increases, the dry matter intake by the animal decreases (Saha et al., 2010).

The CP accounts for the total nitrogen in a forage sample which includes both true protein and non-protein nitrogen, with higher CP preferable for feed. The total N in a forage sample is determined and multiplied by 6.25 to estimate the total crude protein content (Saha et al., 2010). Lignin is a major structural component of a plant cell wall. It cannot be digested by animals and as its concentration increases, the quality of a forage sample declines (Saha et al., 2010).

The RFV is an index used to rank forage samples based on their overall nutritive value. It is based on comparing nutritive value to a fully bloomed alfalfa hay (ADF 41% and NDF 53%) whose RFV is 100. Forage samples with RFV higher than 100 are considered good quality while those with a value below 100 are considered lower quality (Saha et al., 2010). The RFV is calculated using the formula: RFV = DDM (% of DM) × DMI (% of BW) ÷ 1.29, where DM is dry matter and BW is body weight.

Factors affecting yield and quality of forage crops

Several factors affect the quantity and quality of forage crops. Crop genotype, crop maturity, season of the harvest/grazing, and management are some of the important aspects that influence the forage quality and intake of the forage by animals (Adesogan et al., 2012). Several climatic, environmental, and edaphic characteristics also impact forage yield and quality (Moore et al., 2020). Selection of appropriate species and proper agronomic management and are also significant factors to develop a successful forage production operation.

There are several crop species that can be used as a forage crop in monocrop or a multispecies mix. Crops are categorized into warm and cool season crops. Warm season crops include rice, corn, millet, sudangrass, sunflower, soybean, etc. while cool season crops include major cereals (wheat, oat, barley, etc.), brassicas (canola, turnip, radish, etc.) and legumes (peas, vetch, crimson clover, etc.). Cool season crops can tolerate frost and low temperature, while warm season crops require higher temperature and higher light intensities. Nutritive value differs between cool and warm season grasses, where cool season grasses have higher nutritive value than do warm season grasses (Adesogan et al., 2012). However, a proper mixture of crops will have higher forage yield and quality than single species (Wortman et al., 2012).

Legumes usually have higher nutritive value when compared to grasses and can maintain their nutritive value as they mature (Minson, 1990). Conversely, dry matter production is usually higher with grass species compared to legumes (Adegosan et al., 2012). Legumes have a high concentration of nitrogenous compounds (Andrzejewska et al., 2017) and are easily digested while grasses have high concentration of fibers and are comparatively less digestible (Twidwell et al., 1988). Legumes have higher intake by animals compared to grasses, yet the total digestible nutrients among legumes and cool season grasses are similar (Adesogan et al., 2012). Brassica crops are also useful forage crops with high nutritive value compared to grasses (Smart et al., 2004). Forage mixtures need to be properly formulated to obtain high biomass production along with high nutritive value.

Different parts of the plant vary significantly in their contribution to forage quality. Leaves are considered more nutritive compared to the stems (Moore et al., 2020). Stems contain tissues that have higher concentration of lignin and have low digestibility in animals

(Moore and Jung, 2001). Also, there is a difference in composition in plant parts when comparing grasses and legumes. Furthermore, the growth stage of plants also plays a vital role in the nutritive value. Less mature plants have higher nutritive value, although the yield is comparatively lower (Adesogan et al., 2012). As plants get older, there is an accumulation of stem tissue and the amount of lignin is increased in the plants, which reduces the forage quality.

The conditions in which the crops are growing significantly affect the nutritive value of the forage crops. Some of these factors include adaptation, temperature, moisture, light and soil conditions (Moore et al., 2020). Warm season crops need about 30 to 35℃ for optimum production and require at least 10℃ for growth, but cool season crops can thrive as low as 4℃ and can have optimum growth around 20℃ (Cooper and Taiton, 1968; Nelson and Moser, 1994). Temperature also plays a key role in determining forage quality. High temperature increases transpiration and ultimately reduces the forage quality. Crops harvested at lower temperature have higher forage quality (Fick et al., 1988). Similarly, moisture plays a vital role in the determination of forage quality with higher moisture leading to better forage quality (Moore et al., 2020). Water stress or water logging both lead to plant stress and will negatively impact forage quality (Moore et al., 2020). Forage crops grown during drought coincided with high nitrogen amount in soil result in toxic amount of nitrate in forages, which is detrimental to animals (Cash et al., 2002). The spectral quality of light and duration of light also impacts the forage quality, by either enabling or delaying the transition into the reproductive phase in crops (Moore et al., 2020). Additionally, the nutritional status of the soil impacts the growth and quality of the forage crops. Forage crop mixture primarily consisting of grasses grown in a nutrient depleted soil had improved yield and forage quality when fertilized (Malhi et al., 2004).

The agronomic management of a forage crop is crucial to maximizing establishment and biomass production, particularly when working with a multispecies mix. Factors such as seeding depth (White et al., 2015), seeding rate (Karadağ and Büyükburç, 2003), seeding date (Wyffels et al., 2022), termination date (Moore et al., 2020), and storage of the forage crops (Moore et al., 2020) can influence the yield and quality. Seeding depth is highly important when seeding in mixtures. Larger seeds need to be planted deeper while the smaller seeds like clover and brassicas need to be planted shallower for proper germination and establishment (White et al., 2015). Similarly, the proper proportion of seeds in a mixture needs to be determined to maximize the success of each component of a mix. In a mixture of warm and cool season crops, the forage availability during latter part of the season might be affected due to competition between crop species (Wyffels et al., 2022). But inclusion of both crop types helps improve ground coverage and alleviate soil erosion (Sanderson et al., 2018). Additionally, termination or swathing of these crops at proper crop maturity level is important to attain high forage biomass with superior nutritive value (Moore et al., 2020). If grazing directly, pastures should be maintained with a leafy canopy, rotation of land should be done for continuous grazing and animals should be put into the fields at the proper growth stage of the crops before flowering (Adesogan et al., 2012). If hayed, proper care should be taken to maintain the forage quality of the hay by preserving the hay from rain damage using a barn or a tarp (Adesogan et al., 2012). Reducing moisture to less than 15% is highly critical to preserve the hay quality (Adesogan et al., 2012).

Objectives

To address climate variability and impending climate change, diversification of the existing cropping system in the annual and transitional cropping region of the IPNW is necessary. More of a focus on fall seeded crop options would reduce the risk of unusually wet or dry conditions in the spring that might impact planting. Fall seeded crops would also mature earlier in the season than spring planted crops, allowing them to escape some of the hotter summer weather. Winter pea and forage crops are potential crops that can be integrated into our crop rotation in the region. However, the rotational impact of these crops has not been well studied in the IPNW. Furthermore, agronomic strategies for management of winter pea and forage crops need to be optimized to maximize the productivity and economic return for these alternative crops. The specific objectives of this study are 1) to identify the agronomic effect of diversifying the wheat-based cropping system by incorporation of winter pea and forage mixes; 2) to identify the change in farm profitability using diversified or intensified crop rotations; 3) to identify the best agronomic management practices for winter pea with regard to planting date, seeding rate and fertilizer requirement; and 4) to examine the productivity and forage quality of fall seeded forage crops in various mixtures.

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Chapter 2: Integrating winter pea and forage crops into wheat-based cropping systems in the Inland Pacific Northwest

Introduction

The Inland Pacific Northwest (IPNW) is a dryland cropping region that is dominated by a wheat-based cropping system with winter wheat as the main crop. The Pacific Northwest accounts for 13% of the land area planted to wheat production in the United States and has the highest winter wheat and spring wheat yields compared to other wheat growing regions of the country (Vocke and Ali, 2013). Idaho and Washington produced about 3.3 billion kg and 5.1 billion kg of winter wheat from 435,846 ha and 918,636 ha of land, respectively (USDA-NASS, 2021). The region is diverse regarding precipitation with approximately 25 cm annual precipitation in central Washington, increasing to more than 50 cm annual precipitation in northern Idaho. Based on the climatic and edaphic factors, the region is divided into three distinct agroecological classes: 1) crop fallow region with about 25 cm annual precipitation (typical rotation of winter wheat – fallow), 2) transitional region with about 35 cm annual precipitation (typical rotation of winter wheat – spring wheat – fallow), and 3) annual cropping region with more than 50 cm annual precipitation (typical rotation of winter wheat – spring wheat – spring legume/brassica) (Huggins et al., 2014).

Each cropping region in the IPNW struggles with unique challenges. Availability of moisture is the major concern in the crop fallow region, which has required farmers to rely on fallowing every other year with very limited options to diversify with alternative crops. In the transitional region, fallow is usually practiced in one out of three years, increasing the risk of soil erosion, and this region also has been mostly limited to cereal crops. The high precipitation, annually cropped regions rarely employ fallow, but also can have moisture problems such as abnormally wet springs which can delay planting. Excessive spring precipitation can further lead to soil erosion and contribute to increased soil compaction.

In addition to existing challenges, climate change will greatly impact agriculture production in the IPNW. The annual mean temperature has increased by 0.6 to 0.8°C from 1901 to 2012 (Abatzoglou et al., 2014) and projections suggest that the mean annual temperature will rise by 3.3 to 5.6°C by the end of this century (Antle et al., 2013). (Stöckle et al. (2018) projected that by 2040 to 2069 the annual temperature will increase about 2.7°C. Apart from the rise in temperature, the spring will get wetter, and summer will be drier (Abatzoglou et al., 2014; Pan and Borrelli, 2015). These various changes in the weather will impact the cropping system significantly with earlier maturity of winter crops and delay in spring planting. Diversification of these dryland wheat-based systems is a necessity to develop a resilient cropping system to deal with climate fluctuations and seasonal variability. However, due to limitations imposed by temperature and precipitation patterns, there are few alternative crops that can be successfully produced in the region. Incorporation of winter peas and fall-seeded forage mixes into the existing cropping system could be a potential approach to cope with the changing environment and reduce the reliance on spring seeding.

Winter pea has the potential to be incorporated into all the cropping regions of the IPNW. In the intermediate precipitation region, it will help in replacing fallow, reducing the risk of soil erosion and improving soil organic matter and productivity. In the high precipitation region, winter pea could diversify fall planting options and would avoid adverse planting conditions in the spring. The yield of winter pea is typically higher than that of spring pea (McGee et al., 2017) and other spring legumes and produces more above and below ground biomass compared to a spring pea (Chen et al., 2006). Apart from the yield benefits, winter pea is earlier maturing, more competitive against weeds, and provides better ground cover (Kirby et al., 2017) compared to spring pea. Due to the larger seed size, pea can be planted deeper (up to 15 cm deep) which can be important to reach soil moisture, especially in the low precipitation region of IPNW (Schillinger, 2020). Deeper seeding depths of winter pea may not be advantageous in the annual cropping region.

A fall or spring planted forage mix is another option that can be incorporated into the dryland IPNW. Forage mixes are comparatively low input crops and if managed properly, could produce adequate forage biomass for grazing or haying. Incorporating forage mixes increase above and below ground biodiversity, help control soil erosion (Kaspar and Bakker, 2015), and improve physical, chemical, and biological characteristics of the soil (Fageria et al., 2005). Haying or grazing forage crops has the potential to increase net returns for growers (Plastina et al., 2018). If used to replace fallow in the intermediate precipitation region, forage crops may provide an additional source of income to the growers in that region. Several crop species can be used to develop a mix to produce forage crops. However, selection of appropriate crops is important as all crops do not have similar forage qualities or winter hardiness. A proper mixture of legumes, brassica and cereals would be ideal for higher yield as well as maintaining superior forage quality (Farney et al., 2018).

Production of winter pea is gaining in popularity in recent years with increased acreage (Schillinger, 2017). Growers, particularly those with livestock, are also becoming more interested in producing forage crops to diversify their rotation. Limited information is available on the rotational effects of these crops in the intermediate and high precipitation region of the IPNW. The objectives of this study were (i) to identify the agronomic effect of diversifying the wheat-based cropping system in the intermediate and high precipitation region of IPNW by incorporation of winter pea and forage mixes, (ii) to detect the difference in moisture use by various crops in the diversified crop rotations, and (iii) to identify the impact of a diversified crop rotation on farm profitability.

Materials and Methods

Location

A four-year field study (2017-2021) was conducted at Genesee, ID (46.514823°, -116.824010°; 841 m elevation) and St. John, WA (47.119208°, -117.541318°; 622 m elevation). Soil in Genesee was a Naff-Palouse complex (order: Mollisols; sub-order: Xerolls; great group: Argixerolls) and in St. John was a Mondovi silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) (Web Soil Survey). Both sites were managed using direct seeding throughout the study from 2017 to 2021. The site at Genesee has been in direct seeding 16 years before the initiation of the study while the site at St. John has been in direct seeding since 2013 (personal communication). In the year prior to the initiation of the study, the field in Genesee was planted to chickpea and in St. John was planted to winter wheat.

Field Trials

The typical three-year rotation (winter wheat – spring wheat – chickpea) at Genesee was diversified by 1) replacing chickpea with winter pea or 2) substituting a winter forage mix for spring wheat. The typical rotation at St. John is a three-year rotation of winter wheat – spring wheat – fallow. Here, the cropping system was diversified and intensified as fallow was replaced by either winter pea or a spring forage mixture. The three different rotations at Genesee and St. John are summarized in Table 2.1. The diversified rotation with winter pea was designated as the “incremental” rotation while the rotation including forage mix (winter mix at Genesee and spring mix at St. John) was named the “aspirational” rotation. Each trial was laid out in a randomized, complete block design with five replications. These two incremental and aspirational approaches have been discussed by Nelson et al. (2007) and USDA (2012) for the development of a resilient cropping system and sustainable agriculture. Within each block, there were a total of nine treatments, with each of the crops in the three rotations being planted in each year (Figure 2.1). The crop sequence for each year is shown in Table 2.1. Each plot was 9.8 m wide and 23 m deep.

Seeds were treated with appropriate fungicide and insecticide prior to planting following best management practices. Additionally, the legume seeds (winter pea and chickpea) were inoculated with rhizobium inoculant immediately before seeding. The cultivars of each crop and their respective seeding rates that were used for both locations are winter wheat cv Jasper (248 seeds m^{-2}), spring wheat cv WB9518 (301 seeds m^{-2}), winter pea cv Windham (108 seeds m^{-2}), and chickpea cv Billybeans (54 seeds m^{-2}). The winter forage mix used at Genesee included winter wheat (34 kg ha^{-1}), sudangrass (8 kg ha^{-1}), winter lentil (6 kg ha^{-1}), flax (1 kg ha^{-1}), winter oat cv black (22 kg ha^{-1}), crimson clover cv Dixie (2 kg ha^{-1}), winter pea cv Icicle (17 kg ha^{-1}), turnip cv purple top (0.6 kg ha^{-1}), and radish cv daikon (0.6 kg ha^{-1}). Additionally, there was a change in winter forage mix at Genesee after the first year. Winter wheat was included only in 2017/2018 to simulate volunteer winter wheat that was present in subsequent years of the study as previous crop in the land at Genesee was planted into chickpea. Sudan grass, winter lentil and flax were used only during the 2017-18 season and winter oat was added during the 2018-19, 2019-20 and 2020-21 seasons. At St. John the spring forage mix consisted of spring barley cv Haybet (22 kg ha^{-1}), spring oat cv Everleaf 114 (22 kg ha^{-1}), spring pea cv Journey (44 kg ha^{-1}), sunflower (1 kg ha^{-1}), and turnip cv purple top (1.5 kg ha^{-1}).

Crops were planted using the standard planting dates for each region, with planting dates varying between years depending on soil conditions (Table 2.2). Plots were planted using a custom-built AgPro Conservation Drill (AgPro Inc., Lewiston, ID) equipped with eight Bourgault hoe type openers with paired rows (Bourgault Tillage Tolls Ltd., Saint Brieux, SK, Canada) spaced 30.5 cm apart. Prior to seeding each season, soil samples were collected for each treatment to a depth of 120 cm at 30 cm increments to check the fertility status of the soil. The soil samples were analyzed at Northwest Ag. Consultants, Kennewick, WA. Fertilizer requirements for spring wheat (Mahler and Guy, 2006) and winter wheat (Mahler, 2014) were calculated using the northern Idaho fertilizer guide based on projected yield goal for each crop and location. In addition to nitrogen (Table 2.3), 34 kg ha^{-1} of phosphorus and 23 kg ha^{-1} of sulfur were applied to all plots of winter wheat and spring wheat. The fertilizer was banded below and adjacent to the seed through the opener and consisted of solution 32, ammonium phosphate and thiosul. Before planting, each site was sprayed with glyphosate at 2.34 L ha^{-1} to eliminate volunteer crops and weeds. Pre- and post-emergence herbicides were applied to all crops using best management strategies consistent for the region. When necessary, fungicide applications were made to control Ascochyta blight on chickpea and insecticide applications were necessary for pea weevil (*Bruchus pisorum*) management in winter pea. Daily temperature and precipitation were monitored at each site using weather stations (Campbell Scientific, Inc).

Table 2.1. Crop rotations and sequence of each rotation at Genesee and St. John from 2017 to 2021.

Location	Rotations	2017/2018	2018/2019	2019-2020	2020/2021
Genesee	Incremental (WP)	WP[†]	WW	SW	WP
		WW	SW	WP	WW
		SW	WP	WW	SW
	Aspirational (FC)	CP	WW	WFC	CP
		WW	WFC	CP	WW
		WFC	CP	WW	WFC
	Business as Usual	CP	WW	SW	CP
		WW	SW	CP	WW
		SW	CP	WW	SW
St. John	Incremental (WP)	WP	WW	SW	WP
		WW	SW	WP	WW
		SW	WP	WW	SW
	Aspirational (FC)	SFC	WW	SW	SFC
		WW	SW	SFC	WW
		SW	SFC	WW	SW
	Business as Usual	Fallow	WW	SW	Fallow
		WW	SW	Fallow	WW
		SW	Fallow	WW	SW

[†] WP-winter pea; CP-chickpea; WFC-winter forage crop; SFC-spring forage crop; FC-forage crop; SW- spring wheat; and WW- winter wheat

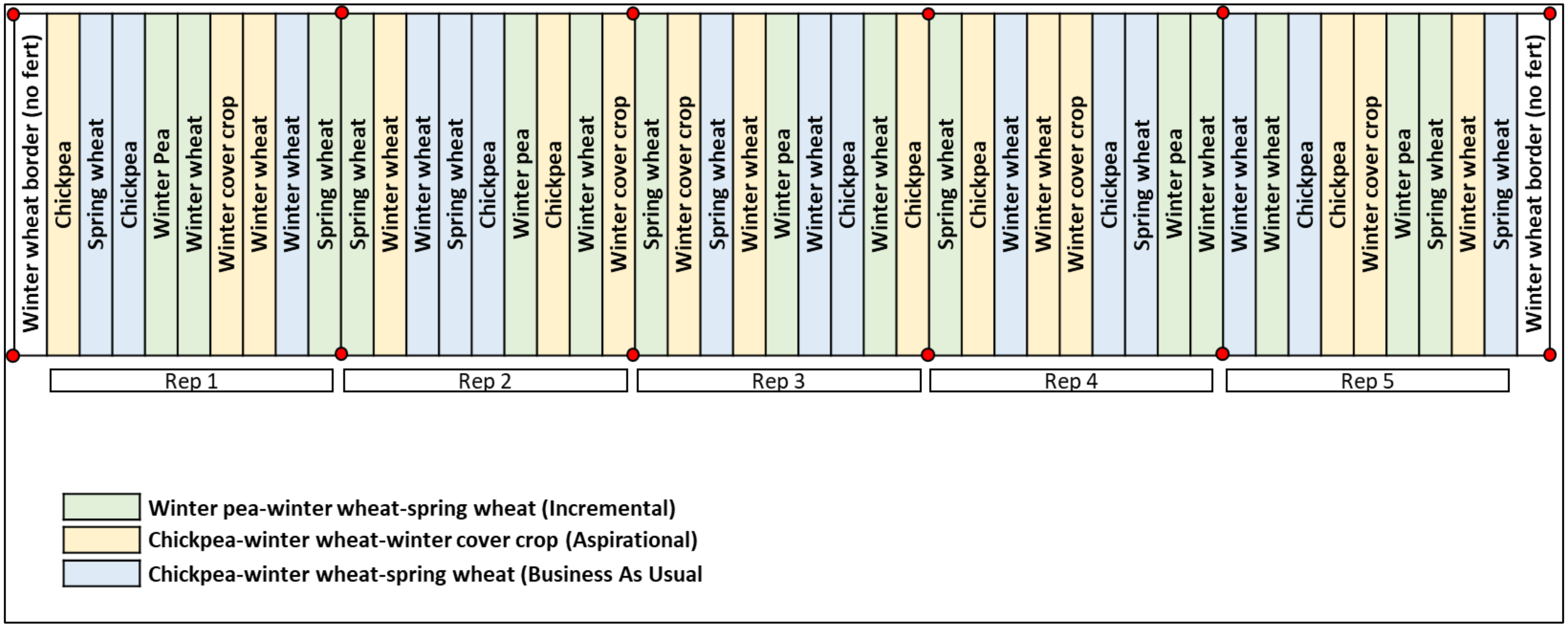

Figure 2.1. Example plot layout of the study at Genesee in 2018/2019.

Table 2.2. Planting and harvest dates of different crops in different rotations at Genesee and St. John from 2017 to 2021.

		Genesee				St. John			
		2017-18	2018-19	2019-20	2020-21	2017-18	2018-19	2019-20	2020-21
Planting dates	Fall	5-Oct-17	4-Oct-18	7-Oct-19	6-Oct-20	3-Oct-17	25-Sep-18	24-Sep-19	30-Sep-20
	Spring	27-Apr-18	2-May-19	21-Apr-20	22-Apr-21	30-Mar-18	25-Apr-19	9-Apr-20	5-Apr-21
Harvest dates	Winter wheat	2-Aug-18	7-Aug-19	6-Aug-20	27-Jul-21	21-Aug-18	20-Aug-19	7-Aug-20	22-Jul-21
	Spring wheat	23-Aug-18	28-Aug-19	25-Aug-20	24-Aug-21	21-Aug-18	27-Aug-19	24-Aug-20	16-Aug-21
	Winter pea	2-Aug-18	7-Aug-19	6-Aug-20	27-Jul-21	3-Aug-18	2-Aug-19	7-Aug-20	22-Jul-21
	Chickpea	23-Aug-18	5-Sep-19	10-Sep-20	2-Sep-21	-	-	-	-
	Forage crops	20-Jun-18	1-Jul-19	7-Jul-20	1-Jul-21	2-Jul-18	12-Jul-19	9-Jul-20	8-Jul-21

Table 2.3: Total nitrogen applied to individual plots at Genesee and St. John at planting.

Location	Rotation	Crop	Preceding crop	2017/2018	2018/2019	2019-2020	2020/2021
				---------------------- N (kg ha^{-1}) ----------------------			
Genesee[†]	Incremental (WP)[§]	WW	WP	101	146	174	112
	Aspirational (FC)	WW	CP	101	168	174	165
	Business as Usual	WW	CP	101	168	174	165
	Incremental (WP)	SW	WW	67	165	210	187
	Aspirational (FC)	-	-	-	-	-	-
	Business as Usual	SW	WW	67	165	210	187
St. John[†]	Incremental (WP)[§]	WW	WP	101	56	84	34
	Aspirational (FC)	WW	FC	101	90	112	112
	Business as Usual	WW	F	101	90	22	34
	Incremental (WP)	SW	WW	129	129	62	90
	Aspirational (FC)	SW	WW	129	129	112	90
	Business as Usual	SW	WW	129	129	56	90

[†] 34 kg ha^{-1} of phosphorus and 22 kg ha^{-1} of sulfur applied in addition to the following nitrogen.

[§] WP = winter pea; FC = forage crop; SW = spring wheat; and WW = winter wheat; CP = chickpea; F = Fallow.

Agronomic data

Upon the end of vegetative growth, plant height or vine length (winter pea) was measured for all crops except for forage mixes. At maturity, plots were harvested using a Wintersteiger plot combine (Table 2.2). Grain yield was measured for all crops, except forage mixes. Grain protein was determined using a Foss Infratec Nova (Foss, Hilleroed, Denmark). Thousand seed weight was calculated for all crops and test weight was measured for spring and winter wheat using the cox funnel method. Additionally, a sample of winter wheat and spring wheat from all years in each location was sent to University of Idaho's Wheat Quality Lab, Aberdeen for analyzing flour quality.

Forage collection and quality analysis

Forage samples were collected using 0.25 m^2 quadrats three to five times a year starting the end of May to mid-July at 7-to-14-day intervals. Samples were weighed for fresh weight at harvest and dry weight after drying for 3 days at 55°C. Prior to collecting biomass samples, plant population for each crop species of the forage mix was determined by counting the number of individual crops in one quadrat in each plot. As the forage crops were approaching heading and flowering in late June to mid-July, the crops were terminated by swathing and removing biomass from the field to simulate haying. Dried biomass samples from the terminal harvest were ground to <1 mm diameter using a Wiley Mill to determine forage quality.

Forage quality parameters measured included crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and lignin. Crude protein was determined using a KjeltecTM 8100 (FOSS, Hilleroed, Denmark) which is a semi-automated distillation unit for Kjeldahl analysis using the guideline standard of AOAC 984.13 (Helrich, 1990). For ADF and NDF determination, ANKOM 200 Fiber Analyzer (ANKOM Technology, Macedon NY, USA) was used as described by Vogel et al. (1999). For determining acid detergent lignin, ANKOM Technology-Method 8 was used, where samples were dissolved in 72% sulfuric acid using a beaker method. Relative feed value (RFV) was estimated using the formula RFV = (%DDM × %DMI) ÷1.29, where DDM is digestible dry matter [calculated as %DDM = 88.9 - (0.779 × %ADF)] and DMI is dry matter intake [calculated as %DMI = 120 ÷ %NDF].

Volumetric water content

In addition to the agronomic parameters, volumetric water content was measured in each plot during the active growing season of the crops using a Delta T-PR2 Profile probe (Delta-T Devices, Houston, Texas). The PR2 probe is a capacitance probe and can measure volumetric water content at depths of 10, 20, 30, 40, 60 and 100 cm. The probe is inserted into access tubes and data is collected via handheld data logger. Access tubes were inserted into each plot after planting and repeated measurements were taken from these tubes during the crop growing season. The access tubes were removed after the crops were harvested before planting the subsequent crop. The moisture content was recorded every 6 to 8 days in the second and third year and 10 to 14 days in the fourth and final year of the study. Water content was not measured in the first year of study.

Economic analysis

Comparison of profitability of different crop rotations was conducted using the “Economic Model to Compare Crop Rotations” a Profitability Decision Tool developed by Dr. Clark Seavert, Oregon State University which helps the user to explore financial impacts of replacing a crop in a particular crop rotation (https://pnwlit.org/profitability-decision-tool). Enterprise budgets for crop rotations included variable and fixed cash costs and non-cash machinery replacement costs. Land area, planted acres for individual crops, seed and grain/hay prices for each crop, fertilizer and chemical amount, costs for chemicals and fertilizers, use of machinery, number of times a particular machine is used, and custom hire operations were input based on the practices and operations that were done in the four years of the study period at both locations. This economic model does not include costs associated with family living withdrawal for unpaid labor, returns to management and land, depreciation and opportunity costs for vehicles, buildings and improvements, and federal, state and local income and property taxes.

A separate economic analysis was conducted for each of the two locations to compare the diversified crop rotations to the business-as-usual rotation. Crop yields used in these models were derived from the 4-year average yields obtained in this study. For the purposes of this analysis, the total farm area is assumed to be 1,012 ha (2,500 acres) for each rotation and each of the three crops in each rotation was planted into one third of the total area. The price of grain and seed, field operations, summary of chemical and fertilizer application, and machine assumptions used in this economic tool is listed in Appendix A. After inputting the yield, input cost, fertilizer and pesticides quantities, machine operations, and custom operations for forage harvest, the net return for each crop in all rotations was estimated. In addition, economic returns for the overall crop rotations were calculated for each rotation for each year. Comparisons were made to see if there was any increase or decrease in total net return with the inclusion of the alternative crops.

Data Analysis

Data were analyzed using SAS version 9.4 (SAS Institute, 2016). Analysis of variance (ANOVA) was performed using the general linear mode and means were separated using Fisher’s LSD at an alpha of 0.05. In a single year, similar crops were compared to determine differences in plant height, yield, and grain quality. A pooled comparison for yield of three crop rotations was performed with the same general linear model considering year as a random effect. For forage mixes, the forage yield and nutritive values were analyzed on a year-to-year basis as the harvest time of forage crops and their composition were not similar in all years. The means were separated using Fisher's LSD at an alpha of 0.05.

Results

Data Analyses

Analyses of variance were conducted to compare the same crop for growth parameters, yield, and quality in different rotations. Yields of each crop were impacted by rotational crops at St. John. However, most of the comparisons at Genesee were not significant for crop growth and quality. Forage crops were analyzed for yield and forage quality and there were significant differences between harvest dates and crops in the mixture. ANOVA and p-values for these comparisons are listed in Appendix B.

Soil Tests

The results of pre-plant soil test results are summarized in Table 2.4 and Table 2.5 for Genesee and St. John, respectively. Nitrogen in the ammonium form was estimated using automated cadmium reduction method. Similarly, the nitrate form of the nitrogen was estimated using automated phenate method. Sulfur was estimated turbidimetrically. Phosphorus in the soil sample was estimated using colorimetric method with Morgan extract. Potassium in the soil samples was estimated using inductively coupled plasma with ammonium acetate extract (NW Ag. Consultants, personal communication).

Soils were slightly acidic at Genesee with pH ranging from 5.2 to 5.6 while the pH ranged from 5.9 to 7.3 at St. John in the top 30 cm soil depth. Organic matter ranged from 2.49

to 4.17% across years and location without any specific trend. The amount of available nitrogen was comparable for similar crops in the three different rotations at Genesee. However, at St. John, quantity of residual fertilizer was higher following fallow in the business-as-usual rotation compared to the quantity of nitrogen following the alternative crops in the incremental and aspirational rotations. The concentration of residual phosphorus and sulfur were comparable between rotations.

Table 2.4. Preplant soil characteristics of the top 30 cm of soil at Genesee, ID from 2017 to 2021.

Year	Rotation	Crop[†]	pH (30 cm)	OM (30 cm) (%)	N (120 cm) (kg ha^{-1})	P (30 cm) (ppm)	K (30 cm) (ppm)	S (30 cm) (ppm)
2017-18	Winter crops		-	-	-	-	-	-
	Spring crops		5.6	3.93	132	20	321	2
2018-19	Incremental	WP	5.4	4.17	41	18	253	4
		WW	5.2	3.76	72	23	268	3
		SW	5.4	3.14	58	22	268	2
	Aspirational	CP	-	-	-	-	-	-
		WW	5.3	3.63	53	13	258	2
		WFC	5.4	3.25	41	21	232	3
	Business as usual	CP	-	-	-	-	-	-
		WW	5.2	3.46	55	24	289	3
		SW	5.6	3.27	66	20	292	3
2019-20	Incremental	WP	5.5	3.48	44	19	195	6
		WW	5.5	3.23	53	18	276	5
		SW	5.5	2.92	56	17	257	2
	Aspirational	CP	5.5	3.2	78	21	302	2
		WW	5.4	3.29	48	19	270	6
		WFC	5.5	3.72	38	18	299	3
	Business as usual	CP	5.4	2.91	71	17	278	2
		WW	5.4	3.34	45	20	263	4
		SW	5.5	2.96	52	17	266	2
2020-21	Incremental	WP	5.4	3.99	69	24	287	3
		WW	5.4	3.29	100	21	280	3
		SW	5.6	3.44	75	24	324	2
	Aspirational	CP	5.5	3.45	123	19	283	2
		WW	5.4	3.85	67	25	312	3
		WFC	5.5	3.66	65	23	312	3
	Business as usual	CP	5.5	3.45	106	22	287	3
		WW	5.3	3.87	67	20	281	3
		SW	5.6	3.62	67	23	266	2

[†] WP-winter pea; CP-chickpea; WFC-winter forage crop; SW- spring wheat; and WW- winter wheat

Table 2.5. Preplant soil characteristics of top 30 cm of soil at St. John, WA from 2017 to 2021.

Year	Rotation	Crop[†]	pH (30 cm)	OM (30 cm) (%)	N (120 cm) (kg ha^{-1})	P (30 cm) (ppm)	K (30 cm) (ppm)	S (30 cm) (ppm)
2017-18	Winter crops		-	-	-	-	-	-
	Spring crops		6.8	2.83	119	10	710	2
2018-19	Incremental	WP	6.4	2.81	111	15	684	6
		WW	6.3	3.24	165	12	712	4
		SW	6.9	3.21	137	18	690	3
	Aspirational	SFC	-	-	-	-	-	-
		WW	6.3	2.72	98	17	659	3
		SW	6.9	2.82	122	16	714	3
	Business as usual	Fallow	-	-	-	-	-	-
		WW	5.9	2.91	106	16	755	4
		SW	6.8	2.9	131	17	741	3
2019-20	Incremental	WP	6.4	2.81	140	21	650	4
		WW	6.9	2.97	126	15	670	3
		SW	7.3	2.61	173	8	689	3
	Aspirational	SFC	7.1	2.62	137	10	661	3
		WW	6.6	2.49	123	16	708	4
		SW	7.2	2.67	120	10	655	3
	Business as usual	Fallow	-	-	-	-	-	-
		WW	6.4	2.57	219	14	670	4
		SW	7.1	2.62	161	12	675	3
2020-21	Incremental	WP	6.8	3.13	120	15	713	4
		WW	6.9	3.02	158	16	691	3
		SW	6.6	2.94	187	16	681	3
	Aspirational	SFC	6	2.89	244	21	629	3
		WW	6.8	2.87	111	13	676	3
		SW	6.3	2.92	208	18	710	3
	Business as usual	Fallow	-	-	-	-	-	-
		WW	6.5	2.96	238	19	686	4
		SW	6.7	2.88	188	17	686	3

[†] **WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.**

Weather

Total annual precipitation was highly variable across the years at both locations (Table 2.6 and 2.7). The total annual precipitation (Sept-Aug) was 56.3 cm, 44.8 cm, 45.5 cm and 32.8 cm at Genesee for the 4 years of the study. Similarly, the total precipitation at St. John was 45.1 cm, 36.1 cm, 38.1 cm and 29.7 cm for the 4 years. The spring of the 2018-19 growing season was particularly wet and the planting was delayed almost a month when compared to other years at both locations. Precipitation in May and June of the 2019-20 growing season was particularly high compared to the other years at both locations. Genesee received 9 to 20% higher precipitation compared to St. John. When comparing the average maximum and minimum temperatures, these were comparable across years and locations except during June and July of the 2020-21 growing season, when the temperatures were unusually high. Less than average precipitation was experienced during the late spring and early summer of 2020-21 as well.

Table 2.6. Mean monthly maximum and minimum temperature and total monthly precipitation for Genesee, ID for the growing seasons from 2017 to 2021.

	2017/2018			2018/2019			2019-2020			2020/2021		
	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Max Temp (°C)	Min Temp (°C)	Rain (mm)	Max Temp (°C)	Min Temp (°C)	Rain (mm)
Sept	22.1	8.9	26.0	21.7	9.1	3.5	20.9	10.7	29.3	24.9	12.6	9.8
Oct	13.1	4.2	59.2	14.1	4.7	20.5	10.8	1.7	30.0	14.5	6.1	57.5
Nov	6.2	1.8	69.6	6.7	0.7	56.6	6.9	0.2	14.5	6.4	1.3	48.8
Dec	-0.8	-4.4	104.8	1.7	-2.3	60.6	3.4	-1.0	48.8	3.7	-1.0	37.0
Jan	4.0	0.6	62.9	2.0	-2.3	34.9	4.2	-0.1	54.6	4.7	-0.1	53.1
Feb	2.5	-3.2	52.3	-1.8	-7.2	61.8	5.6	-0.5	86.3	1.8	-3.4	54.6
Mar	7.7	0.3	29.2	6.5	-3.9	16.2	8.5	0.8	26.1	10.2	0.6	18.5
Apr	12.6	4.0	60.6	13.2	4.5	90.7	14.3	3.4	24.6	15.8	3.5	8.4
May	20.0	9.8	53.7	19.9	9.0	52.8	17.7	7.2	85.3	19.3	7.3	3.5
Jun	21.3	9.9	35.8	22.1	10.9	30.5	20.0	10.0	48.1	28.2	14.5	13.9
July	30.3	14.6	0.0	27.0	13.3	11.3	27.6	13.3	4.3	33.1	17.6	6.1
Aug	28.5	14.9	8.7	29.5	15.5	8.8	28.9	16.2	3.2	28.1	15.5	17.6

Table 2.7. Mean monthly maximum and minimum temperature and total monthly precipitation for St. John, WA for the growing seasons from 2017 to 2021.

	2017/2018			2018/2019			2019-2020			2020/2021		
	Max Temp (° C)	Min Temp (° C)	Rain (mm)	Max Temp (° C)	Min Temp (° C)	Rain (mm)	Max Temp (° C)	Min Temp (° C)	Rain (mm)	Max Temp (° C)	Min Temp (° C)	Rain (mm)
Sept	22.8	9.9	17.0	21.0	8.0	0.4	20.4	9.3	30.1	24.8	8.8	3.5
Oct	13.5	3.8	51.7	14.6	3.2	12.1	10.8	0.8	36.9	13.8	3.9	47.9
Nov	6.7	2.1	62.9	6.8	-0.7	44.4	6.9	-1.1	13.4	6.2	0.8	57.9
Dec	0.0	-4.1	70.0	2.5	-2.1	74.8	3.7	-0.8	32.8	3.8	-1.4	45.8
Jan	5.0	0.8	45.6	3.2	-1.2	39.8	4.4	-0.4	46.8	3.6	0.0	50.6
Feb	2.6	-3.4	46.2	-1.6	-7.0	60.2	5.1	-1.7	61.2	0.7	-4.6	49.6
Mar	8.3	0.7	30.0	5.3	-4.7	13.5	8.7	-1.0	14.5	9.9	0.2	17.5
Apr	12.9	3.4	49.6	13.4	3.8	57.0	14.2	1.9	9.1	15.1	2.6	8.3
May	21.5	9.8	40.2	20.2	8.4	24.3	17.4	6.2	85.7	19.0	5.9	7.3
Jun	21.3	8.7	29.6	23.3	10.4	11.2	20.3	9.2	44.9	27.6	11.3	0.2
July	30.1	12.5	1.4	27.0	12.5	5.6	28.1	11.4	4.5	32.8	13.8	1.0
Aug	28.3	13.0	6.7	28.5	14.0	17.5	28.8	12.2	1.2	27.0	12.5	7.5

Grain Yield

Grain yield of each crop varied significantly across years, with 2019-20 being the most productive and 2020-21 being the least productive for all crops (Table 2.8 and 2.9). At Genesee, the winter pea yield in the incremental rotation varied from 620 to 5,650 kg ha^{-1} across years, forage dry weight yield ranged from 4,652 to 7,542 kg ha^{-1}, chickpea yield ranged from 1,265 to 2,701 kg ha^{-1}, winter wheat yield ranged from 3,321 to 9,428 kg ha^{-1}, and spring wheat yield ranged from 1,500 to 5,897 kg ha^{-1}. While there were differences in yield between years for the same crop, incorporation of a winter pea or winter forage crop did not influence the yield of other crops in the rotation compared to the business as usual.

At St. John, the winter pea yield ranged from 431 to 2,788 kg ha^{-1} during the study period, the dry spring forage weight production ranged from 2,472 to 5,050 kg ha^{-1}, the spring wheat yield ranged from 840 to 4,151 kg ha^{-1}, and the winter wheat yield ranged from 4,280 to 7,798 kg ha^{-1}. Incorporating winter pea and spring forage mix did not have any impact on the yield of hard red spring wheat compared to the business-as-usual rotation with fallow. However, the winter wheat yield in 2018-19 was reduced by 22 and 21% when following winter pea and spring forage, respectively, compared to fallow. Similarly, in 2020-21 there was a reduction of 28 and 21% in yield of winter wheat following winter pea and spring forage, respectively, compared to the business-as-usual rotation at St. John. There was not a significant difference in winter wheat yield between rotations in 2019-20.

The yield of crops in rotation were pooled over the years for both locations to see the rotational impact of alternative crops on subsequent crops in the rotation. The yield of alternative crops was pooled from 2017 to 2019 while the subsequent crops were pooled only from the second year from 2018-2021. The incorporation of winter pea in the rotation replacing chickpea did not have any influence on the yield of subsequent winter wheat and spring wheat at Genesee (Table 2.10). Also, the winter pea yield was 3,876 kg ha^{-1} compared to 2,301 kg ha^{-1} for chickpea. At the same location winter forage produced 6,387 kg ha^{-1} of dry matter while the yield of spring wheat was 3,905 kg ha^{-1} (Table 2.11). The integration of the forage mix in the rotation did not have any effect on the production of subsequent chickpea and winter wheat in the aspirational rotation compared to the business as usual. At St. John, the average yield of winter pea was 2,292 kg ha^{-1} and the average dry weight of the spring forage was 3,835 kg ha^{-1} (Table 2.12). With the incorporation of these diverse crops in the rotation, the winter wheat yield in the incremental and aspirational rotation was significantly reduced. The spring wheat yield was not impacted by the incorporation of winter pea and spring forage.

Table 2.8. Yield of all crops in three different rotations at Genesee from 2017 to 2021.

Year	Rotation	WP[§]	CP	WW	WFC	SW
		Yield (kg ha^{-1})				
2017-18	**Incremental (WP)**	3,151		8,699		3,013 b[†]
	Aspirational (WFC)		2,104	8,823	7,542	
	Business as usual (CP/SW)		1,950	8,834		3,109 a
2018-19	**Incremental (WP)**	2,827		6,905		4,926
	Aspirational (WFC)		2,307	7,095	5,252	
	Business as usual (CP/SW)		2,252	6,674		4,701
2019-20	**Incremental (WP)**	5,650		9,396		5,733
	Aspirational (WFC)		2,483	9,106	6,084	
	Business as usual (CP/SW)		2,701	9,428		5,897
2020-21	**Incremental (WP)**	620		3,321		1,666
	Aspirational (WFC)		1,265	3,575	4,652	
	Business as usual (CP/SW)		1,283	3,357		1,500

[§] WP-winter pea; CP-chickpea; WFC-winter forage crop; SW- spring wheat; and WW- winter wheat.

†Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table 2.9. Yield of all crops in three different rotations at St. John in four years from 2017 to 2021.

Year	Rotation	WP	SFC	WW	SW
		Yield (kg ha^{-1})			
2017-18	**Incremental (WP)** [§]	2,282		4,471	2,510
	Aspirational (SFC)		2,648	4,885	2,922
	Business as Usual (Fallow)			4,914	2,520
2018-19	**Incremental (WP)**	1,807		5,932 b[†]	3,869
	Aspirational (SFC)		3,806	6,000 b	4,151
	Business as Usual (Fallow)			7,616 a	3,976
2019-20	**Incremental (WP)**	2,788		7,395	3,298
	Aspirational (SFC)		5,050	7,798	3,594
	Business as Usual (Fallow)			7,583	3,411
2020-21	**Incremental (WP)**	431		4,280 b	1,012
	Aspirational (SFC)		2,472	4,774 ab	1,220
	Business as Usual (Fallow)			5,933 a	840

[§] WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.

[†] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table 2.10. Yield of crops in incremental and business as usual rotation summarized over four years from 2017 to 2021 at Genesee.

Rotation	WP[§]	CP	WW	SW
	Yield (kg ha^{-1})			
Incremental (WP)	3,876		6,541	3,700
Business as usual (CP)		2,301	6,846	3,699

[§]WP-winter pea; CP- chickpea; SW- spring wheat; and WW- winter wheat.

Table 2.11. Yield of crops in aspirational and business as usual rotation summarized over four years from 2017 to 2021 at Genesee.

Rotation	WFC[§]	SW	CP	WW
	Yield (kg ha^{-1})			
Aspirational (WFC)	6,397		2,395	6,341
Business as usual (SW)		3,905	2,477	6,393

[§]WFC-winter forage crop; SW- spring wheat; CP- chickpea and WW- winter wheat.

Table 2.12. Yield of crops in all rotations summarized over four years from 2017 to 2021 at St. John.

Rotation	WP[§]	SFC	WW	SW
	Yield (kg ha^{-1})			
Incremental (WP)	2,292		5,869 b[†]	2,440
Aspirational (SFC)		3,835	6,190 b	2,539
Business as usual (CP/SW)			7,044 a	2,125

[§]WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.

†Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Plant height, grain protein, 1000 seed weight of all crops and grain and flour quality of spring and winter wheat

There was no significant difference in plant height (or vine length in case of winter pea) between the same crops in different rotations in all years at both locations except in 2018-19 at Genesee where spring wheat heights were significantly different between incremental and aspirational crop rotation. Similar observations were collected for grain protein, where the protein was constant for same crops in an individual year at both locations except in 2018-19 at Genesee when there was significant difference in protein, however, the difference was less than 0.4%. Similarly, the 1000 seed weight were similar for same crops at both locations in all years. The grain and flour quality of winter and spring wheat were also similar in most years. There were some differences in some years for a few qualities, but the differences were not consistent. In 2018-19, comparing the flour yield on winter wheat at Genesee, there was a significant difference between the winter wheat treatments. In the same year at Genesee, the test weight of the spring wheat from two rotations differed significantly, At St. John, the only difference was seen in the test of winter wheat in 2019-20 where the winter wheat following fallow had significantly higher test weight and flour yield. The mean values of all the parameters mentioned above are located in Appendix C.

Forage yield and quality

The winter forage mix at Genesee consisted of winter wheat, sudangrass, proso millet, crimson clover, winter pea, winter lentil, turnip, radish, and flax in the first year of study. However, crops other than winter pea, winter wheat and crimson clover did not emerge or establish. As a result, the mixture was modified in the second year and all subsequent growing seasons to include winter oat, winter pea, crimson clover, radish, and turnip while also anticipating that volunteer winter wheat would contribute to the mix. The spring mix at St. John had spring pea, spring barley, spring oat, turnip and sunflower and all crops established and contributed towards forage production.

Plant population varied across years at both locations. The highest plant population was observed in 2018-19 followed by 2017-18, 2019-20 and 2020-21 at Genesee (Figure 2.2). Winter wheat had the highest plant population in all years except for the final year where winter pea had a higher population at Genesee. Winter wheat comprised 75, 82, 67 and 20% of the total plant population while winter pea contributed 17, 10, 19 and 47% of the total plant population in the 4 years of the study, respectively. Crimson clover and winter oat had similar plant population while turnip was observed only during the 2018-19 and 2020-21 growing season. At St. John, all crops from the spring forage mix established well, although the population of sunflower was consistently lower compared to other crops in the spring mix (Figure 2.3). Spring oat and spring barley were the top two contributors to the plant population contributing 27-39% and 24-28% of the plant stand, respectively. Winter pea (16-31%) and turnip (12-18%) were usually lower in population.

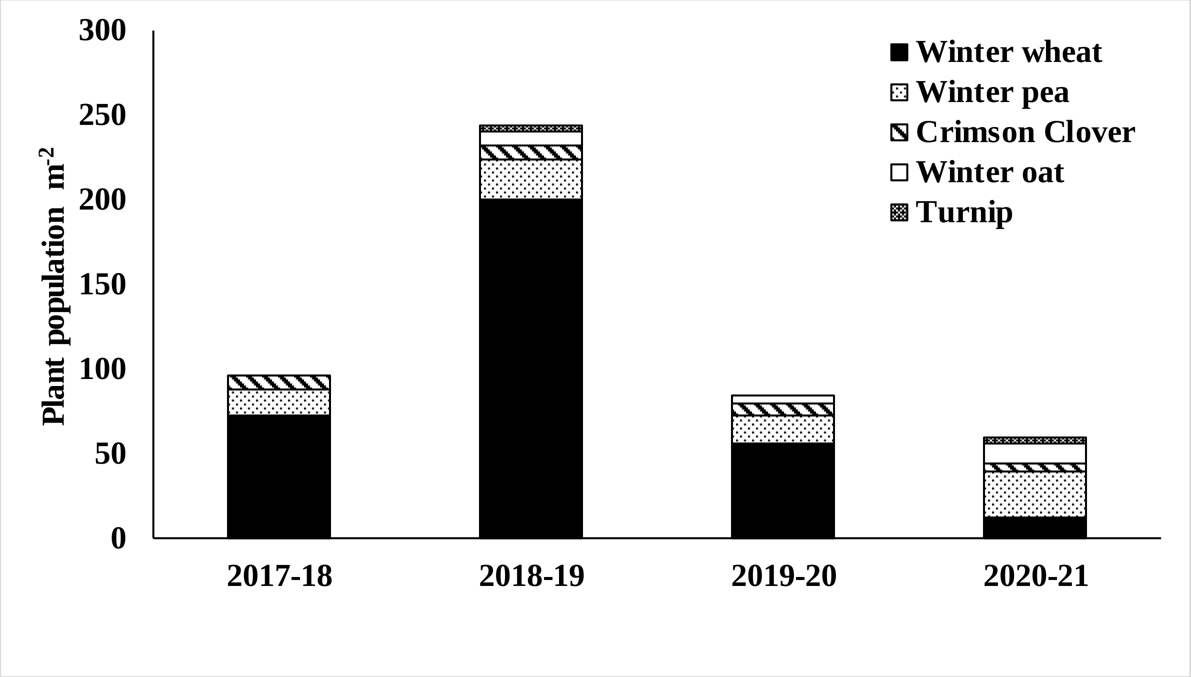

Figure 2.2. Plant population of individual components in the winter forage mix at Genesee from 2017 to 2021.

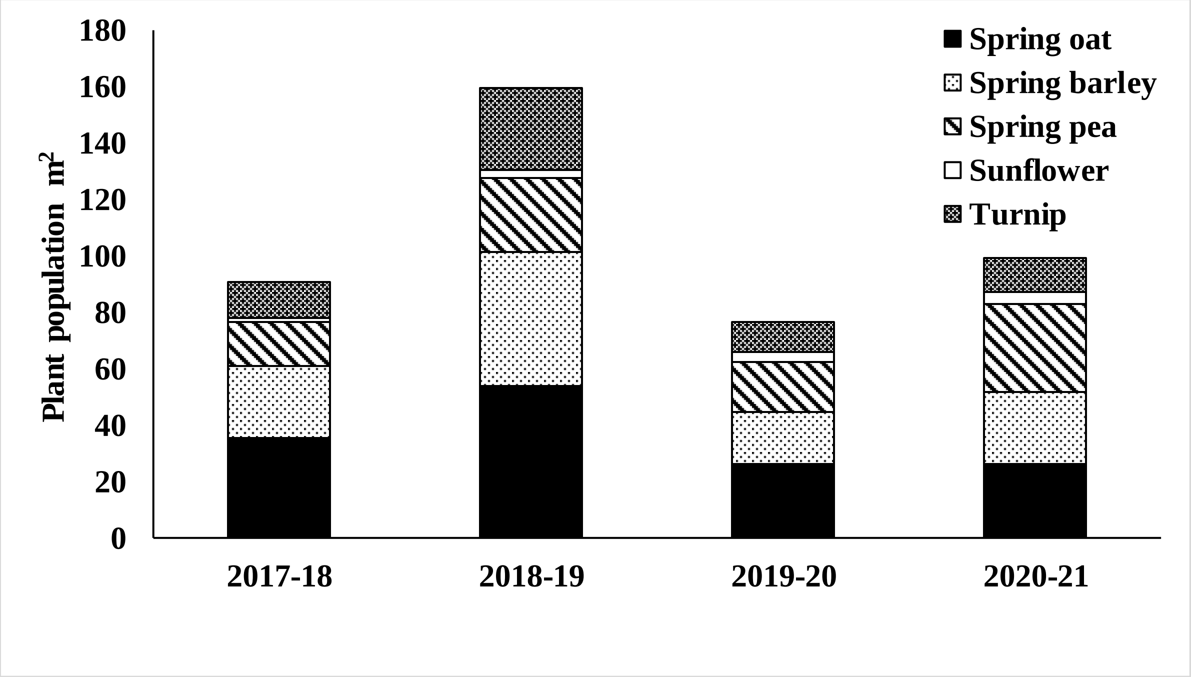

Figure 2.3. Plant population of individual components in the spring forage mix at St. John from 2017 to 2021.

The forage crops were sampled every 8 to 15 days depending on year and site for forage biomass starting from late May or early July at both locations, except for 2017-18 at St. John when sampling was started in mid-May (Table 2.13 and Table 2.14). There was a significant increase in forage dry weight as the growing season progressed with maximum forage yield occurring in late June or early July. The winter forage crop at Genesee had a higher dry matter production in three of four years when compared to the dry matter production from the spring forage crops at St. John. The highest dry matter was obtained in 2017-18 with 7,542 kg ha^{-1} in Genesee, while the highest dry matter at St. John was 5,050 kg ha^{-1} in 2019-20.

Table 2.13. Dry weight of the winter forage crop harvested at different dates at Genesee from 2017 to 2021.

2017-18			2018-19			2019-20			2020-21		
Forage dry weight (kg ha^{-1}) †											
15-May	1,212	d	**30-May**	1,258	c	**3-Jun**	3,316	b	**2-Jun**	2,708	c
29-May	3,536	c	**13-Jun**	2,496	b	**17-Jun**	3,392	b	**17-Jun**	3,760	b
11-Jun	5,743	b	**25-Jun**	5,474	a	**1-Jul**	6,944	a	**1-Jul**	4,652	a
20-Jun	7,542	a	**1-Jul**	5,252	a	**7-Jul**	6,084	a			

†Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

Table 2.14. Dry weight of the spring forage crop harvested at different dates at St. John from 2017 to 2021.

2017-18			2018-19			2019-20			2020-21		
Forage dry weight (kg ha^{-1}) †											
29-May	467	c	**29-May**	143	c	**1-Jun**	395	c	**3-Jun**	712	b
11-Jun	920	c	**13-Jun**	809	c	**18-Jun**	2,060	b	**17-Jun**	1,140	b
25-Jun	2,082	b	**25-Jun**	2,786	b	**29-Jun**	2,385	b	**2-Jul**	1,972	a
2-Jul	2,648	a	**9-Jul**	3,806	a	**9-Jul**	5,050	a	**8-Jul**	2,472	a

†Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

ADF, NDF, CP and lignin were determined for all forage samples, with relative feed value (RFV) being calculated from the NDF and ADF (Table 2.15 and Table 2.16). In all years, there is a significant incremental increase in NDF, ADF and lignin content as the crops mature from late May to late June or early July. Conversely, the CP and RFV tended to decline throughout the sampling season at both locations, except 2019-20 at Genesee where the CP remained similar at all sampling dates. While a statistical comparison was not done between locations, the CP and RFV values for the spring forage at St. John were superior to the winter forage at Genesee.

Table 2.15. Forage quality of winter forage mixes harvested at different dates at Genesee from 2017 to 2021.

Year	Crops	NDF[†] (%)	ADF (%)	Lignin (%)	CP (%)	RFV (%)
2018	**15-May**	48 c[§]	26 c	2.3 b	19 a	134 a
	29-May	54 b	30 b	2.3 b	13 b	114 b
	11-Jun	57 a	32 a	2.6 b	9 c	104 c
	20-Jun	57 a	33 a	3.2 a	9 c	103 c
2019	**30-May**	50 b	29 b	4.2 b	14 a	123 a
	13-Jun	55 a	33 a	4.0 b	11 b	107 b
	25-Jun	54 ab	33 a	4.6 ab	11 b	110 b
	1-Jul	57 a	35 a	5.3 a	11 b	102 b
2020	**3-Jun**	52 b	28	3.3 b	10	119 a
	17-Jun	57 a	31	3.5 b	8	106 b
	1-Jul	51 b	30	4.6 a	10	119 a
	7-Jul	52 b	30	4.6 a	9	117 a
2021	**2-Jun**	44 b	23 b	2.2 b	8 a	149 a
	17-Jun	56 a	31 a	3.7 a	7 b	108 b
	1-Jul	57 a	33 a	4.7 a	5 c	104 b

[†] Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV)

[§] Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

Table 2.16. Forage quality of spring forage mixes harvested at different dates at St. John from 2017 to 2021.

Year	Crops	NDF [†]		ADF		Lignin	CP		RFV	
		(%)		(%)		(%)	(%)		(%)	
2018	**29-May**	41	b[§]	24	b	3.9	18	a	160	a
	11-Jun	41	b	23	b	2.6	13	b	162	a
	25-Jun	53	a	29	a	3.8	12	b	117	b
	2-Jul	53	a	28	a	2.4	9	c	119	b
2019	**29-May**	35	c	21	b	5.6	27	a	195	a
	13-Jun	45	b	28	a	4.8	18	b	142	b
	25-Jun	45	b	28	a	4.0	14	c	140	b
	9-Jul	52	a	30	a	4.6	10	d	119	b
	12-Jul	51	a	30	a	4.0	10	d	121	b
2020	**1-Jun**	31	c	18	c	4.9	19	a	227	a
	18-Jun	39	b	23	b	4.1	17	a	170	b
	29-Jun	42	ab	23	b	3.6	12	b	159	bc
	9-Jul	43	a	25	a	3.4	13	b	150	c
2021	**3-Jun**	32	c	20	b	4.1	24	a	212	a
	17-Jun	32	c	23	b	5.4	20	b	208	a
	2-Jul	44	b	27	a	5.5	17	c	144	b
	8-Jul	50	a	29	a	4.7	13	d	122	b

[†] Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV)
[§] Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

Individual components of the forage crop mix at both locations were sampled during the terminal harvest for forage quality estimation. The majority of crops planted as a part of the winter forage mix at Genesee did not establish and the crops included in the forage quality estimation were crimson clover, winter pea, winter wheat, winter oat, and turnip (Table 2.17). In all years, crimson clover, winter wheat and winter oat, when present, had the highest quantity of ADF and NDF. Winter pea and turnip had the lowest fiber (ADF and NDF) content. Lignin content was higher in crimson clover and did not differ among the other crops. Winter pea always had significantly higher CP and RFV compared to other crops in the mix, except for turnip which had the highest RFV in 2018-19. Crimson clover, when present, had the second highest CP after WP, but RFV was lower when compared to cereals in the mixture except in 2017-18.

Table 2.17. Forage quality of individual crops from the winter forage mix sampled during the last harvest at Genesee during 2018 to 2021.

Year	Crops	NDF[†]	ADF	Lignin	CP	RFV
		(%)	(%)	(%)	(%)	(%)
2018	**CC[Φ]**	50 b[§]	35	7.4 a	13 b	115 b
	WP	43 c	31	5.7 b	18 a	145 a
	WW	60 a	33	2.8 c	8 c	98 b
2019	**CC**	59 a	43 a	11.4 a	14 b	87 c
	Tur	26 c	19 c	6.1 b	12 b	284 a
	WO	60 a	33 b	4.8 b	8 c	98 c
	WP	40 b	30 b	5.3 b	18 a	154 b
	WW	59 a	34 b	4.6 b	7 c	98 c
2020	**CC**	54 ab	37 a	10.0 a	13 a	104 c
	WO	52 b	28 c	3.6 c	7 b	119 b
	WP	36 c	26 d	4.3 bc	14 a	178 a
	WW	56 a	30 b	4.7 b	7 b	109 bc
2021	**WO**	60 a	33 a	3.5 b	6 b	98 c
	WP	41 c	31 b	4.0 a	11 a	146 a
	WW	54 b	31 b	4.3 a	6 b	112 b

[†]Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV)

[Φ]Crimson clover (CC), winter pea (WP), winter wheat (WW), winter oat (WO), turnip (Tur)

[§]Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

Forage quality of crops in the spring mix at St. John is shown in Table 2.18. Spring oat consistently had higher NDF and ADF concentrations closely followed by spring barley in all years, except for spring pea in 2019 and 2021, which had an ADF similar to oat and barley.

Turnip consistently had the lowest NDF and ADF concentration, although not significantly different from sunflower in 2019 and 2020. Lignin content varied considerably for crops across years. Depending on the year, sunflower, turnip and/or spring pea had significantly higher lignin content than did the other crops. Numerically, spring oat consistently had the lowest lignin content. When comparing CP, turnip and spring pea had significantly higher CP than did other crops in 2018 and 2019. In 2020 and 2021, turnip had significantly higher CP than other crops. The CP of sunflower, spring oat and spring barley were similar in each year. The RFV of spring oat and barley were usually significantly lower compared to the other crops. Turnip in all years had the highest RFV followed by sunflower and spring pea.

Table 2.18. Forage quality of individual crops from the spring forage mix sampled during the last harvest at St. John during 2018 to 2021.

Year	Crops	NDF [†] (%)	ADF (%)	Lignin (%)	CP (%)	RFV (%)
2018	**Sun[Φ]**	34 d[§]	26 c	7.3 a	8 b	190 b
	SB	55 b	28 bc	2.3 b	9 b	113 cd
	SO	60 a	32 a	1.7 b	8 b	100 d
	SP	45 c	29 ab	5.6 a	16 a	137 c
	Tur	25 e	16 d	2.4 b	18 a	285 a
2019	**Sun**	26 d	20 b	4.5 bc	12 b	264 a
	SB	59 b	31 a	2.8 c	9 c	101 b
	SO	65 a	34 a	2.8 c	8 c	90 b
	SP	44 c	33 a	6.2 ab	16 a	134 b
	Tur	25 d	19 b	7.0 a	18 a	279 a
2020	**Sun**	30 c	23 c	5.0 a	11 c	219 b
	SB	58 a	30 ab	2.9 b	9 c	106 d
	SO	60 a	31 a	2.4 b	10 c	101 d
	SP	39 b	27 b	5.6 a	16 b	164 c
	Tur	20 d	14 d	3.2 b	28 a	369 a
2021	**Sun**	29 d	22 c	4.4 b	13 b	235 b
	SB	58 b	30 b	3.8 bc	11 b	104 d
	SO	61 a	31 ab	2.7 c	13 b	98 d
	SP	45 c	33 a	6.4 a	14 b	129 c
	Tur	21 e	15 d	3.8 bc	25 a	349 a

[†] Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV)

[Φ] Spring barley (SB), spring oat (SO), spring pea (SP), sunflower (Sun), and turnip (Tur)

[§] Mean followed by different letters in a single column in a year are statistically different using Fishers LSD at *P* = 0.05.

Volumetric water content

Volumetric water content (VWC) was recorded at soil depths of 10, 20, 30, 40, 60 and 100 cm every 7 to 15 days for all plots at Genesee and St. John during the second, third and fourth year of the study. The VWC of soil planted to the same or similar crops from the three different crop rotations were compared at the abovementioned depths. At Genesee, VWC was compared between (i) winter pea from incremental and two chickpea crops from aspirational and business-as-usual rotations, (ii) the winter wheat from the three different rotations, and (iii) spring wheat from the incremental and business-as-usual and winter forage mix from the aspirational rotation. Similarly, at St. John, VWC was compared between (i) winter pea from incremental, spring forage mix from aspirational and fallow from business-as-usual rotation, (ii) the winter wheat from the three different rotations, and (iii) spring wheat from three different rotations. For all crops at both locations, the top 10, 20, 30 and 40 cm had a gradual decline in VWC throughout the growing season. However, at the 60 and 100 cm depth, there was a lower rate of decline in water content. Almost all crops compared to one another had similar VWC during early spring.

In comparing the VWC between fallow and the two alternative crops at St. John, the VWC for fallow was often higher compared to the winter pea or the spring forage later in the growing season (Figure 2.4, 2.5 and 2.6). In the top 10 cm depth, the VWC of fallow land was 15.0, 13.2 and 6.1 % for the three years while the VWC for winter pea was 7.2, 8.7 and 2.7% and for spring forage mix was 7.3, 6.9 and 6.7%. Water use was similar between the spring forage crop and winter pea. The winter wheat from the three rotations at St. John had similar VWC throughout the growing season in the 10, 20, 30 and 40 cm depths. There were some differences in the deeper depths, but there was no obvious trend. The measured VWC values for spring wheat at St. John within the three rotations were similar. At Genesee, similar trends were observed when VMC was compared among similar or same crops in the three different rotations. There was no difference among the crops in rotations. The figures for the rest of St. John and all of Genesee for comparison of VMC are attached in Appendix D.

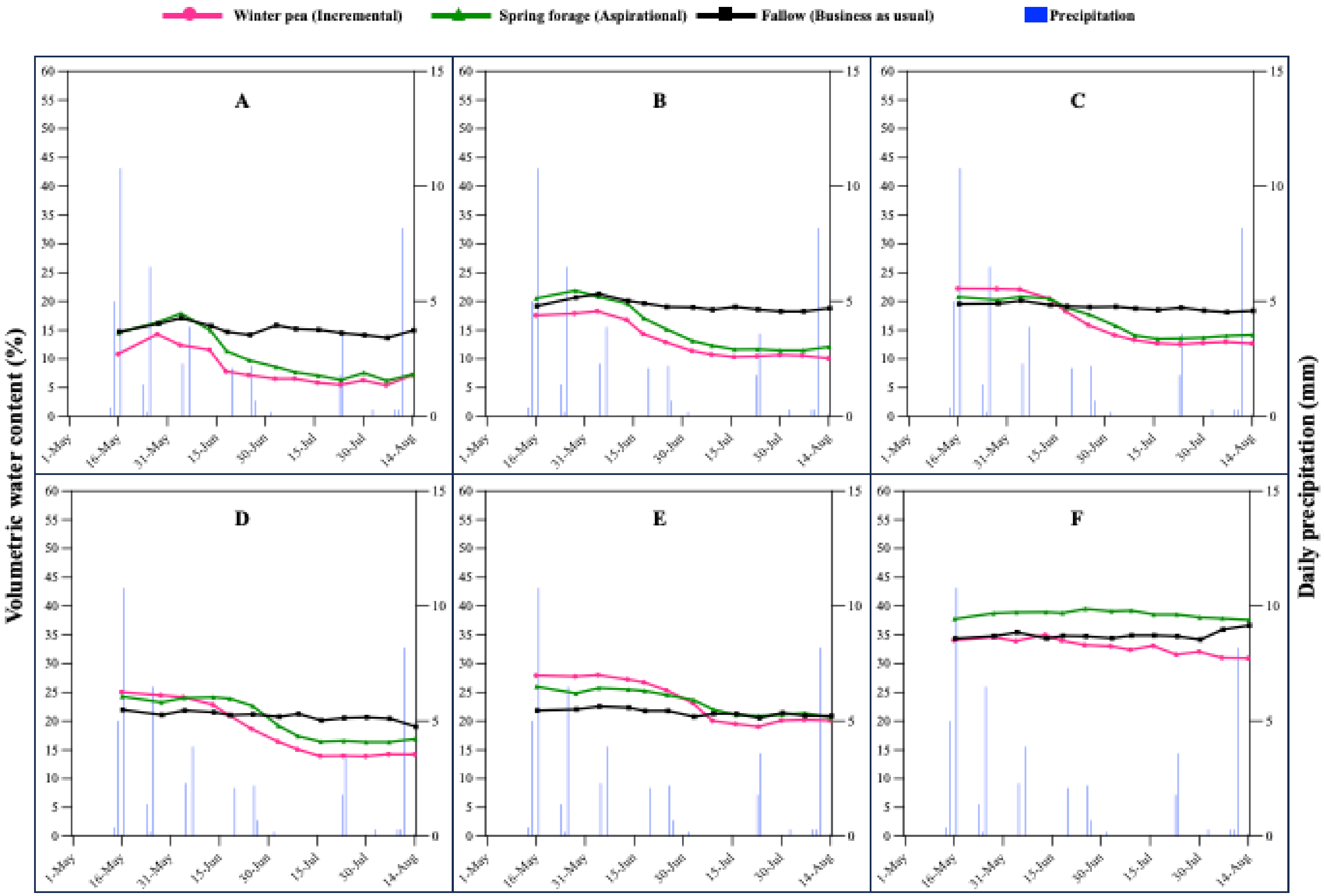

Figure 2.4. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019.

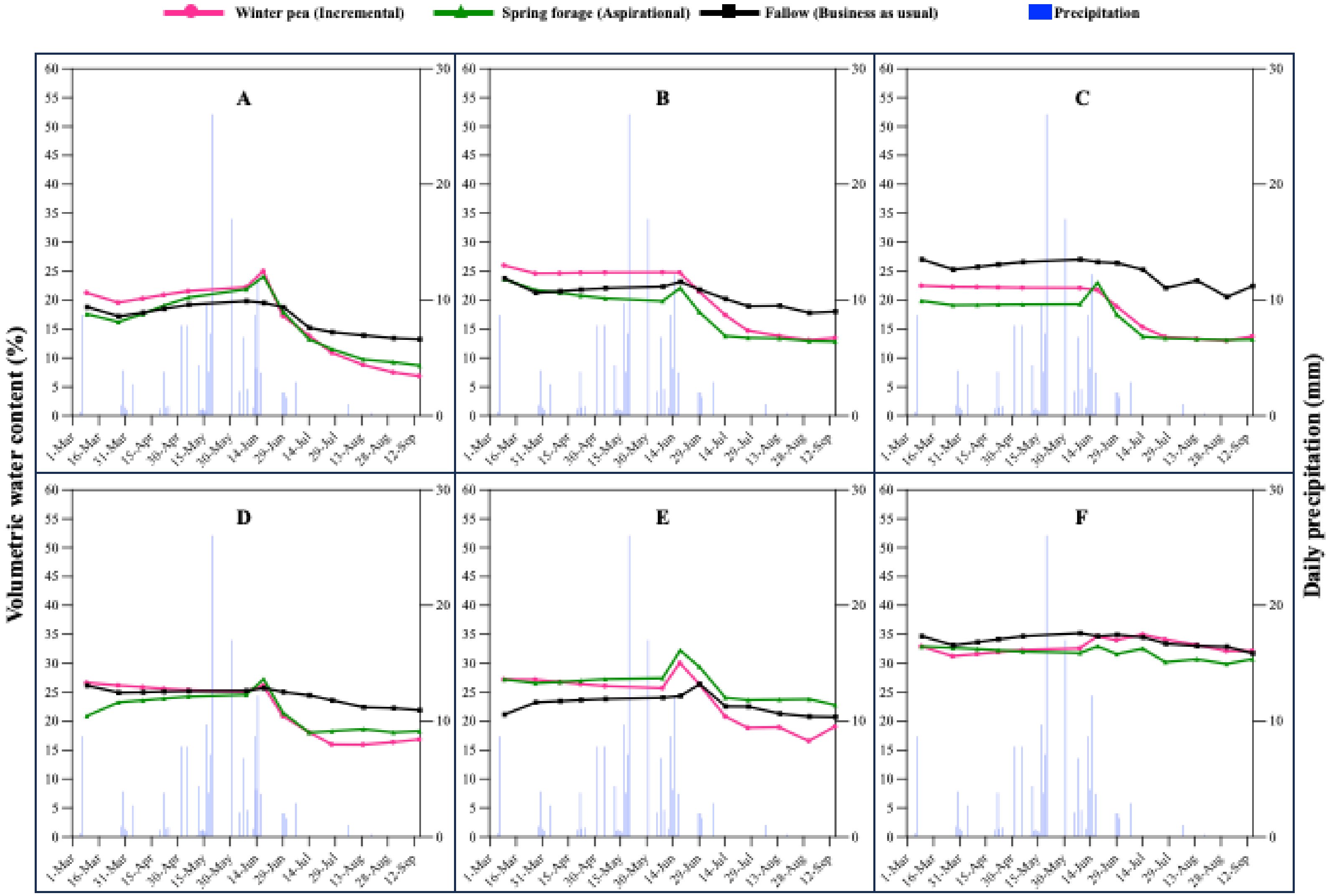

Figure 2.5. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020.

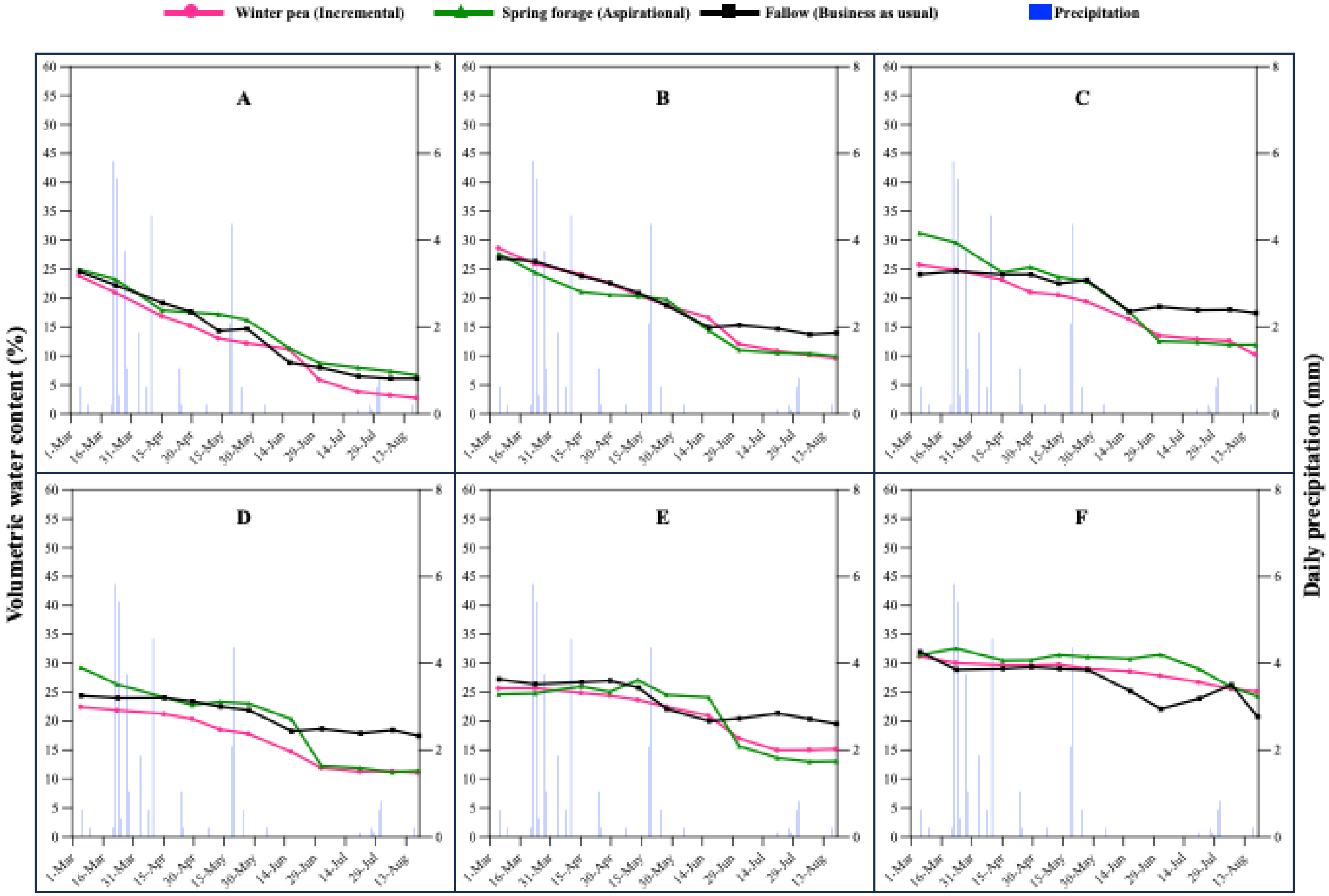

Figure 2.6. Daily precipitation during growing season and volumetric water content of winter pea (WP), spring forage mix (SFC) and Fallow in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021.

Economic Analysis

An estimate of the total gross return, annual cost and net return for individual crops in all three rotations at Genesee (Table 2.19) and St. John (Table 2.20) was completed. Seed cost for winter pea, winter wheat, spring wheat, chickpea, spring forage mix and winter forage mix were \$285.65, \$64.25, \$86.73, \$170.26, \$73.17, and \$69.04 per hectare, respectively. Additional cost of production for all crops included fertilizer cost, chemical costs (includes herbicides, fungicide and insecticide), insurance (except for fallow and forage crops), forage operation (for forage crops only), machinery operation (cost of labor, repair and fuel) and machinery replacement costs. Legumes and forage crops did not have any fertilizer costs. Forage operation cost included mowing, raking, and baling which totaled \$102.47 per hectare. All costs associate with individual crops are listed in Table 2.19 for Genesee and Table 2.20 for St. John.

At Genesee, winter pea had the highest total net return of \$1,241.36 per hectare compared to other crops. Winter wheat from incremental, aspirational, and business-as-usual rotations had similar net returns of \$454.75, \$403.15, and \$422.85 per hectare, respectively. Likewise, similar net returns were observed for chickpeas from aspirational and business-as-usual rotations with a total net return of \$704.79 and \$689.62 per hectare, respectively. Winter forage produced a total net return of \$863.46 per hectare.

At St. John, the highest return was obtained from winter wheat from the business-as-usual rotation with a net return of \$626.68 per hectare. Winter wheat from incremental and aspirational rotations had similar net returns of \$390.30 and \$430.41 per hectare, respectively. Winter pea in the incremental rotation had a net return of \$417.11 per hectare. Spring forage had a net return of \$400.34 per hectare. Spring wheat had a negative return in all three rotations with a net loss of -$119.82, -$97.71, and -$165.49 per hectare from the incremental, aspirational, and business-as-usual rotations, respectively.

Using values from the Genesee trial and the simulated 1,012 ha farm areas, the aspiration rotation which included winter forage crop in place of hard red spring wheat had an increase in net returns of 62.2% compared to the business-as-usual rotation (Table 2.21). However, the incremental rotation had a substantial decrease in quantity of seed (15.2%), chemical fertilizers (52.9%), and pesticides (23.4%) as well as savings in labor (29.9%). There were also substantial reductions in cost associated with fuel (28.0%), machinery repair (33.5%), and machinery replacement costs (19.2%) in the aspirational rotation when compared to the business-as-usual rotation. Similarly, the incremental rotation which included winter pea in place of a chickpea had a 45.6% increase in total net return compared to the business-as-usual rotation. There was a slight decrease in amount of fertilizer (5.7%), however, increase in the seed quantity (1.7%), pesticide and adjuvants quantities (3.9%), labor (2.1%), fuel (3.6%), machinery repairs (2.8%) and machinery replacement cost (3.9%) were associated with the incremental rotation compared to business as usual.

At St John, the aspirational rotation which used spring forage in place of fallow resulted in a 76.7% increase in net return when compared to the business-as-usual rotation (Table 2.22). There was a slight increase in some of the inputs when compared to the business-as-usual rotation, but substantial increases in the quantity of seed (37.2%), quantity of fertilizer (34.6%) and machinery repairs (36.1%). There also was a decrease of 13.0% in the use of pesticides in the aspirational rotation when compared to the business-as-usual rotation. Replacing fallow with winter pea in the incremental rotation resulted in an increase in total net return of 65.7% when compared to the business-as-usual rotation. Additionally, there was also a substantial increase in inputs and cost of production with an increase in total seed quantity (61.5%), pesticides quantities (20.8%), labor (43.0%), fuel (37.6%), machinery repair (101.9%), and machinery replacement costs (51.0%). The amount of fertilizer used increased slightly (5.4%) with winter pea when compared to business as usual.

Table 2.19. Total returns, total annual cost, and total net return for individual crops in incremental, aspirational, and business-as-usual rotations at Genesee using a land area of 1,012 ha.

	Business-as-usual Rotation			Aspirational Rotation			Incremental Rotation		
	Chickpea	**Winter wheat**	**Spring wheat**	**Chickpea**	**Winter wheat**	**Winter forage crop**	**Winter pea**	**Winter wheat**	**Spring wheat**
Yield (kg/ha)	2,389	6,439	3,802	2,395	6,341	6,397	3,876	6,541	3,700
Crop price ($/kg)	$0.55	$0.18	$0.22	$0.55	$0.18	$0.18	$0.51	$0.18	$0.22
Return									
Gross Return ($/ha)	$1,316.45	$1,135.70	$838.18	$1,320.16	$1,118.30	$1,128.18	$1,965.33	$1,153.69	$815.69
Total Returns ($/ha)	***$1,316.45***	***$1,135.70***	***$838.18***	***$1,320.16***	***$1,118.30***	***$1,128.18***	***$1,965.33***	***$1,153.69***	***$815.69***
Costs									
Seed Cost ($/ha) [†]	$170.26	$64.25	$86.73	$170.26	$64.25	$69.04	$285.65	$64.25	$86.73
Fertilizer Cost ($/ha) [§]	$0.00	$198.57	$221.70	$0.00	$198.57	$0.00	$0.00	$178.11	$221.70
Chemical Cost ($/ha)	$146.36	$110.73	$92.59	$146.36	$110.73	$11.81	$119.85	$110.73	$92.59
Forage Operations ($/ha)	$0.00	$0.00	$0.00	$0.00	$0.00	$102.47	$0.00	$0.00	$0.00
Machine (Labor, Fuel and Repairs) ($/ha)	$143.54	$169.98	$169.98	$136.53	$162.74	$40.15	$157.11	$170.53	$170.53
Other Expenses (5%) ($/ha)	$25.72	$29.65	$30.64	$25.38	$29.28	$11.17	$30.34	$29.68	$30.69
Interest on Operating Inputs (6.75%) ($/ha)	$27.35	$31.53	$32.59	$26.98	$31.16	$11.89	$32.27	$31.56	$32.62
Crop Insurance ($/ha)	$54.36	$49.42	$42.01	$54.36	$49.42	$0.00	$44.48	$49.42	$42.01
Machine Replacement Costs ($/ha)	$59.23	$58.71	$58.71	$55.50	$68.99	$18.19	$54.26	$64.67	$64.67
Total Annual Costs ($/ha)	***$626.83***	***$712.85***	***$734.96***	***$615.37***	***$715.15***	***$264.72***	***$723.97***	***$698.94***	***$741.54***
Net Returns ($/ha)	$689.62	$422.85	$103.22	$704.79	$403.15	$863.46	$1,241.36	$454.75	$74.16

[†] Cost of seed: winter pea $1.9 kg^{-1}, winter wheat 0.5 kg^{-1}, spring wheat 0.7 kg^{-1}, chickpea 1.2 kg^{-1}, and winter forage crop 1.0 kg^{-1}.

[§] Price of Nitrogen, phosphorus and sulfur assumed in the study were $8 kg^{-1}, $1.3 kg^{-1} and $0.9 kg^{-1}, respectively.

Table 2.20. Total returns, total annual cost, and total net return for individual crops in incremental, aspirational and business-as-usual rotations at St. John using a land area of 1,012 ha.

	Business-as-usual Rotation			Aspirational Rotation			Incremental Rotation		
	Fallow	**Winter wheat**	**Spring wheat**	**Spring forage crop**	**Winter wheat**	**Spring wheat**	**Winter pea**	**Winter wheat**	**Spring wheat**
Yield (kg/ha)	0	7,045	2,125	3,836	6,190	2,539	2,292	5,869	2,440
Crop Price ($/kg)	$0.00	$0.18	$0.22	$0.18	$0.18	$0.22	$0.51	$0.18	$0.22
Return									
Gross Return ($/ha)	$0.00	$1,242.45	$468.51	$676.48	$1,091.81	$559.69	$1,162.26	$1,035.07	$537.95
Total Returns ($/ha)	***$0.00***	***$1,242.45***	***$468.51***	***$676.48***	***$1,091.81***	***$559.69***	***$1,162.26***	***$1,035.07***	***$537.95***
Costs									
Seed Cost ($/ha) †	$0.00	$64.25	$86.73	$73.17	$64.25	$86.73	$285.65	$64.25	$86.73
Fertilizer Cost ($/ha) §	$0.00	$102.50	$122.07	$0.00	$146.98	$144.31	$0.00	$110.51	$124.74
Chemical Cost ($/ha)	$23.65	$110.73	$92.59	$11.81	$110.73	$92.59	$119.85	$110.73	$92.59
Forage Operations ($/ha)	$0.00	$0.00	$0.00	$102.47	$0.00	$0.00	$0.00	$0.00	$0.00
Machine (Labor, Fuel and Repairs) ($/ha)	$13.44	$158.12	$158.12	$40.08	$162.92	$162.92	$157.11	$170.53	$170.53
Other Expenses (5%) ($/ha)	$1.85	$24.24	$25.08	$11.37	$24.49	$25.33	$30.34	$24.74	$25.70
Interest on Operating Inputs (6.75%) ($/ha)	$1.98	$25.77	$26.66	$12.08	$26.02	$26.91	$32.25	$26.42	$27.28
Crop Insurance ($/ha)	$0.00	$49.42	$42.01	$0.00	$49.42	$42.01	$44.48	$49.42	$42.01
Machine Replacement Costs ($/ha)	$5.36	$80.73	$80.73	$25.16	$76.60	$76.60	$75.47	$88.19	$88.19
Total Annual Costs ($/ha)	***$46.28***	***$615.76***	***$634.00***	***$276.14***	***$661.40***	***$657.40***	***$745.15***	***$644.77***	***$657.77***
Net Returns ($/ha)	-$46.28	$626.68	-$165.49	$400.34	$430.41	-$97.71	$417.11	$390.30	-$119.82

†Cost of seed: winter pea $1.9 kg^{-1}, winter wheat 0.5 kg^{-1}, spring wheat 0.7 kg^{-1}, chickpea 1.2 kg^{-1}, and winter forage crop 1.0 kg^{-1}.
§Price of Nitrogen, phosphorus and sulfur assumed in the study were $8 kg^{-1}, $1.3 kg^{-1} and $0.9 kg^{-1}, respectively.

Table 2.21. Summary of total net returns, quantity of inputs and percentage change from the business-as-usual rotation for incremental and aspirational crop rotations at Genesee using a land area of 1,012 ha.

	Business as Usual	Aspirational		Incremental	
Outputs for Each Crop Rotations	**Value**	**Value**	**% (+/-)**	**Value**	**% (+/-)**
Total Net Returns ($)	409,966	664,825	(62.2)	597,004	(45.6)
All Crop Seeds (kg)	132,676	112,453	(-15.2)	134,944	(1.7)
All Fertilizers (mt. ton)	164	77	(-52.9)	155	(-5.7)
All Pesticides & Adjuvants (liters)	7,056	5,407	(-23.4)	7,332	(3.9)
Machinery Labor (hours)	1,883	1,320	(-29.9)	1,923	(2.1)
Machinery Fuel Use (liters)	317,870	229,023	(-28.0)	329,257	(3.6)
Machinery Repairs ($)	41,425	27,560	(-33.5)	42,573	(2.8)
Machinery Replacement Costs ($)	59,575	48,120	(-19.2)	61,912	(3.9)

Table 2.22. Summary of total net returns, quantity of inputs and percentage change from the business-as-usual rotation for incremental and aspirational crop rotations at St. John using a land area of 1,012 ha.

	Business as Usual	Aspirational		Incremental	
Outputs for Each Crop Rotations	**Value**	**Value**	**% (+/-)**	**Value**	**% (+/-)**
Total Net Returns ($)	139,930	247,200	(76.7)	231,825	(65.7)
All Crop Seeds (kg)	83,537	114,623	(37.2)	134,944	(61.5)
All Fertilizers (mt. ton)	81	109	(34.6)	85	(5.4)
All Pesticides & Adjuvants (liters)	6,070	5,281	(-13.0)	7,332	(20.8)
Machinery Labor (hours)	1,344	1,394	(3.7)	1,923	(43.0)
Machinery Fuel Use (liters)	239,247	252,944	(5.7)	329,257	(37.6)
Machinery Repairs ($)	21,091	28,702	(36.1)	42,573	(101.9)
Machinery Replacement Costs ($)	56,258	60,151	(6.9)	84,938	(51.0)

Discussion

In this study, an incremental crop rotation that included winter pea and an aspirational crop rotation that included a winter or spring forage crop was compared to the standard crop rotation in two different cropping regions of the IPNW. In the annual cropping system, winter pea replaced a spring legume and winter forage replaced hard red spring wheat. Likewise in the intermediate precipitation region, the traditional fallow was replaced with either winter pea or spring forage. At Genesee, an annually cropped region of the IPNW, incorporation of winter pea did not have any significant impact on the production of subsequent winter and spring wheat crops. Additionally, when replacing spring wheat with a winter forage mix, there was no impact on the production of chickpea or winter wheat. However, at St. John, a transitional cropping region, when winter pea and spring forage replaced fallow in the cropping system, there was a yield reduction of 12 and 16% in winter wheat, respectively. However, there was the added benefit of a winter pea crop or a spring forage crop which resulted in an average yield of 2,292 kg ha^{-1} for winter pea and 3,835 kg ha^{-1} dry biomass for the spring forage crop. Diversification of the cropping systems was advantageous both in terms of productivity and profitability at both locations. The first year of the study was a baseline year since the previous crop was the same across the site and rotational impacts could not be evaluated. Comparisons of cropping systems were done after the completion of an entire 3-year rotation.

The historical average annual precipitation of the high precipitation region is 50 cm compared to 35 cm in the intermediate precipitation region (Papendick, 1996). Weather in the IPNW has been projected to be impacted significantly by climate change. Projections have shown that changes in precipitation and temperature will reduce the hectares of annual cropping and there will be a corresponding increase in the hectares of transitional cropping (crops grown in 2 of 3 years) and winter wheat – summer fallow in the next 32 to 62 years (Kaur et al, 2017). Some of the significant changes that are likely to occur include warmer and wetter spring conditions resulting in earlier maturation of winter crops and delayed planting of spring crops. Summers in the IPNW will get drier and warmer, increasing heat and drought stress and reducing the yield potential.

The weather data collected during this study in some years resembles predicted models with wet springs and hot and dry summer conditions. Planting in spring of 2019 was significantly delayed until late April to early May due to heavy precipitation in the spring (Feb-April). Winter crops benefited due to higher precipitation during active growing season through kernel development in second and third year of the study. This partially explains higher winter wheat yield in 2018-19 and even higher yield in 2019-20 at both locations. In addition, the only year when rotation did not impact winter wheat yield was during the 2019-20 season at St. John, when precipitation was higher in the spring resulting in above average grain yields. Also, the unusually dry and warm summer (June-July) in 2021 resulted in significant drought stress and early plant maturity leading to reduced yield and quality of all crops. The increased grain protein content along with low test weights and 1,000 seed weights in 2020-21, particularly in the soft white winter wheat, indicates drought stress (Mahdavi et al., 2022). The forage yield and nutritive value of forage crops are also negatively impacted by heat stress (Nelson and Moser, 1994), and this was evident in 2020-21. Projections from Stöckle et al. (2018) have shown that winter wheat will have increased yield over spring wheat in the intermediate region while in the high precipitation region, winter wheat, winter pea and winter canola would benefit more from this seasonal variability over the period of this century compared to spring crops. Fall planted crops that will mature earlier and are more likely to avoid heat stress during the summer could be advantageous compared to crops that are planted in the spring (Chen et al., 2006; Chen et al., 2012).

Incorporation of winter peas in the intermediate and high rainfall region of the IPNW is promising in regard to yield potential. Compared to chickpea at Genesee, the yield of winter pea was 40% higher. Previous work in the region has shown similar gains in productivity with winter pea. Schroeder et al. (2019) reported an average winter pea production of 3,115 kg ha^{-1} compared to 2,285 kg ha^{-1} for spring peas from variety trials in the Genesee area. Other studies in Genesee have shown winter pea yield being about 1,800 kg ha^{-1} higher than spring peas (Chen et al, 2006). Similarly, replacing fallow at St. John with winter pea produced 2,292 kg ha^{-1} of seed, improving the productivity of the system. In the low precipitation region of IPNW, Schillinger (2020) reported winter pea yield of 2,560 kg ha^{-1} compared to 870 kg ha^{-1} for spring pea.

Forage crops planted in the intermediate and high precipitation region in the IPNW produced an average of 5,883 kg ha^{-1} of dry matter from the winter mix at Genesee and 3,494 kg ha^{-1} of dry matter from the spring mix at St. John. Research on forage production in the IPNW is very limited. Studies conducted in Kansas and Tennessee have produced comparable forage yield (Holman et al., 2018; Bracey et al., 2022) with fall seeded forage crops. Holman et al. (2018) reported biomass production ranging from 301 to 4,161 kg ha^{-1} which included crops such as hairy vetch, winter lentil, and winter pea alone or planted with winter triticale. A study in Tennessee evaluated several fall-seeded cover crops species such as peas, vetches, clovers, cereals and brassicas for forage biomass production and the dry matter production ranged from 475 to 4,282 kg ha^{-1} (Bracey et al., 2022). A diverse winter forage crop was difficult to establish in Genesee with only winter peas, winter wheat, winter oat and crimson clover contributing towards the dry weight. The difference in seed size between species and the need to place seeds at different soil depth plays a crucial role for better establishment of these mixtures. This can be potentially resolved by using mixtures with similar seed sizes along with seeding the mixture during periods of adequate soil moisture (Kumar et al., 2020). Conversely, the spring forage crop at St. John performed well in terms of crop establishment, forage production and forage nutritive value. Planting in the spring provides a distinct advantage because a greater diversity of crops can be incorporated into the mix and cold-sensitive species do not have to contend with winter conditions.

The timing of haying and grazing as well as composition of the forage mix are crucial to maximize yield and maintain forage quality. As the crops matured in this study, there was a significant improvement in the yield although the forage quality declined significantly. Forage quality declines with advancing maturity where the digestibility of forage decreases, intake by animals decreases and the fiber amount increases (Ball et al., 2001). The forage quality of the mix depends highly on the component of the mixtures. Legumes such as pea, clover, vetch, etc. provide forage with high nutritive value along with fixing atmospheric nitrogen (Schultze-Kraft et al., 2018). Brassicas such as canola, radish, rape, turnip, etc. have rapid growth under optimum temperature (Villalobos and Brummer, 2017) and provide high quality forage (Dillard et al., 2020) along with providing a grazing opportunity until late in the season. Cereals such as wheat, oat, barley, rye, etc. have excellent dry matter production (Eskandari et al., 2009), but the forage quality is lower than brassicas and legumes. An ideal mixture of legumes and cereals is important for stable forage yield with superior quality (Brink et al., 2015). A greater diversity of plant species has higher multifunctionality compared to monocultures (Finney et al., 2017).

In addition to maximizing forage yield and quality, timing of termination is highly important to conserve moisture for subsequent crops in the rotation, particularly in the intermediate precipitation region. Delaying the termination of the forage mix until late summer can reduce the moisture content in the soil and will significantly impact the production of the subsequent crop in the rotation (Schlegel and Havlin, 1997; Nielsen and Vigil, 2005; Holman et al., 2018). As observed at St. John, replacing fallow with a spring forage or winter pea significantly reduced the yield of the following winter wheat crop. Furthermore, if the forage crops produce seed that becomes physiologically mature, volunteer plants could be a nuisance in subsequent crops, requiring additional management or reducing the quality of that crop.

The two regions examined in this study had differing responses to the incorporation of winter pea and forage crops. While the yield of winter wheat was not impacted by incorporation of either winter pea or winter forage mix at Genesee there was a significant reduction in winter wheat yield when following spring forage or winter pea compared to fallow at St. John in 3 out of 4 years of study. The Genesee region has higher annual precipitation and can therefore support more diverse crops in the cropping system and a greater frequency of cropping (Huggins et al., 2015). Conversely, at St. John fallow is often practiced in the year prior to winter wheat production due to the lower annual precipitation. Previous work in various dryland cropping systems has demonstrated that replacement of fallow by various crops will reduce the yield of winter wheat (Nielson and Vigil, 2017; Miller et al., 2018). However, the productivity of winter pea and forage mixes in place of fallow helped to offset the loss that occurred due to reduced winter wheat yields. Thus, the overall productivity increased with intensification of the cropping system in the intermediate precipitation region.

The incremental and aspirational crop rotations had differences in the amount of fertilizer used. There was a slight reduction in the quantity of nitrogen fertilizer required for winter wheat at Genesee following winter peas compared to the winter wheat in the business-as-usual rotation. Winter peas have a higher quantity of biological nitrogen fixation compared to spring peas and/or other spring legumes. This is due to a greater duration of time in which nitrogen fixation can occur in winter peas as well as a more robust root system compared to spring peas (McGee et al., 2017). The quantity of applied nitrogen was considerably lower for winter wheat in the business-as-usual rotation at St. John compared to incremental and aspirational rotations. This was not completely unexpected due to higher mineralization in fallow (Campbell and Paul, 1978) due to relatively high moisture in the fallow land (Myers et al., 1982) compared to cropped land. While a greater rate of nitrogen was required when winter wheat followed winter pea compared to when it followed fallow, the quantity was still significantly lower than that for winter wheat following the forage crop. This reflects increased nitrogen availability from growing winter pea.

The quantity of chemical pesticides and adjuvants used in controlling weeds and pests differed between the rotations. There was a reduction (23.4 at Genesee and 13.4% at St. John) in the use of pesticides with the aspirational rotation while there was an increase (3.9% at Genesee and 20.8% at St. John) with the incremental rotation. The increase in use of pesticide in the incremental rotation at both locations could be accounted for the use of insecticides for the control of pea pod weevil and pre- and post-plant herbicide for weed control in winter peas. Forage mixes from the aspirational rotation, being a low input crop, required less use of chemicals at both locations compared to spring wheat at Genesee and fallow at St. John.

Competition with forage crops has shown weed suppression in dryland cropping of the great plains (Entz et al., 2002), decreasing the need to use of herbicides for weed control.

Apart from increasing productivity and farm profitability, the diversified rotations at St. John would improve the sustainability of the cropping system. Fallow is presently used in the intermediate precipitation regions but is often associated with loss of soil organic carbon (Blanco-Canqui et al., 2010), increased wind and water erosion (Sharratt and Feng, 2009) and degraded soil properties (Shaver et al., 2003). Incorporation of winter peas or spring forage could reduce or eliminate fallow in these systems. Likewise, adding additional options for fall seeding in the annually cropped, higher precipitation region of northern Idaho and eastern Washington would reduce the reliance on spring planting. Fall seeded crops would benefit the cropping system by providing ground cover during the winter months and reducing the risk of water erosion during the late fall and winter months (Dabney et al., 2001; Olivera et al., 2019).

Volumetric water content was measured in all rotations throughout the duration of the study. While few dramatic differences in VWC were observed between rotations, replacement of fallow at St. John with either winter pea or spring forage crops significantly reduced the soil moisture content in the top 30 cm of soil. This likely contributed to the reduction in yield of winter wheat following winter pea and spring forage. Given the lower annual precipitation at this location, this result was not unexpected. Adequate seed zone moisture in the fall is crucial for adequate establishment of winter wheat, especially in the lower precipitation regions. Winter pea is a low water use crop (McGee et al., 2017) and forage crops were documented to be efficient users of available water and precipitation (Nielsen et al., 2005) compared to a winter or spring wheat, leaving more water in the profile for a subsequent crop. However, reduction in soil moisture near surface and seed zone significantly impacts fall emergence and overall productivity of winter wheat (Granatstein, 1992). Similar reductions in available water for winter wheat production were reported by Nielsen and Vigil (2017) in semi-arid dryland system in Akron, CO when fallow was replaced by pea. Lyon et al. (2004) stated a 22 to 43% reduction in winter wheat yield when fallow was replaced by either oat/pea or canola in western Nebraska. Miller et al. (2018) found about 15% reduction in winter wheat yield when followed by winter pea for forage compared to fallow. In the driest region of the IPNW, annual no-till cropping was practiced with incorporation of winter wheat, spring wheat, spring barley, yellow mustard and safflower in various combinations, which protected against soil erosion and helped improved soil health (Schillinger et al., 2007). However, there were risks associated with low profitability and income variability compared to the winter wheat-fallow rotation. Young et al. (2015) observed similar findings like improved soil quality but lower economic returns from annual no till spring cereal cropping system in Ralston, WA. Yet, the diversified cropping systems were more productive and profitable in the high and intermediate precipitation region of IPNW.

With the incorporation of winter peas and forage mixes in the crop rotation, there was an increase in farm profitability over three years compared to the traditional rotation. Winter forage mix and winter pea had higher productivity as well as an increased total net return compared to the crops they replaced in the traditional rotation at Genesee. Although winter wheat productivity was decreased when winter pea and spring forage mix replaced fallow at St. John, the farm profitability increased by more than 65% with the annual rotation including winter pea or spring forage crop. Rosenzweig et al. (2018) reported a 70 to 80% increase in net operating income following diversification of cropping a system with crops such as corn, sorghum, millet and peas compared to traditional winter wheat-fallow rotation in semi-arid high plains. Nielsen et al. (2016) also reported an increase in farm profitability with the incorporation of forages in the crop rotation in the central great plains.

Conclusion

Diversification of the cropping system in the IPNW by incorporation of winter pea or forage crops into the crop rotation was successful. Spring legume and spring cereals in the high precipitation region of IPNW were replaced with fall planted peas and forage crops, while fallow in the intermediate precipitation region was replaced with winter pea and spring forage crops. Not only did these alternative crops improve the total productivity of the cropping system, but they increased the farm profitability. Additionally, there was a decrease in the use of fertilizers and pesticides within the crop rotations that integrated forage crops, reducing the dependency on synthetic chemicals.

The recent release of new winter pea cultivars from regional breeding entities such as the USDA-ARS and ProGene LLC as well as increasing knowledge of optimal agronomic practices to maximize productivity are positioning this crop to become a more substantial component to cropping systems in the IPNW. However, some challenges to adoption of winter pea or winter forage crops on a large scale remain. For winter peas, future research should focus on broadleaf weed and pea pod weevil control. In the case of forage crops, there is a need to identify or develop additional forage crops adapted to the region that can be fall seeded to increase the diversity of the forage mix, improve forage yield and maximize the nutrition of the resulting forage. Another key point that must be addressed to increase the success of these diversified crops in the IPNW is to increase marketing. Successful production of green and yellow colored food grade winter peas and improving the nutritive value of forage crops will help to fetch a higher price in the market, but increased access to markets will be needed.

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Chapter 3: Optimizing Winter Pea Production in the Inland Pacific Northwest

Introduction

The Inland Pacific Northwest (IPNW) is the rainfed region of the Pacific Northwest consisting of northeastern Oregon, eastern Washington, and northern Idaho. The IPNW is dominated by a cereal-based cropping system, winter wheat being the main crop in a typical rotation. The IPNW is truly diverse in terms of topography, climate, and soil characteristics. There exists a precipitation gradient across the region with annual precipitation ranging from 18 cm in the west to above 50 cm in the east. Based on this precipitation gradient, the IPNW is divided into three distinct cropping zones: low precipitation region, intermediate precipitation region and high precipitation region (Karimi et al., 2018). These three regions have their own distinct cropping system. The common cropping pattern in the low precipitation region is a two 2-year (winter wheat – fallow) rotation, the intermediate precipitation region is a 3-year (winter wheat – spring wheat – fallow) rotation while the high precipitation region often is either a 3-year (winter wheat - spring cereal - spring legume or brassica) or a 2-year (winter wheat – spring legume or brassica) rotation. The majority of the precipitation across the IPNW is observed during the cool winter and early spring months which are typically followed by a hot and dry summer. Due to the climatic conditions, growers have very few alternatives crops to use in the region (Kirby et al., 2017).

The IPNW will likely be impacted by climate change and seasonal variability. Stöckle et al. (2018) projected that by 2040 to 2069 AD that the annual temperature will increase by 2.7°C. Pan and Borrelli (2015) projected warmer temperature throughout the year along with wetter spring and drier summers. These conditions will potentially cause water-logged conditions and delays in planting in the spring with increased drought stress during the growing season. Additionally, with these projected changes in climate, Kaur et al. (2015) further suggested that there will be a shift of cropping regions with portions of the high precipitation acreage changing to intermediate acreage and intermediate precipitation acreage shifting to low precipitation acreage. Due to these projected changes and greater climate variability, there is a need to develop a robust and resilient cropping system for the IPNW with identification and inclusion of suitable alternative crops in the rotation.

Spring legumes like chickpea, lentil and spring pea are already being grown and are well adapted in the intermediate and high precipitation region of the IPNW. However, in some instances, spring seeding is delayed or prevented due to wet planting conditions (Kirby et al., 2017). Delayed seeding can result in these legume crops flowering later during very hot and dry conditions in late spring and early summer, reducing seed set and grain yield of these crops. Winter pea (*Pisum sativum* L.) is a potential crop that can be planted in place of spring legumes. Winter pea is an excellent rotational crop for cereal crops (McGee et al., 2017) and can be grown successfully in the intermediate and high precipitation regions of the IPNW. Additionally, winter pea has been successfully produced in the driest region of the IPNW (Schillinger, 2020). Inclusion of legumes in a cropping system has been found to provide numerous benefits to subsequent crops (Krupinsky et al., 2006).

Pea is an annual cool season crop that was domesticated about 10,000 years ago (Mikić, 2012) and has been cultivated since for various purposes ranging from food, animal feed, forage, cover crop, and green manure (Pavek, 2012). In the IPNW, Austrian winter pea has been grown since 1932 as a source of seed for green manure or cover crop. The first cultivar developed in the region was reported in 1973 with the release of Austrian winter pea ‘Fenn’ (Murray and Slinkard, 1973). Public and private sectors in the IPNW are continually developing superior cultivars that are well adapted to the region (Kirby et al., 2017). The goals of current winter pea breeding programs include increased winter hardiness, improved seed size, as well as green and yellow seed color and clear seed coat. In 2009, there was a change in regulation and peas were categorized on the basis of seed characteristics rather than based on the time of year when they were planted (USDA-GIPSA, 2009). Some of the newer varieties have improved disease and pest resistance, improved yield and superior seed quality as well. Some recent studies evaluated productivity of winter pea in the IPNW, with a focus on the low precipitation region. This expanded access for winter pea to be sold in the food market and shifted the breeding focus toward developing improved food grade winter pea cultivars. Dry edible pea (including dry edible spring pea, dry edible winter pea and Austrian winter pea) were cultivated on nearly 27,500 ha in Washington state and 11,330 ha in Idaho in 2021 (USDA-NASS, 2021). While there is no documentation of acreage of winter pea versus spring pea production in Washington and Idaho, observations of fields and conversations with seed suppliers and breeders indicate that the majority of the pea acres were spring pea.

Winter pea clearly has an advantage over spring legumes, especially spring pea. Winter pea typically produces higher yield compared to spring pea. McGee et al. (2017) reported the winter pea yield being as high as 300% compared to spring pea. Apart from being higher yielding, winter pea produces higher above and below ground biomass (Chen et al., 2006), have better weed competitiveness, early flowering and maturity, and provide better ground cover compared to spring pea (Kirby et al., 2017). Winter pea is widely adapted to various climatic conditions, and assist in breaking weed, disease, and pest incidence in the cereal-based cropping system. Pea is a relatively low input crop and can fix atmospheric nitrogen in symbiosis with *Rhizobium leguminosarum* (McGee et al., 2017). Due to the greater above and below ground biomass, there is the potential for more nitrogen to be fixed in a winter pea crop compared to spring pea. Kirby et al. (2017) estimated that 34 kg ha^{-1} of residual nitrogen will be available to subsequent cereal crops with 4200 kg ha^{-1}grain production of winter pea. Due to the larger seed size compared to cereal crops, winter pea can be planted as deep as 15 cm below the soil surface in drier areas of the IPNW, which is beneficial for our rainfed setting (Schillinger, 2020). Seeding 15 cm deep is required in the winter wheat-fallow region to reach soil moisture at planting but would likely be too deep in the high and intermediate precipitation regions.

These previous studies provide valuable information on the production potential of winter pea. However, there has been little work done to optimize the production of winter pea. Guidelines have been developed by seed companies and research institutions in the region for spring pea, but few resources exist for winter pea. Details on agronomic factors like appropriate planting time, seeding depth, seeding rate, effect of application of starter fertilizers for winter peas are lacking. While the acreage of winter pea production is growing, there is a need to refine the guidelines for winter pea production in the high and intermediate precipitation regions of IPNW. The objectives of this study were to identify the best agronomic management practices for winter pea in the annual and transitional cropping region of the rainfed IPNW with regard to planting date, seeding rate and fertilizer requirement and to estimate the impact on total net returns of winter pea with variable seeding rates.

Materials and Methods

Location

Field studies were established in Genesee, ID (46.59°N 116.95°W, 841 m elevation) and St. John, WA (47.10°N 117.58°W, 632 m elevation) during the growing season from 2018 to 2020 to determine the effect of planting date, fertilizer application and seeding rate on two winter pea cultivars. Soil in Genesee was characterized as a Palouse silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) and in St. John for first and second year, the soil was Calouse silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) while for third year it was Covello silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) (Web Soil Survey, NRCS). Composite soil samples were collected from each site every year from soil surface to 120 cm deep at 30 cm increments and were sent to Northwest Ag. Consultants (Kennewick, WA) to determine the soil nutritional status prior to planting.

Experimental Design

The three planting dates tested in the study included late September, mid-October and late October or early November, hereafter referred to as early, intermediate, and late planting, respectively. The specific planting dates for each year at each location are in Table 3.1.

Table 3.1. Planting dates for winter pea from 2017 to 2019 at Genesee, ID and St. John, WA.

	2017-18		2018-19		2019-20	
Planting	Genesee	St. John	Genesee	St. John	Genesee	St. John
Early	27 Sept	29 Sept	27 Sept	27 Sept	30 Sept	27 Sept
Intermediate	17 Oct	17 Oct	16 Oct	16 Oct	17 Oct	17 Oct
Late	30 Oct	30 Oct	30 Oct	30 Oct	7 Nov	7 Nov

Within each planting date, strips of plots with and without fertilizer application were randomly assigned. The plots receiving the fertilizers received phosphorus and sulfur (23 kg ha^{-1} each) in the form of triple superphosphate and sulfate of potash. Within each strip of the presence and absence of fertilizer treatment, four seeding rates of 65, 87, 108 and 130 seeds m^{-2} and two cultivars of winter pea were assigned in a factorial arrangement. The winter pea cultivars included Windham developed by ARS-USDA, Pullman, WA (McPhee et al. 2007) and Blaze developed by ProGene Inc., Othello, WA. Both of these cultivars are feed grade winter pea.

The experimental design was a strip-split plot design. Planting dates were assigned as the main plot while fertilizer application was randomly assigned as a sub plot within each main plot. Within each fertilizer treatment, winter pea cultivars and seeding rate were nested. Each treatment was replicated four times. Each individual plot was 1.5 m wide and 6.1 m in length which were reduced to 4.6 m in length for harvest.

Field trial management

Windham and Blaze seeds were treated with fungicides, insecticide and molybdenum prior to planting (Apron 0.10 ml kg^{-1}, Maxim 0.05 ml kg^{-1}, Cruise 0.33 ml kg^{-1} and molybdenum 0.07 ml kg^{-1}). Additionally, seeds were inoculated with *Rhizobium leguminosarum* (Brand: EXCEED Superior Legume Inoculant) on the same day of planting at the rate of 160 g kg^{-1} of seed. The trial was seeded into spring barley stubble at Genesee and spring wheat stubble at St. John in all years using a 5-row direct-seed drill equipped with Flexi-coil Stealth hoe-type openers that plants in paired rows with 25 cm row spacing and allows fertilizer to be banded below and between paired rows. Seeding depth was maintained between 3.75 to 5 cm depending on soil and moisture conditions. Prior to planting, each site was sprayed with glyphosate to eliminate weeds and volunteer crops. Both pre- and post-emergence herbicides were applied to control weeds following strategies consistent with winter pea production in the area. Fields were swept for pea weevil, *Bruchus pisorum*, and management was conducted using insecticides during flowering at 10 to 12 days interval depending on the weevil infestation.

Data collection

Plant population was measured every spring, counting the total number of plants in a 1 m row from three random points in each plot. After podding, vine length was measured and just prior to harvest, canopy height of the winter pea was estimated. Plots were harvested using a Wintersteiger plot combine. The harvest date for each year at both sites is listed in Table 3.2. At harvest, data collected included grain yield, grain protein and 1,000 seed weight. Grain protein was determined using a Foss Infratec Nova (Foss, Hilleroed, Denmark). Economic analyses were conducted to determine whether variables examined in this study influenced returns.

Volumetric water content was measured in the plots planted during the late September planting using the Delta T-PR2 Profile probe (Delta-T Devices, Houston, Texas). Access tubes were installed in each plot after planting. Probes were inserted into the access tubes at 6 to 8 or 10-to-14-day intervals, depending on the year. Measurements were recorded at depths of 10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm.

Table 3.2. Harvest dates for winter pea from 2018 to 2020 at Genesee and St. John.

	2017-18		2018-19		2019-20	
Harvest	Genesee	St. John	Genesee	St. John	Genesee	St. John
Early	25 Jul	18 Jul	1 Aug	18 Jul	12 Aug	3 Aug
Intermediate	31 Jul	26 Jul	8 Aug	18 Jul	12 Aug	3 Aug
Late	31 Jul	26 Jul	8 Aug	26 Jul	12 Aug	24 Aug

Data analysis

Data analysis was conducted using SAS version 9.4 (SAS Institute, 2016). Analysis of variance (ANOVA) was performed using the general linear model. Data were analyzed separately for each location and were pooled over three years. Year, planting date, seeding rate, and cultivar were considered random effects while fertilizer application was a fixed effect. The means were separated using the Fisher's least significant difference with an alpha of 0.05.

Economic Analysis

Enterprise budgets were created for different seeding rates of winter peas using the same model that is described in Chapter 2. Total net returns were estimated for each seeding rate using the same assumptions and procedures.

Results

Soil Tests

Pre-plant soil samples were analyzed by Northwest Agricultural Consultants, Kennewick, WA for each trial location (Table 3.3). The analytical methods for each of the estimated soil characteristics are the same procedures as outlined in Chapter 2. The soil at both locations had pH between 5.0 and 5.6. Organic matter ranged from 2.97 to 3.08% at Genesee and from 2.16 to 2.45% at St. John. The total nitrogen at Genesee was 114, 20 and 47 kg ha^{-1} for 2018, 2019 and 2020, respectively. At St. John, the total nitrogen was 74, 20 and 52 kg ha^{-1} for the same three years, respectively. Concentration of phosphorus was between 3 to 4 ppm at both locations during the study period. Potassium ranged between 233 to 281 ppm at Genesee and 184 to 256 at St. John. Sulphur concentration was 3 ppm at both locations in 2018, however for the second and third year, concentration was 2 ppm at both locations.

Table 3.3. Soil characteristics of top 30 cm of soil at Genesee, ID and St. John, WA during three growing seasons from 2017 to 2020.

		pH	OM (%)	N (kg ha^{-1})	P (ppm)	K (ppm)	S (ppm)
Genesee	2017-18	5.2	2.97	114	4.0	281	3
	2018-19	5.6	3.08	20	3.4	258	2
	2019-20	5.3	3.01	47	3.1	233	2
St. John	2017-18	5.2	2.16	74	3.2	184	3
	2018-19	5.5	2.17	20	3.8	256	2
	2019-20	5.3	2.45	52	3.3	207	2

Weather

Total annual precipitation during the growing season (September-August) varied across location and years (Tables 3.4 and 3.5) (NOAA weather stations). The 2017/18 growing season received higher precipitation compared to the 2018/19 and 2019/20 seasons with 56.3 and 45.1 cm at Genesee and St. John, respectively. The total precipitation was 44.8 and 45.5 cm in 2018/19 and 2019/20, respectively at Genesee while at St. John, it was 36.1 and 38.1 cm in 2018/19 and 2019/20, respectively. Comparing the two locations, Genesee received about 19.5%, 19.8% and 16.2% higher annual precipitation than St. John for each of the three growing seasons.

Among the three years, the maximum, minimum and average temperatures during fall months (Sep-Nov) were slightly cooler in 2019/20 when compared to 2017/18 and 2018/19 at both locations. The winter (Dec-Feb) and spring (Mar-May) months of 2018/19 were cooler than the other two years. Looking at the summer months (Jun-Aug), the temperatures were similar in all years at both locations. The 2018/19 growing season had minimum temperature as low as -7.2°C at Genesee in February and -7.0° C at St. John. The highest maximum temperature recorded during the study period was 30.3° C and 30.1° C in July of the first year.

Table 3.4. Mean monthly temperature and total monthly precipitation for Genesee, ID for the growing season from 2017 to 2020.

Month	2017/2018				2018/2019				2019/2020			
	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)
Sept	22.1	8.9	15.3	26.0	21.7	9.1	13.5	3.5	20.9	10.7	13.8	29.3
Oct	13.1	4.2	7.0	59.2	14.1	4.7	8.0	20.5	10.8	1.7	4.5	30.0
Nov	6.2	1.8	2.8	69.6	6.7	0.7	2.5	56.6	6.9	0.2	1.3	14.5
Dec	-0.8	-4.4	-3.2	104.8	1.7	-2.3	-1.2	60.6	3.4	-1.0	0.8	48.8
Jan	4.0	0.6	1.2	62.9	2.0	-2.3	-0.9	34.9	4.2	-0.1	0.3	54.6
Feb	2.5	-3.2	-1.1	52.3	-1.8	-7.2	-4.8	61.8	5.6	-0.5	0.6	86.3
Mar	7.7	0.3	2.8	29.2	6.5	-3.9	-0.4	16.2	8.5	0.8	2.9	26.1
Apr	12.6	4.0	7.1	60.6	13.2	4.5	7.3	90.7	14.3	3.4	7.6	24.6
May	20.0	9.8	14.1	53.7	19.9	9.0	13.3	52.8	17.7	7.2	11.4	85.3
Jun	21.3	9.9	14.7	35.8	22.1	10.9	15.5	30.5	20.0	10.0	14.0	48.1
July	30.3	14.6	20.5	0.0	27.0	13.3	18.5	11.3	27.6	13.3	18.8	4.3
Aug	28.5	14.9	20.0	8.7	29.5	15.5	20.6	8.8	28.9	16.2	20.9	3.2

(NOAA weather data)

Table 3.5. Mean monthly maximum and minimum temperature and total monthly precipitation for St. John, WA for the growing season from 2017 to 2020.

Month	2017/2018				2018/2019				2019/2020			
	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)	Max Temp (° C)	Min Temp (° C)	Ave Temp (° C)	Precip. (mm)
Sept	22.8	9.9	17.2	17.0	21.0	8.0	15.4	0.4	20.4	9.3	15.3	30.1
Oct	13.5	3.8	9.0	51.7	14.6	3.2	9.8	12.1	10.8	0.8	6.2	36.9
Nov	6.7	2.1	4.6	62.9	6.8	-0.7	3.6	44.4	6.9	-1.1	3.1	13.4
Dec	0.0	-4.1	-2.2	70.0	2.5	-2.1	0.8	74.8	3.7	-0.8	0.2	32.8
Jan	5.0	0.8	2.8	45.6	3.2	-1.2	1.1	39.8	4.4	-0.4	0.5	46.8
Feb	2.6	-3.4	0.1	46.2	-1.6	-7.0	-5.1	60.2	5.1	-1.7	2.3	61.2
Mar	8.3	0.7	5.0	30.0	5.3	-4.7	1.3	13.5	8.7	-1.0	4.1	14.5
Apr	12.9	3.4	8.6	49.6	13.4	3.8	8.9	57.0	14.2	1.9	8.6	9.1
May	21.5	9.8	16.3	40.2	20.2	8.4	14.8	24.3	17.4	6.2	12.6	85.7
Jun	21.3	8.7	16.2	29.6	23.3	10.4	17.5	11.2	20.3	9.2	15.7	44.9
July	30.1	12.5	22.2	1.4	27.0	12.5	20.3	5.6	28.1	11.4	23.3	4.5
Aug	28.3	13.0	21.6	6.7	28.5	14.0	21.8	17.5	28.8	12.2	24.0	1.2

(NOAA weather data)

Analysis of Agronomic Measurements

The agronomic measurements from winter pea grown at Genesee were analyzed. The ANOVA table for Genesee and St. John is attached in Appendix E. In most instances, main effect of year, planting date, seeding rate and cultivar had significant impact on the growth, yield, and quality of winter pea. However, the main effect of fertilizer application did not have any significant impact except for grain yield at St. John. There was also a significant interaction between year and planting date for all growth parameters. There are numerous three-way and four-way interactions at 95% level of significance, however, these interactions have no practical implication on the data. Therefore, the following results will focus on the main effects and two-way interactions.

Plant population

Plant population was variable across the years (Table 3.6). The highest plant density was observed in 2019 at both locations while the lowest plant density occurred at Genesee in 2018. Plant densities at St. John were similar in 2018 and 2020. Comparing the various planting dates, the early planting had a significantly higher plant population at Genesee than the intermediate or late planting dates with 57 plants m^{-2}. However, at St. John there were significantly more plants at the intermediate planting date (71 plants m^{-2}) compared to the early and late planting dates. Fertilizer application did not impact plant population at either site. Seeding rate had the biggest effect on plant populations at both locations. The seeding rate of 130 seeds m^{-2} had significantly more plants with decreasing populations for the 108, 87 and 65 seeds m^{-2}. Windham had a slightly higher plant population at Genesee, but it was the same as Blaze at St. John.

Vine length and canopy height

Vine length was variable across years (Table 3.6) and significantly influenced by cultivar. Blaze was 5% and 3% taller than Windham at Genesee and St. John, respectively. Early and intermediate planting dates produced longer vine lengths at Genesee, but planting dates were statistically similar at St. John. Application of phosphorus and sulfur as well as seeding rates did not affect vine length.

As observed with vine length, Blaze plant always had significantly higher canopy height at both locations compared to Windham (Table 3.6). Blaze had 16% and 5% taller canopy than Windham at Genesee and St. John respectively. The intermediate planting date at Genesee had higher canopy height than early or late planting, but the planting date had no effect on canopy height at St. John. Fertilizer application and seeding rate did not have any effect on canopy height.

Table 3.6. Main effects of year, planting date, fertilizer application, seeding rate and cultivar on plant population, vine length and canopy height of winter pea at Genesee, ID and St. John, WA from 2018-2020.

		Genesee, ID			St. John, WA		
		Plant population (plants/m^2)	Vine Length (cm)	Canopy Height (cm)	Plant population (plants/m^2)	Vine length (cm)	Canopy Height (cm)
Year	2018	33 c[†]	83 b	64 a	48 b	56 b	41
	2019	69 a	79 c	43 c	89 a	54 b	42
	2020	51 b	87 a	48 b	48 b	71 a	44
Planting date	Early	57 a	85 a	49 b	59 b	61	43
	Intermediate	51 b	83 a	54 a	71 a	62	44
	Late	50 b	80 b	50 b	61 b	56	41
Fertilizer application	no	53	82	51	64	59	43
	yes	52	83	51	64	60	43
Seeding rate (seeds m^{-2})	65	39 d	82	53	47 d	59	42
	87	49 c	83	53	58 c	60	43
	107	56 b	83	51	70 b	59	43
	130	74 a	84	45	89 a	62	43
Cultivar	Blaze	50 b	85 a	56 a	64	61 a	44 a
	Windham	55 a	81 b	47 b	64	59 b	42 b

† Mean followed by different letters in a single column for a main effect are statistically different (* Significant at *p*<0.05, ** Significant at *p*<0.01, * Significant at *p*<0.001, and ns: non-significant).**

Yield

Yield was significantly impacted by all main factors except the fertilizer application at Genesee. At Genesee, the highest winter pea production was in 2019 with a yield of 4,952 kg ha^{-1} while at St. John, 2020 was the most productive year with yield of 2,548 kg ha^{-1} (Figure 3.1). Planting dates significantly influenced the yield of winter pea (Figure 3.2). At Genesee, the early planting had significantly higher winter pea yield (4,425 kg ha^{-1}) than the intermediate or late planting dates. However, at St. John, yields for the early (2,616 kg ha^{-1}) and intermediate planting (2,533 kg ha^{-1}) were significantly higher than the late planting. While application of phosphorus and sulfur did not have any effect on grain yield at Genesee, there was a small, but significant increase of 97 kg ha^{-1} at St. John when fertilizer was applied (Figure 3.3). The 130 seeds m^{-2} seeding rate had significantly higher grain yield at both locations than lower seeding rates with 4,680 kg ha^{-1} at Genesee and 2,685 kg ha^{-1} at St. John (Figure 3.4). Compared to the yield of the seeding rate of 130 seeds m^{-2}, the lower seeding rates resulted in 14%, 16% and 20% lower yield for the 107, 87 and 65 seeds m^{-2} at Genesee, respectively. At St. John, compared to the highest seeding rate, the 107, 87 and 65 seeds m^{-2} had 10%, 13% and 21% lower yield, respectively.

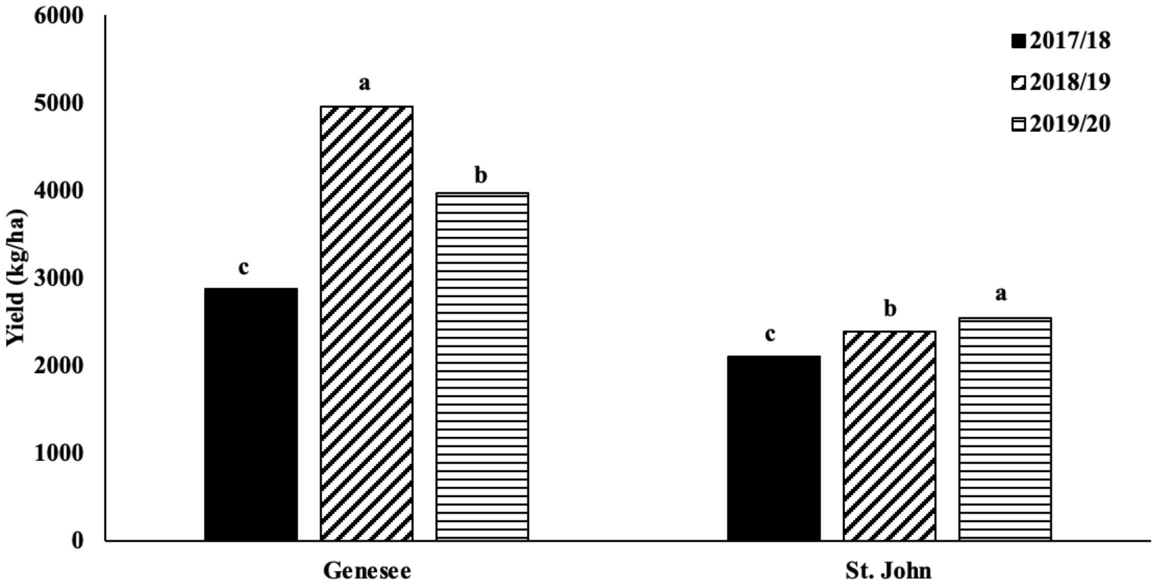

Figure 3.1. Grain yield of winter pea planted at Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at p = 0.05 within a location.

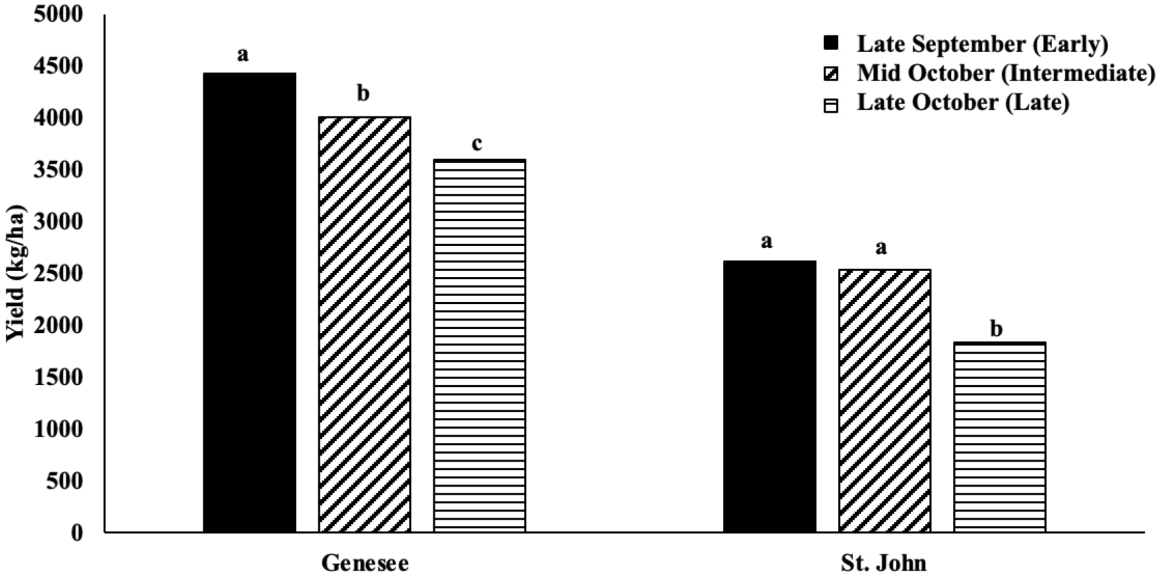

Figure 3.2. Grain yield of winter pea planted at three different planting times in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at p = 0.05 within a location.

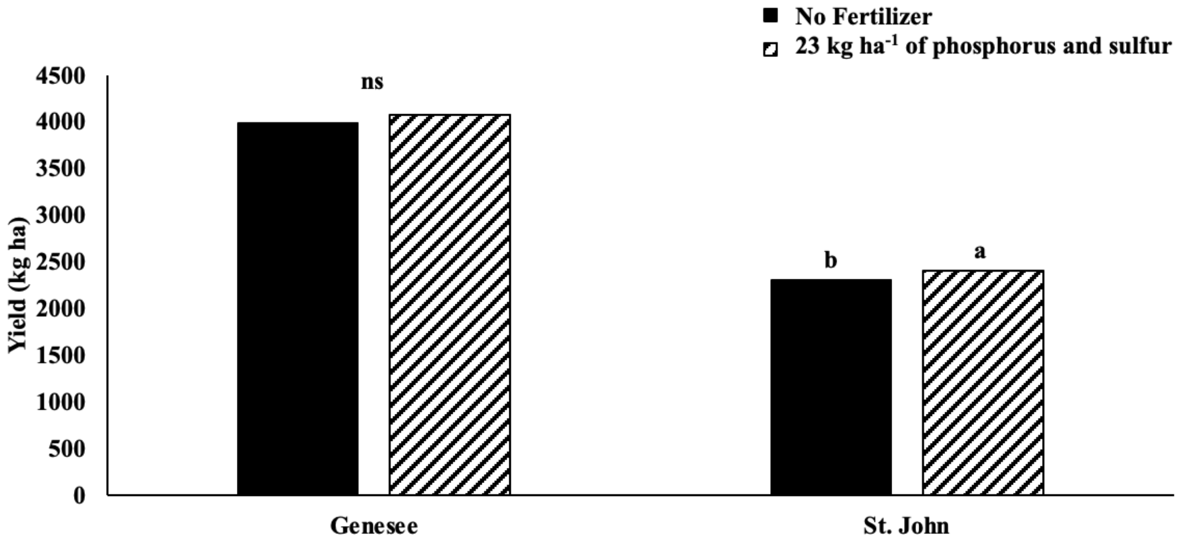

Figure 3.3. Grain yield of winter pea planted with or without application of 23 kg ha^{-1} of phosphorus and sulfur in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location; ns indicates non-significant.

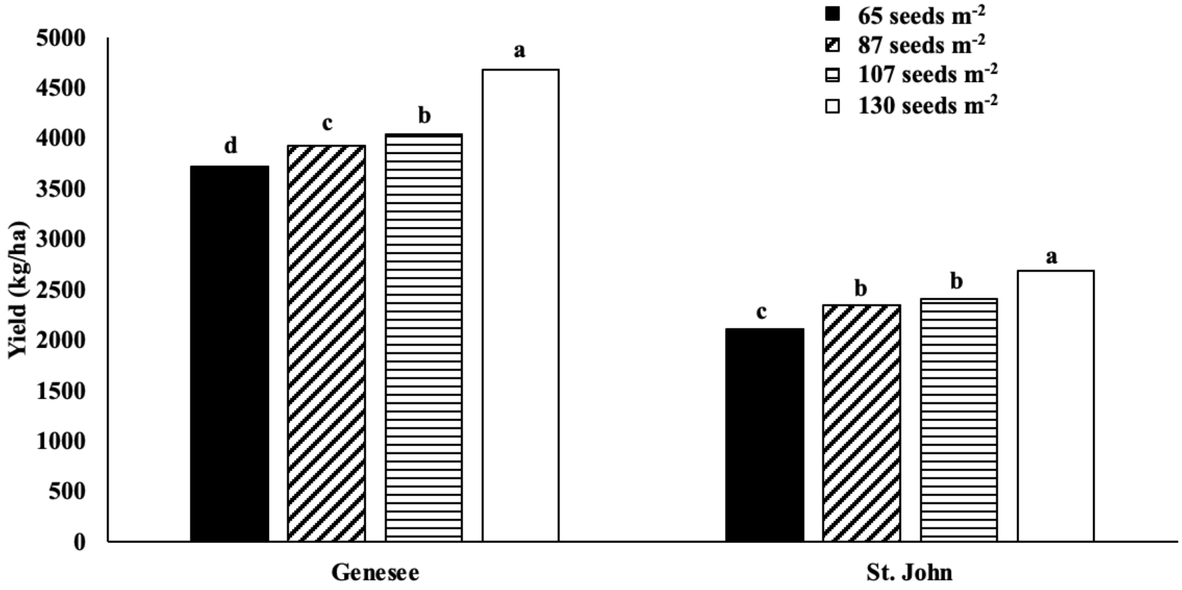

Figure 3.4. Grain yield of winter pea planted at various seeding rates in Genesee, ID and St. John, WA from 2018 to 2020. Different letters at the top of each bar indicate significant difference at $p = 0.05$ within a location.

Seed weight

The 1,000 seed weight was significantly affected by year and cultivar at both locations (Table 3.7). Seeds of cultivar Blaze were significantly bigger than Windham with a 1,000 seed weight of 199 g and 191 g at Genesee and St. John, respectively. Fertilizer application did not affect the 1,000 seed weight at either location. Seeds were significantly larger for the early and intermediate planting dates at Genesee compared to the late planting date. However, 1,000 seed weight were similar for all planting dates at St. John. Seeding rate had no effect on 1,000 seed weight at Genesee. At St. John the lowest seeding rate of 65 seeds m^{-2} had the highest 1,000 seed weight (168 g) while the highest seeding rate of 130 seeds m^{-2} had the lowest 1,000 seed weight (159).

Protein content

Grain protein content was significantly impacted by year, planting date, seeding rate and cultivar (Table 3.7). At Genesee, grain protein was significantly higher for the intermediate (17.5%) and late (17.2%) planting dates than the early planting date (16.7%). However, at St. John, the intermediate planting date had significantly higher protein content (16.9%) than the early or late planting dates. The seeding rate did not affect the protein content at Genesee, but at St. John, the highest seeding rate (130 seeds m^{-2}) had significantly higher protein than the lower seeding rates. At Genesee, Windham had slightly higher protein content than Blaze, but at Genesee Blaze protein content was higher. Fertilizer application had no effect on the protein content of winter pea.

Table 3.7. Main effects of year, planting date, fertilizer application, seeding rate and cultivar on 1,000 seed weight and grain protein content at Genesee, ID and St. John, WA from 2018-2020.

		Genesee, ID		St. John, WA	
		1,000 seed weight (g)	Grain protein (%)	1,000 seed weight (g)	Grain protein (%)
Year	2018	168 b[†]	13.8 c	176 a	12.2 c
	2019	185 a	20.1 a	173 b	17.8 b
	2020	164 c	16.7 b	147 c	18.3 a
Planting date	Early	176 a	16.9 b	165	15.9 b
	Intermediate	176 a	17.5 a	167	16.9 a
	Late	167 b	17.2 a	164	16.1 b
Fertilizer application	No	173	17.1	165	16.2
	Yes	173	17.2	165	16.4
Seeding rate	65	173	16.8	168 a	15.7 b
	87	173	16.8	167 b	15.9 b
	107	173	16.9	166 b	16.1 b
	130	175	18.7	159 c	18.4 a
Cultivar	Blaze	199 a	17.1 b	191 a	17.0 a
	Windham	151 b	17.3 a	143 b	15.6 b

†Mean followed by different letters in a single column for a main effect are statistically different (* Significant at *p*<0.05, ** Significant at *p*<0.01, * Significant at *p*<0.001, and ns: non-significant).**

Soil Moisture

Volumetric water content was measured in the late September planted plots at both locations throughout the growing season. Moisture content was recorded for six soil depths at 10 cm, 20 cm, 30 cm, 40 cm, 60 cm and 100 cm every 6 to 8 days for 2018 and 2019 while in 2020, the moisture was recorded at 10 to14-day intervals at both sites. There was no significant difference between the moisture content of soil for cultivar, seeding rate and fertilizer application (ANOVA not shown).

Soil moisture, at each site and across years, declined at all depths during the growing season, but the rate of decline at various depths was highly variable across years and sites. The greatest decline in soil moisture was usually at the 10 cm soil depth. Genesee consistently had higher soil moisture in the spring compared to St. John. Soil moisture was also greater after harvest at all depths in Genesee. Water content at the 10 cm depth was consistently lower than the other depths and the 100 cm depth always had the highest water content. The water content in the 20 cm, 30 cm, 40 cm, and 60 cm were similar and did not show any specific trends. Increases in moisture content in the shallow depths, especially at 10 cm in 2020 was due to precipitation events. After harvest, Genesee had an average of 7 to 9% and 15 to 20% volumetric water content at the 10 cm and 20 cm depth, respectively. Similar postharvest volumetric water content at St. John was 4 to 8% and 9 to 18% at 10 cm and 20 cm depth, respectively.

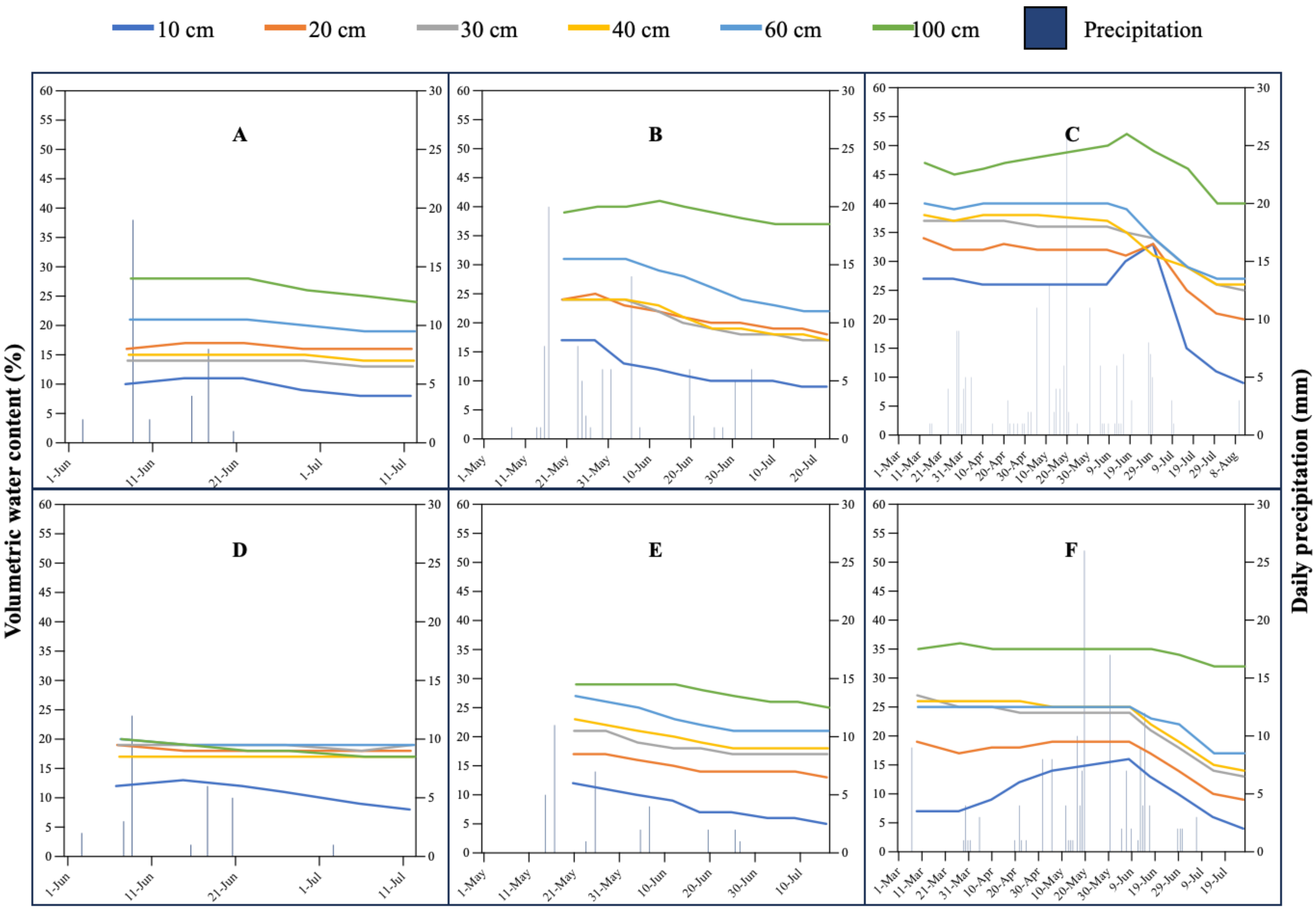

Figure 3.5. Daily precipitation during growing season and average volumetric water content at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm) at Genesee and St. John from 2018 to 2020. (A-Genesee, 2018; B-Genesee, 2019; C-Genesee, 2020; D- St. John, 2018; E- St. John, 2019; and F- St. John, 2020) in late September planted winter peas.

Economic Analysis

The impact of increasing seeding rate and seeding cost on the overall profitability of the farm was assessed. An assumption in calculating the production costs is that the farmland is 1,012 ha (2,500 acres) for each seeding rates and procedures including chemicals, planting, spraying, harvesting and transport are based on this same land area. The only difference in cost is the seed cost associated with each seeding rate. Chemical, machinery, and machine replacement costs are the same for all treatments.

A summary of the economic analysis for Genesee and St. John are shown in Tables 3.8 and 3.9, respectively. Seeds costs were \$207.94, \$275.15, \$344.46, and \$413.78 per ha for seeding rates of 65, 87, 107 and 130 seeds m^{-2}, respectively. Using the yield data from this study, the overall yield of Genesee was higher than for St. John. As a result, the net return was higher in Genesee than at St. John. The lowest net return in Genesee was associated with the lowest seeding rate (\$1,242.15 per ha), although this return was not substantially different from the 87 and 107 seeds m^{-2}. The highest net return at Genesee was observed with the 130 seed m^{-2} seeding rate (\$1,501.57 per ha). Similar results were observed at St. John with the highest net return from the high seeding rate of 130 seed m^{-2} (\$490.49 per ha), followed by 87 seed m^{-2} (\$472.35 per ha), 107 seed m^{-2} (\$426.01 per ha), and 65 seed m^{-2} (\$426.01 per ha).

Table 3.8. Economic analysis for winter peas seeded at different seeding rates from 2018 to 2020 at Genesee.

	65 seeds m^{-2}	**87 seeds m^{-2}**	**107 seeds m^{-2}**	**130 seeds m^{-2}**
Grain yield (kg/ha)	3,720	3,925	4,041	4,680
Grain price ($/kg)	$0.51	$0.51	$0.51	$0.51
Return				
Gross return ($/ha)	$1,886.33	$1,990.33	$2,048.87	$2,372.83
Total Returns ($/ha)	***$1,886.33***	***$1,990.33***	***$2,048.87***	***$2,372.83***
Costs				
Seed cost ($/ha)	$207.94	$275.15	$344.46	$413.78
Fertilizer cost ($/ha)	$0.00	$0.00	$0.00	$0.00
Chemical cost ($/ha)	$119.84	$119.84	$119.84	$119.84
Forage Operations ($/ha)	$0.00	$0.00	$0.00	$0.00
Machine (Labor, Fuel and Repairs) ($/ha)	$158.81	$158.81	$158.81	$158.81
Other Expenses (5%) ($/ha)	$26.55	$29.91	$33.38	$36.85
Interest on operating inputs (6.75%) ($/ha)	$28.23	$31.80	$35.49	$39.17
Crop Insurance ($/ha)	$44.48	$44.48	$44.48	$44.48
Machine Replacement Costs ($/ha)	$58.34	$58.34	$58.34	$58.34
Total Annual Costs ($/ha)	***$644.18***	***$718.33***	***$794.79***	***$871.25***
Net Returns ($/ha)	$1,242.15	$1,272.01	$1,254.08	$1,501.57

Table 3.9. Economic analysis for winter peas seeded at different seeding rates from 2018 to 2020 at St. John.

	65 seeds m^{-2}	**87 seeds m^{-2}**	**107 seeds m^{-2}**	**130 seeds m^{-2}**
Grain yield (kg/ha)	2,111	2,348	2,408	2,686
Grain price ($/kg)	$0.51	$0.51	$0.51	$0.51
Return				
Gross return ($/ha)	$1,070.19	$1,190.68	$1,220.80	$1,361.75
Total Returns ($/ha)	***$1,070.19***	***$1,190.68***	***$1,220.80***	***$1,361.75***
Costs				
Seed cost ($/ha)	$207.94	$275.15	$344.46	$413.78
Fertilizer cost ($/ha)	$0.00	$0.00	$0.00	$0.00
Chemical cost ($/ha)	$119.84	$119.84	$119.84	$119.84
Forage Operations ($/ha)	$0.00	$0.00	$0.00	$0.00
Machine (Labor, Fuel and Repairs) ($/ha)	$158.81	$158.81	$158.81	$158.81
Other Expenses (5%) ($/ha)	$26.55	$29.91	$33.38	$36.85
Interest on operating inputs (6.75%) ($/ha)	$28.23	$31.80	$35.49	$39.17
Crop Insurance ($/ha)	$44.48	$44.48	$44.48	$44.48
Machine Replacement Costs ($/ha)	$58.34	$58.34	$58.34	$58.34
Total Annual Costs ($/ha)	***$644.18***	***$718.33***	***$794.79***	***$871.25***
Net Returns ($/ha)	$426.01	$472.35	$426.01	$490.49

Discussion

Winter pea production is gradually increasing in the dryland setting of the IPNW. As the interest in winter pea production increases, there is a need to develop guidelines for winter pea production for the region. The aim of this study was to identify the best agronomic management practice(s) for winter pea in the rainfed IPNW with regard to planting date, seeding rate and fertilizer requirement. From the study, we found that planting winter pea earlier in the fall resulted in earlier establishment and increased productivity. A higher seeding rate of 130 seeds m^{-2} produced the best yield and net return. However, banding of phosphorus and sulfur fertilizers at planting did not significantly influence yield or quality of winter pea.

Annual weather patterns were highly variable during the study at both locations. Genesee had an annual precipitation of 55.5 cm, 44.8 cm, and 46.1 cm respectively during the three-growing season from 2017 to 2020 (September to August). However, when considering total precipitation during the active growing period from April to July at Genesee, the 2018/19 season received about 41% of the total precipitation during that period compared to 27% and 35% in 2017/18 and 2019/20, respectively. The grain yield during the 2018/19 growing season was the highest at Genesee, demonstrating the production potential of winter pea during a favorable year with timely rains during active growth in the spring. Similarly, the annual precipitation was 44.6 cm, 35.0 cm, and 39.7 cm, respectively for the three growing seasons, at St. John. About 27%, 28% and 36% of that total precipitation occurred during April to July of 2018, 2019 and 2020, respectively, at the same location. The grain yield during the 2019/20 growing season was highest at St. John which was likely favored by the higher precipitation during the peak growing period of winter pea.

The optimum growing temperature for winter pea is from 13 to 18°C (Hartman et al., 1988). Blaze is reported to survive temperatures as low as -20°C and Windham is reported to tolerate temperature as low as -17°C. During the winter months, winter pea in general can tolerate temperature as low as -10°C without cover but can tolerate temperature of -30°C under snow cover (Elzebroek and Wind, 2008). The winter temperature in our sites never dropped below -8°C and temperature during the growing season from April to July was within or above the optimum growing temperature range. The temperature in the region over the three years was suitable for winter pea production.

Crop establishment is highly dependent on availability of soil moisture and other growing conditions. When there was adequate soil moisture for germination at planting, early seeding resulted in improved plant establishment in the fall, leading to higher winter pea yield. However, when seeding conditions were dry, germination was delayed and seeding date had less impact on yield. Even with later planting dates in mid-October or early November, the grain yield was higher than a comparable spring planted pea. Chen et al. (2006) evaluated planting dates (mid Oct and Late Oct/early Nov) in Genesee, ID. In 2002, there was no decline in yield with delayed planting while in 2003, the later planted crop had an increased yield. A study conducted by Murray et al. (1984) compared various seeding dates of three winter pea cultivars. The authors reported decline in seedling vigor and seed yield as the planting was delayed from September to October at Grangeville, ID, however, there was no decline in the same characteristics at Moscow. Strydhorst et al. (2015) compared three different planting dates: early fall (late Aug/early Sep), mid fall (mid Sep) and late fall (late Sep/early Oct) in a study in Canada at five different locations. The effect of planting dates differed between locations. However, for southern Alberta, the third week of September is the recommended date for winter pea planting. Results from this current study at Genesee and St. John differ from some of the previous studies in that earlier planting dates (late Sept and mid Oct) produced higher yields than the late planted winter peas.

Previous studies have reported better winter pea growth and an increase in productivity of winter pea with the application of sulfur and phosphorus fertilizers (Henry et al., 1995; Kumar, 2011; Singh et al., 2014). Kasturikrishna and Ahlawat (2000) reported an increase in root and plant growth parameters when 26.5 kg P ha^{-1} was applied in peas in India. They further reported that the addition of 40 kg S ha^{-1} increased growth of plants and resulted in improved yield. Kumar (2011) conducted an experiment to examine rates of phosphorus and sulfur on vegetable peas and reported that 60 kg P ha^{-1} and 40 kg S ha^{-1} produced the highest green pod yield. Singh et al. (2014) reported that application of 60 kg P ha^{-1} and 40 kg S ha^{-1} enhanced plant growth, nodulation, and yield attributes of peas. There are also studies showing positive effects on growth and yield of peas by foliar application of boron, manganese, and zinc (El-Aidy et al., 2018). Another study in Bulgaria reported increased grain yield with foliar application of boron, molybdenum, potassium, sulfur, magnesium, and phosphorus (Milev, 2014). In this current study, the addition of 23 kg ha^{-1} each of phosphorus and sulfur fertilizer did not influence any growth parameters. There was a small, but significant grain yield increase of 97 kg ha^{-1} at St. John. Assuming the cost of triple super phosphate and sulfate of potash to be \$1.32 kg^{-1} and 0.88 kg^{-1} and grain price to be \$0.51 kg^{-1}, there is a gross loss of about \$1 ha^{-1} when fertilizer is applied compared to no fertilizer application. The lack of response to phosphorus and sulfur application was unexpected. The soil test indicated the presence of 3.1 to 4 ppm of phosphorus and 2 to 3 ppm of sulfur in the soil at the study sites. The northern Idaho fertilizer guide for spring peas suggests applying phosphorus and sulfur when the concentration is below 4 ppm for both nutrients (Mahler, 2015). Despite the northern Idaho recommendations for applying phosphorus and sulfur in pea fields, growers in this region rarely apply fertilizers in legume fields due to limited return on the investment. Yet the studies mentioned above clearly suggested significant improvement in plant growth and grain yield when using phosphorus and sulfur fertilizers. Soils with lower concentrations of phosphorus and sulfur than those from this study might show a response to application of these fertilizers. Further work on these nutrients as well as examining micronutrients in winter pea production may be warranted.

Seeding rates had a linear relationship with plant population and grain yield. As expected, the plant population nearly doubled between seeding rates of 65 seeds m^{-2} and 130 seeds m^{-2}. At Genesee, the germination ranged from 52 to 60% while at St. John, it ranged from 65 to 72%. The plant population was 74 (Genesee) and 89 (St. John) plants m^{-2} at the seeding rate of 130 seeds m^{-2}, which resulted in the highest grain yield at both locations. Strydhorst et al. (2015) suggested planting winter peas to obtain a plant population of 75 plants m^{-2} to obtain maximum yield in a study conducted in Alberta, Canada. Knott and Belcher (1998) also suggested targeting the plant population to 75 to 80 plants m^{-2} for maximum yield and higher net return. The north Idaho variety testing program at the University of Idaho uses 107 seeds per m^{-2} for testing winter pea in the region (Schroeder et al., 2019). Chen et al. (2006) conducted studies at Moccasin and Amsterdam, MT; Rosalia, WA; and Genesee, ID where a seeding rate of 87 seeds m^{-2} was used and winter pea grain yield was reported to be as high as 4,000 kg ha^{-1} at Genesee in 2002. Uzun and Açikgöz (1998) reported a higher yield of 2,743 kg ha^{-1} of winter peas when planted with a seeding rate of 100 seeds m^{-2} compared to seeding rate of 25 and 50 seeds m^{-2} from a study conducted in Bursa, Turkey. In addition to the planting rate of 130 seeds m^{-2} used in this current study having the highest grain yield, the economic analyses suggest this seeding rate provided the greatest net return at both trial locations and the plant populations obtained with this seeding density are similar to the optimum identified in previous studies.

Winter pea has a tremendous yield potential and can outyield spring pea by as much as 300% (McGee et al., 2017). In this study the average grain yield at Genesee was 4,092 kg ha^{-1} and at St. John was 2,359 kg ha^{-1}. Three-year average yield data (2016 to 2018) for spring pea from the north Idaho variety testing program at Genesee was 2,285 kg ha^{-1} (Schroeder et al., 2019). Schillinger (2020) reported an 8-year average winter pea yield of 2,560 kg ha^{-1} from a study done in the low precipitation region of the IPNW at Ritzville, WA under 3-year rotation with winter pea – spring wheat - fallow. In the same study, spring pea was planted in one year due to winter pea winter killed, where the spring pea yield was only 870 kg ha^{-1}. Chen et al. (2006) reported winter pea production as high as 4,000 kg ha^{-1} at Genesee during 2002 and little less than 3,000 kg ha^{-1} in 2003. The same study reported higher yield with winter peas with one of the cultivars in both years compared to spring peas which had yield ranging from 1,500 to 3,000 kg ha^{-1} depending on year.

Moisture content was measured throughout the study to determine whether seeding rate, fertilizer use, or cultivar would impact water use and availability for the subsequent crop. However, there was no significant difference in moisture content due to different seeding rate, fertilizer application and cultivars. The water use was similar when compared to the different seeding rates of winter pea and application of fertilizer had no effect on the moisture content. Likewise, similar water use was seen in both cultivars of winter peas. In this study, the volumetric water content in the top 10 cm soil profile was about 10% and 5% at Genesee and

St. John, respectively at the time of harvest. The soil moisture data suggests that changes to agronomic management strategies will not substantially influence water use and availability for subsequent crops.

Both cultivars, Windham and Blaze, used in this study performed well at both locations. Windham is a winter pea cultivar developed by the USDA-ARS in Pullman, WA with yellow seed, mottled seed coat and 1,000 seed weight of 140 g (McPhee et al., 2007). Blaze is a comparatively newer cultivar developed and released by ProGene LLC (Othello, WA) in 2017 which is taller and has better cold tolerance than Windham, but still a mottled seed coat and 1,000 seed weight of 180 g. Both cultivars are typically used for both human consumption and pet food markets. However, due to small seed size and mottled seed coat, they do not meet the criteria for the whole food and split pea market. Both cultivars of winter pea used in this study had comparable yield. Blaze plants were significantly taller and had greater canopy height when matured. There was a slight difference in grain protein between Windham and Blaze, but the difference was less than 1.6%.

When the study was initiated, Windham and Blaze were commonly grown commercial cultivars and most similar to food quality winter pea that were in development. However, numerous cultivars targeted towards food market has been developed since then. Historically, fall seeded peas could not be sold into food quality markets. A change in regulations in 2009 removed the seeding date restriction, allowing fall seeded peas to enter the food market as smooth green or yellow peas (USDA-GIPSA, 2009). The USDA-ARS Grain Legume Genetics Physiology Research unit in Pullman, WA recently released three new cultivars USDA-Dint, USDA-MiCa and USDA-Klondike which will be marketed as food grade winter peas. Similarly, ProGene LLC also released new food grade cultivars Vail (ProGene LLC, 2019a) and Keystone (ProGene LLC, 2019b) which are already being marketed in the food grade winter pea market. These newer cultivars have some or all improved characteristics which includes superior yield, higher nutritive value, better winter hardiness, larger seed size, green or yellow seed color similar to spring food peas.

Conclusion

Winter pea has the potential to be an excellent alternative crop to spring legumes in the intermediate and higher precipitation cropping system of the IPNW. Early planting is ideal for plant establishment and to maximize yield, but emergence can be delayed when soil conditions are dry at planting. Seeding rates of 107 to 130 seeds m^{-2} provided the highest yields, while 130 seeds m^{-2} provided the greatest return on investment. Data did not support the use of sulfur and phosphorus fertilizer at planting, but further work may be warranted. The recent release of improved food quality cultivars of winter pea by breeders in the region will potentially expand market access and profitability in growing winter pea as opposed to a spring legume, reducing risk, and increasing the economic return to the growers in the region.

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Chapter 4: Evaluation of fall-seeded forage crop mixtures in the Inland Pacific Northwest

Introduction

Cropping systems in the rainfed regions of the Inland Pacific Northwest (IPNW) are dominated by cereal crops. Based on precipitation and edaphic factors, several different cropping systems exist (Huggins et al., 2014). These include the low precipitation regions that typically consist of a winter wheat – fallow rotation, the intermediate precipitation region that includes primarily winter and spring wheat with fallow in the third year of the rotation, and the high precipitation region that is annually cropped with an emphasis on winter wheat, but includes spring cereals, legumes, and oilseed crops. The cropping systems in the IPNW are influenced by seasonable variability in weather and climate change. The mean annual temperature has increased by 0.6 to 0.8°C from 1901 to 2012 (Abatzoglou et al., 2012) and is projected to increase by another 2.7°C by 2040 to 2069 (Stöckle et al., 2018). Apart from the rise in temperature, the precipitation pattern is also going to change considerably. Pan and Borrelli (2015) projected wetter springs causing delayed planting for spring crops and drier summers.

To help build a more resilient cropping systems in all regions of the IPNW, alternative crop options are needed particularly those that can be fall seeded. Incorporation of forage crops could be a part of the solution. Forage crops could replace fallow in the intermediate rainfall region, while increasing crop diversity. In the high rainfall region, fall seeded forage crops can be incorporated into the system possibly replacing one of the spring crops to diversify the current cropping system and mitigate risks associated with spring crops (unusually wet or dry spring and early summer). The projected wetter spring conditions might delay or prevent planting of spring crops.

Cover crops are grown to conserve soil when a primary crop is not present and can be incorporated into the soil for soil enrichment. There are numerous benefits of planting cover crops such as control of soil erosion (Kaspar and Bakker, 2015), alleviation and/or prevention of soil compaction (Pratt et al., 2014), nutrition scavenging (Delgado, 1998), enhancement of soil organic matter (Steenworth and Belina, 2008), and improvement of the water holding capacity of the soil (Duncan et al., 2022). Additionally, the presence of legumes in the cover crop mixture aids in enhancing the nutrients for subsequent crops, potentially reducing the amount and cost of inorganic fertilizer required (Duncan et al., 2022). Furthermore, the use of deep-rooted crops such as brassicas, aids in alleviating soil compaction and improving soil structure. With the use of cover crops, it may be possible to achieve suppression of weed growth (Baraibar et al., 2018) and improve above and below ground biodiversity.

Multi-species forage crops can provide some of the same benefits realized with cover crops in addition to providing a source of income from grazing or haying. A study done in Iowa by Plastina et al. (2018) suggested that there was positive net return when the cover crops were grazed compared to when the cover crops were not grazed or used as forage. Holman et al. (2018) reported an increase in 26 to 240% in net farm return when forage crops were used compared to a decrease of 50 to 100% net return when used as cover crop. Many of the cover crop species that are grown for other purposes can also be used as a potential forage crop with nutritive value (Hansen et al., 2013). While all the cover crop species have certain forage nutritive value, some species have higher values than others, so selecting crops is the key to successful forage crop production.

There are several crop species available to be used in a forage mixture, which are categorized either into cool season or warm season crops. Warm season crops include crop species like millet, sorghum, sudangrass, sunflower, etc. which require at least 10°C for growth and need almost 30 to 35°C for optimum production. Cool season crops like cereals (e.g., oats, wheat, triticale, barley, etc.), brassicas (e.g., turnip, radish, etc.) and legumes (e.g., vetch, peas, clover, etc.) can emerge at temperatures as low as 4°C and can have optimum growth around 20°C (Cooper and Taiton, 1968; Nelson and Moser, 1994). Both types of forage crops have been grown in monoculture or multi-crop mixtures. However, studies have shown that mixtures of two to eight crops were more productive than monocropping (Wortman et al., 2012: Mirsky et al., 2013; Smith et al., 2014). When mixing species, the environment in which forage crops are grown can plays a vital role in establishment and success of the crops. With a mixture of warm and cool season crops, issues like competition among the crops might lead to no emergence of certain species, and planting time should be adjusted to ensure establishment and biomass production for both crop types or the overall productivity might be reduced (Wyfells et al., 2022).

While there are numerous benefits of incorporating these forage crop mixtures in the cropping system, there are some challenges and considerations. One of the important factors is the additional cost associated with growing a forage crop with an intention to hay or graze the crops. When comparing grazing and haying, additional costs associated with grazing are seed cost, planting, fencing, herding and watering facilities (Tanaka et al., 2023). For hay production there are higher start up and maintenance cost which includes equipment for mowing, raking, baling, storage and transportation (Pogue et al., 1996). In addition, the precipitation pattern and shorter growing season in the IPNW relative to other parts of the country potentially restrict the number of species of forage crops that would be suitable in the region (Pavek, 2014). Based on the climatic necessity, warm season crops would not work well as part of a fall seeded mixture due to winter sensitivity, limiting the options to cool season crops. Timing of crop termination also is crucial as terminating too late reduce the forage quality of the forage crops (Lai et al., 2022), may reduce the plant available water for the subsequent cash crop in the rotation (Pavek, 2014) and may pose contamination issues in future crops if the seeds are allowed to be set and produced (Michel et al., 2020). Finally, there might be a potential risk of incidence of pest and disease in the crop rotation (Dabney et al, 2007) possibly due to bridging by crop mixtures between cash crops.

The nutritive value of forage crops can be of primary importance when selecting species to include in a mix. Some of the factors affecting forage nutritive value are the type of crop, crop growth stage, climatic conditions, crop management and anti-quality factors (Nelson and Moser, 1994). Legumes typically have higher forage nutritive value (higher protein and lower fiber content) than grasses. Cereals on the other hand have high biomass production with lower protein content and slightly higher fiber content than the legumes (Adesogan et al., 2012). Brassica crops can also be considered high quality forage crops with high protein content (Smart et al., 2004). An optimal forage crop mix will have both high dry matter production and high forage nutritive value. The environment in which the crop grows will have a significant impact on the overall forage nutritive value. Crops should be adapted to a region in which they are grown to maximize forage production. Apart from adaptation, climatic factors like temperature, light, moisture availability and edaphic factors play a vital role in determining forage quality (Moore et al., 2020). Termination or swathing of these crops at proper crop maturity level is important to attain high forage biomass with superior nutritive value (Moore et al., 2020). Proper crop management practices must be employed, using the proper ratio of crop species and optimum planting date so that maximum forage production and quality is achieved.

Forage nutritive value of these crops is usually measured based on numerous parameters like crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), lignin and the relative feed value (RFC) of the crops. Guidelines for forage quality determination are outlined by Newman et al. (2009). The CP is the measure of amount of nitrogen in the plant sample and for forage crops, a higher CP is preferred. The NDF is a measure of total fiber containing cellulose, hemicellulose and lignin. The ADF is a measure of cellulose, lignin and silica (if present in the sample). The quantities of these fibers can range from 5 to more than 60% depending on the crop. Higher fiber values usually represent lower digestibility so lower values are preferred for forage mixes. The relative feed value (RFV) is an index of forage quality that uses ADF and NDF to predict forage quality. The RFV for a fully bloomed alfalfa crop is 100 and this is the standard value used for comparing other forages (USDA-NRCS, 2021). When considering a crop or mixture to be used as a forage crop/mixture the CP should be higher than 19%, ADF less than 31%, NDF less than 40% (Ball et al., 2001) and the relative feed value as high as possible.

There is significant potential to incorporate cover crops intended for haying in the dryland setting of the IPNW, and many growers have experimented with cover crops, especially spring seeded cover crops. While the concept of incorporating multispecies cover or forage crops into existing rotations is new to the region, it is gaining popularity among the growers due to its numerous benefits to the overall cropping system and sustainability. Very little research has been conducted in the region on fall seeded forage crops. While there is some information about winter survivability of forage crop species, there is little to no information in terms of forage yield and nutritive value, and differing fall seeded cover crop mixes have not been tested. The objectives of this study were 1) to examine the productivity of winter barley, winter pea, winter oat, crimson clover, balansa clover and radish in various combinations to determine the quantity of biomass produced and 2) to evaluate the forage nutritive value of these crop mixes in the intermediate and high precipitation regions of the IPNW.

Materials and Methods

Location

A three-year field study was initiated at two locations in the rainfed region of the IPNW from 2018 to 2021 to evaluate six forage crops and their mixtures in 15 different combinations for their performance in the region. The study sites included Genesee, ID (46.586344°, -116.947104°), 841 m elevation) and St. John, WA (47.095020°, -117.584103°, 632 m elevation). Genesee has an average annual precipitation of 55 cm and is annually cropped with a typical three-year rotation consisting of winter wheat, spring wheat and spring legume. St. John in the transitional cropping region, receives about 30 to 35 cm of precipitation and has a typical rotation of winter wheat, spring wheat and fallow every third year. Soil at the study site in Genesee was a Palouse silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) and in St. John was a Calouse silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) for the first year and Covello silt loam (order: Mollisols; sub-order: Xerolls; great group: Haploxerolls) for second and third year (Web Soil Survey, NRCS).

Field Trials

The crops used in this study included winter barley (WB) cultivar Verdant, black winter oat (WO), winter pea (WP) cultivar Lynx, crimson clover (CC) cultivar Dixie, balansa clover

(BC) cultivar Fixation, and daikon radish (Rad). The small seed crops crimson clover, balansa clover and radish were mixed in equal proportion based in seed number and considered a single unit. These four constituents were mixed to make fifteen different combinations of forage crops that included all combinations of monocropping, two-way mixes, three-way mixes and four-way mix. The small seed mix crops (CC, BC and Rad) cultivars were chosen from testing that was done by NRCS in Pullman based on their winter survival results while WB, WO and WP cultivars were selected based on local adaptability and availability of seed. Seeding rates were determined as per local recommendation for single crops and were adjusted proportionally for each mixture (Table 4.1). The monocropping seeding rate of the WB, WO, WP, CC, BC and Rad were 248, 248, 108, 215, 215 and 108 seeds m^{-2}, respectively.

Table 4.1. Seeding rates (seeds m^{-2}) for the forage crop species planted at Genesee and St. John.

Treatments	**WB**[†]	**WO**	**WP**	**CC**	**BC**	**Rad**
	seeds m^{-2}					
WB	248					
WO		248				
WP			108			
[CC + BC + Rad]				72	72	36
WB + WO	124	124				
WB + WP	124		54			
WO + WP		124	54			
WB + [CC + BC + Rad]	124			36	36	18
WO + [CC + BC + Rad]		124		36	36	18
WP + [CC + BC + Rad]			54	36	36	18
WB + WO + WP	83	83	36			
WB + WO + [CC + BC + Rad]	83	83		24	24	12
WB + WP + [CC + BC + Rad]	83		36	24	24	12
WO + WP + [CC + BC + Rad]		83	36	24	24	12
WB + WO + WP + [CC + BC + Rad]	62	62	27	18	18	9

[†]WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.

In all years, the crops were planted into spring barley stubble at Genesee and spring wheat stubble at St. John. All plots were direct seeded using a custom-made drill equipped with Flexi-Coil Stealth openers spaced 25 cm apart. Each plot was 1.5 m wide and 6.1 m in length. The trial was arranged as a randomized complete block with four replications. Prior to seeding, all sites were sprayed with glyphosate and 2,4-D at 2.34 L ha^{-1} each in all years for preplant weed management. No fertilizers or herbicides were applied in the plots after planting. Seeding was conducted in late September or early October in all three years (Table 4.2).

Table 4.2. Planting and harvest dates for forage crops at Genesee and St. John from 2018 to 2021.

		Genesee, ID			**St. John, ID**		
		2018/19	**2019/20**	**2020/21**	**2018/19**	**2019/20**	**2020/21**
Planting date		3 Oct	30 Sept	29 Sept	3 Oct	27 Sept	29 Sept
Harvest dates	**First**	30 May	1 Jun	1 Jun	29 May	-[†]	3 Jun
	Second	13 Jun	17 Jun	17 Jun	12 Jun	-	17 Jun
	Third	2 Jul	1 Jul	1 Jul	26 Jun	-	2 Jul

[†]Study was terminated in the spring for 2019/20 at St. John due to high weed infestation and very poor crop emergence.

Data collection

In the spring of each year, plant population was determined in each plot. All crops within a 0.25 m^2 quadrant were counted. Each plot was then sampled at biweekly intervals from early June to early July to determine biomass production by randomly harvesting a 0.25 m^2 quadrants (Table 4.2). Each sample was weighed to determine fresh biomass and then dried in an oven for 3 days at 55°C. After drying, each bag was weighed again to obtain dry weight. The samples were ground to 1 mm using a Wiley Mill for forage quality assessment.

Forage quality parameters including crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF) and lignin were determined for each mixture for the last set of samples harvested in late June or early July. These parameters were analyzed and estimated using the procedures outlined in Chapter 2. An enterprise budget was calculated for each crop mixture at both locations to compare the farm profitability. Details for the economic analysis are outlined in Chapter 2.

Data analysis

Data were analyzed using SAS version 9.4 (SAS Institute, 2016). Plant population, forage biomass, dry matter yield, CP, ADF, NDF, lignin and RFV were subjected to analysis of variance (ANOVA) using the general linear model (PROC GLM). Data were pooled over 3 years for each location. Year was considered random, and the treatments were considered fixed effect. Means were compared using Fisher's least significant difference at 95% level of significance. Normality and homogeneity assumptions were determined using PROC UNIVARIATE and PROC GLM. An ANOVA table for both locations are listed in Appendix F.

Results

Plant population

The small seed mix of clovers and radish did not emerge at either location in any year of the study. While counting the number of plants, volunteer crops (spring barley at Genesee and spring wheat at St. John) were also counted along with the planted crops. Plant counts were done for each crop and categorized into cereals (WB, WO, and volunteer crop) and broadleaves which included only WP as the small seed mix did not emerge. At Genesee, WB+WO+WP, WB, and WB+WP had the highest emergence (Figure 4.1), with WP and WB making up most of the population. At Genesee, there were very few volunteer SB that emerged in the spring in all years. The mixture of WB+WO+WP had the highest plant population of 81 plants per m^2 which included 55 cereal and 26 broadleaf plants per m^2. The WB only treatment had a plant population of 78 plants per m^2. The lowest plant populations at this location were observed for the WO, WO+[CC+BC+Rad] and [CC+BC+Rad] treatments. At St. John, volunteer spring wheat was present in all years and contributed significantly to the total plant population as evident in the [CC+BC+Rad] treatment which contained only volunteer plants (Figure 4.2). The highest plant population at this location was from the mixture that had all six crops with 84 cereal and 13 broadleaf plants per m^2. At Genesee, winter pea contributed 3 to 91% of the plant population when winter pea was present in the mix except for monocropping WP (was 100%), depending on the mix. At St. John, winter pea when present in the mix made up 4 to 75% of total plant population.

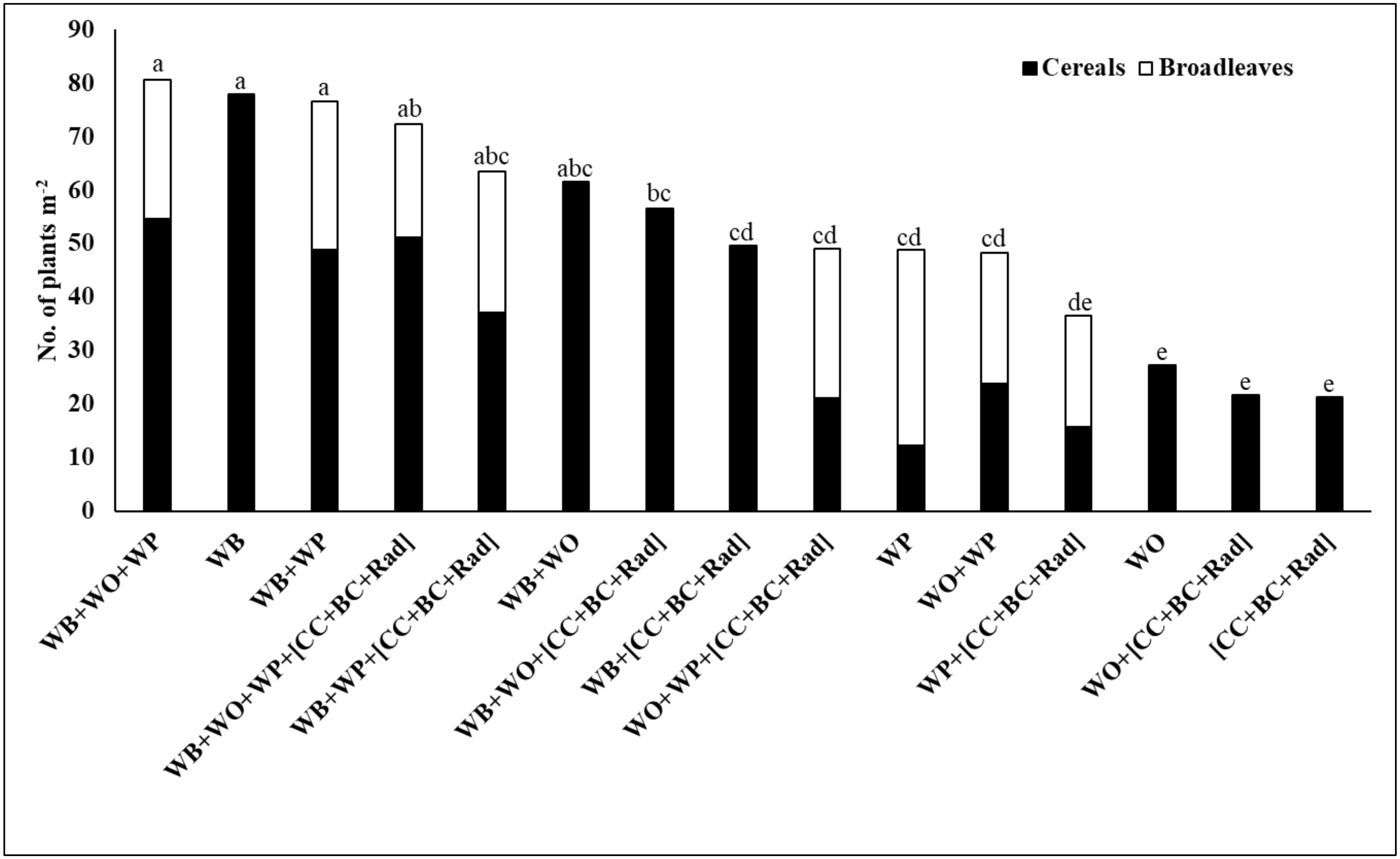

Figure 4.1. Total number of plants per m^2 for all treatments at Genesee pooled over three years at Genesee, ID from 2019 to 2021 [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at *P* = 0.05.

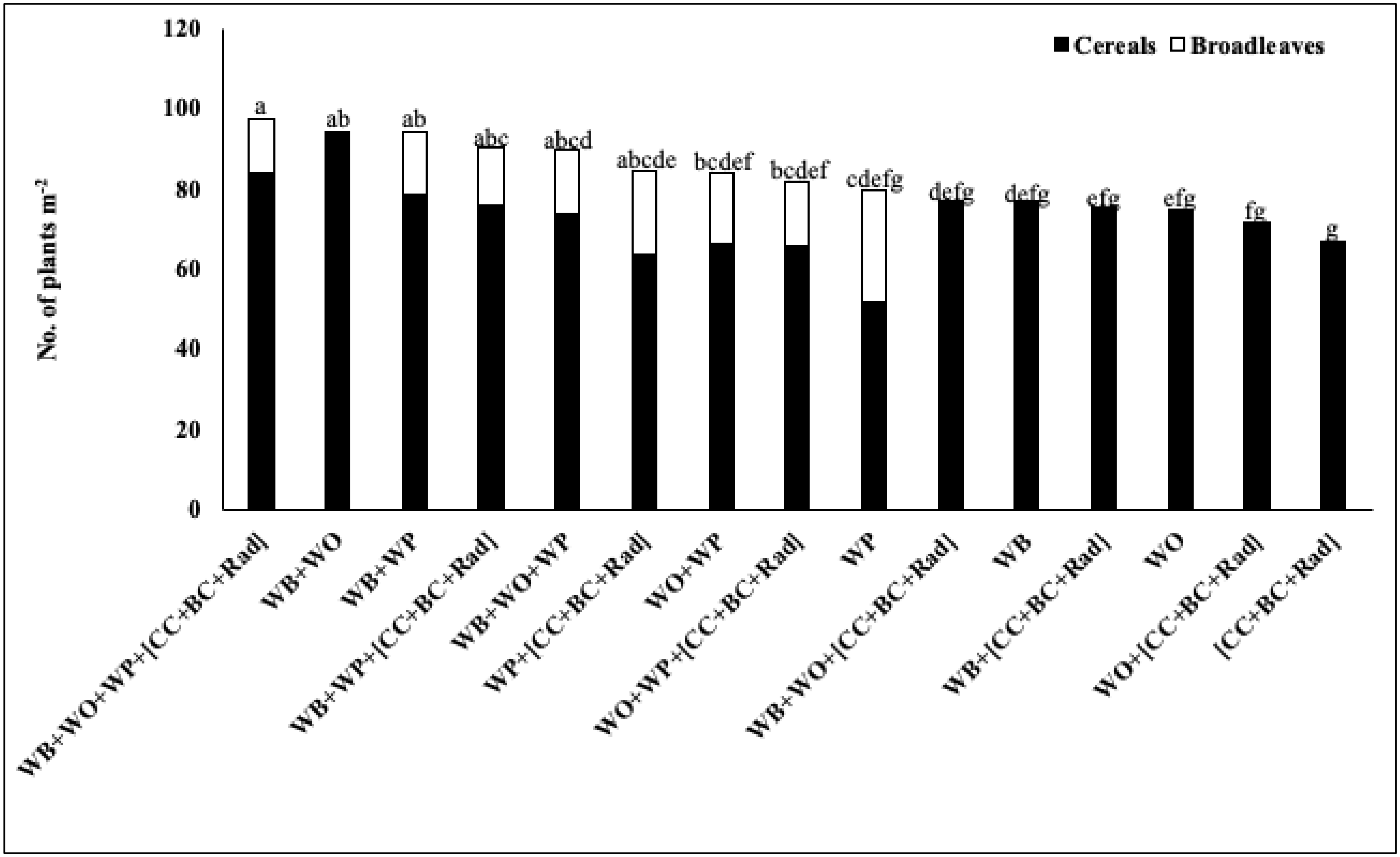

Figure 4.2. Total number of plants per m^2 for all treatments at Genesee pooled over two years at St. John in 2019 and 2021 [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at *P* = 0.05.

Fresh weight

Plant samples were harvested from each plot every 2 weeks starting the end of May to early July depending on the year. Genesee had higher fresh weight compared to St. John at the last harvest date in all years (Figure 4.3). There was a significant increase in fresh weight at Genesee from June to July in all years. A similar trend was observed at St. John in 2019, but in 2021, the fresh weight of the third harvest was significantly lower than the second harvest and similar to the first harvest date.

At Genesee, the fresh weight production varied substantially from 6,695 (CC+BC+Rad) to 21,511 kg ha^{-1} (WP) at the final harvest date (Table 4.3). At each sampling dates, WP consistently had the highest fresh weight. During the first and second sampling, monocrop WP and WB+WP had the highest fresh weight while during the final sampling date, monocrop WP had significantly higher fresh weight than other treatments. At all sampling dates, the small-seed mix (CC+BC+Rad) had significantly lower fresh weight than other treatments.

At St. John, there was less variation between the treatments for fresh weight (Table 4.4), partially due to the abundance of volunteer spring wheat in all treatments. The final fresh weight ranged from 5,294 to 7,558 kg ha^{-1} between treatments. At the first sampling, monocrop WO (7,236 kg ha^{-1}) had the highest fresh weight while at the second sampling monocrop WP (8,124 kg ha^{-1}) and monocrop WO (8,016 kg ha^{-1}) had the highest fresh weight. At the final sampling, WO+WP (7,558 kg ha^{-1}), WB+WO (7,361 kg ha^{-1}) and monocrop WO (7,157 kg ha^{-1}) had the highest fresh weight, although only statistically higher than monocrop WB.

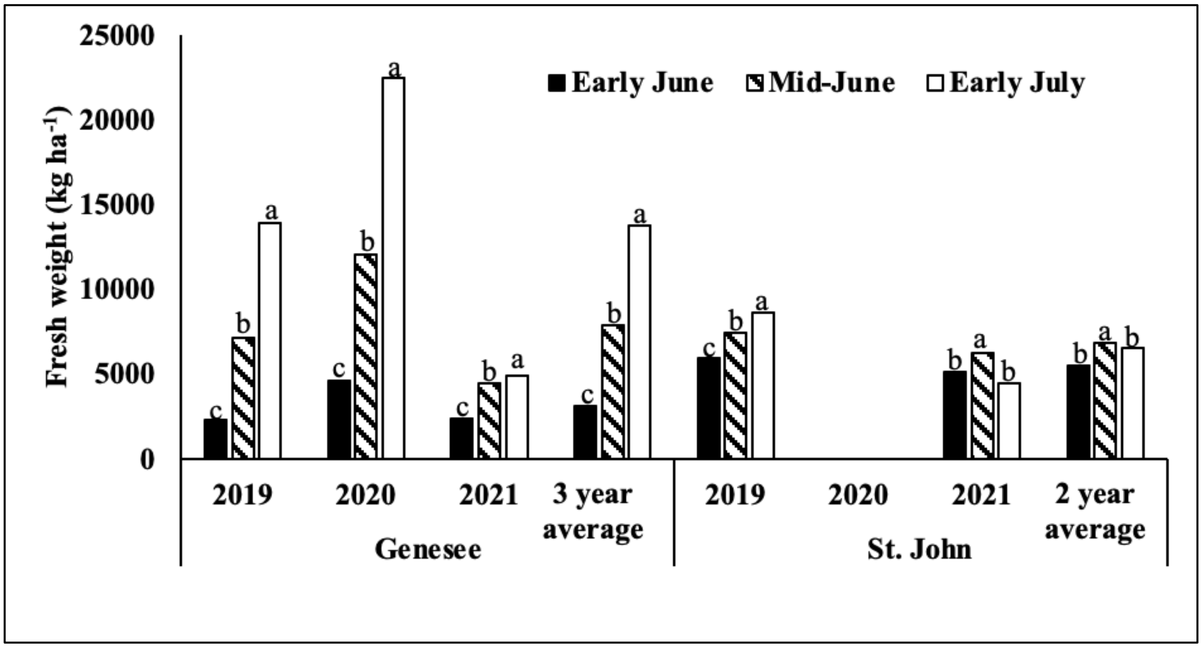

Figure 4.3. Forage fresh weight across three years at Genesee and two years at St. John and summarized fresh weight from 2019 to 2021. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at *P* = 0.05.

Table 4.3. Fresh weight biomass production for all treatments at three different sampling times at Genesee, ID averaged over 2019 to 2021.

Treatment	Early June		Mid-June		Early July	
	kg ha^{-1}					
WB[§]	2,752	de[†]	6,397	ef	11,311	c
WO	1,637	e	4,123	fg	8,211	cd
WP	4,699	a	14,027	a	21,511	a
[CC+BC+Rad]	1,093	f	2,920	g	6,695	d
WB+WO	2,765	de	7,237	de	11,075	c
WB+WP	4,891	a	12,472	ab	18,083	b
WO+WP	4,413	ab	11,019	bc	17,945	b
WB+[CC+BC+Rad]	3,333	bcd	7,275	de	10,715	c
WO+[CC+BC+Rad]	1,339	g	3,395	g	8,338	cd
WP+[CC+BC+Rad]	2,883	cd	8,360	de	16,493	b
WB+WO+WP	2,741	de	8,304	de	15,571	b
WB+WO+[CC+BC+Rad]	2,259	de	6,349	ef	10,555	c
WB+WP+[CC+BC+Rad]	4,616	a	8,507	cde	15,751	b
WO+WP+[CC+BC+Rad]	3,144	cd	8,779	cde	18,301	b
WB+WO+WP+[CC+BC+Rad]	3,997	abc	9,341	cd	16,161	b

[†] Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.

[§] WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.

Table 4.4. Fresh weight biomass production for all treatments at three different sampling times at St. John, WA averaged from 2019 and 2021.

Treatment	Early June	Mid-June	Early July
		kg ha^{-1}	
WB[§]	4,044 c[†]	5,964 ab	5,294 b
WO	7,236 a	8,016 a	7,157 a
WP	6,220 abc	8,124 a	6,627 ab
[CC+BC+Rad]	4,676 bc	5,912 ab	5,968 ab
WB+WO	5,068 abc	6,452 ab	7,361 a
WB+WP	5,632 abc	7,236 ab	6,557 ab
WO+WP	6,112 abc	7,508 ab	7,558 a
WB+[CC+BC+Rad]	4,828 bc	5,348 b	6,283 ab
WO+[CC+BC+Rad]	5,084 abc	6,896 ab	6,516 ab
WP+[CC+BC+Rad]	4,036 c	6,100 ab	5,818 ab
WB+WO+WP	5,448 abc	7,092 ab	6,240 ab
WB+WO+[CC+BC+Rad]	6,312 abc	7,896 ab	6,443 ab
WB+WP+[CC+BC+Rad]	5,536 abc	6,536 ab	6,761 ab
WO+WP+[CC+BC+Rad]	6,348 abc	7,204 ab	6,880 ab
WB+WO+WP+[CC+BC+Rad]	6,432 ab	6,880 ab	6,284 ab

[†] **Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.**

[§] **WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.**

Dry weight

At both locations, there was a significant increase in dry weight from early June to early July, where the early July harvest had the highest dry weight in all years (Figure 4.4). During 2019 and 2021, St. John had a higher dry weight compared to Genesee with the exception of the terminal harvest in 2019. The between year dry weight production was highly variable at Genesee as compared to St. John.

The final dry weight production ranged from 1,909 to 5,890 kg ha^{-1} (Table 4.5) at Genesee. At Genesee, WB+WP consistently had the highest dry weight production at all sampling dates and was significantly higher than most of the other treatments. As observed for the fresh weight, the small seed mix produced the lowest quantity of dry matter. At St. John, the final dry weight ranged from 2,338 to 3,188 kg ha^{-1} (Table 4.6). At St. John, WO had the highest dry weight during the first and second sampling, but during the final sampling WO+WP had the highest dry weight (3,269 kg ha^{-1}), although only significantly higher than WB and WP+[CC+BC+Rad]. WB had the lowest dry weight at the final sampling.

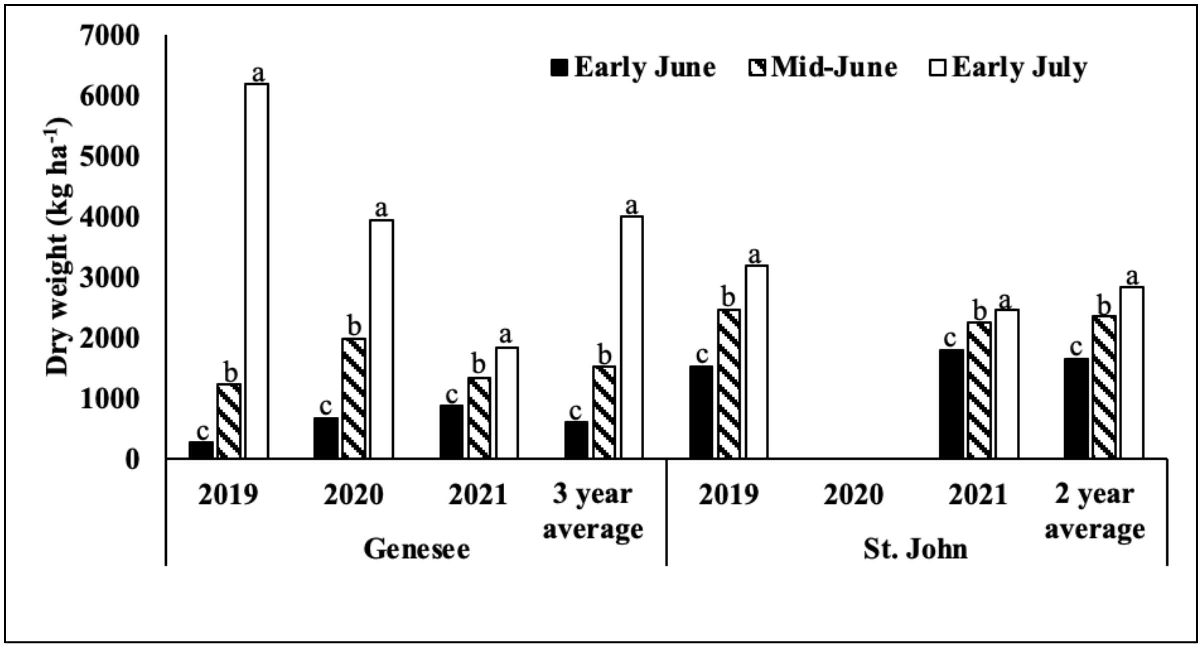

Figure 4.4. Forage dry weight across three years at Genesee and two years at St. John and summarized dry weight from 2019 to 2021. Bars followed by different letters in a single year at a location are statistically different using Fisher's LSD at *P* = 0.05.

Table 4.5. Dry matter production for all treatments at three different sampling times at Genesee, ID averaged from 2019 to 2021.

Treatment	Early June		Mid-June		Early July	
			kg ha^{-1}			
WB[§]	643	cdef[†]	1,579	bc	3,841	def
WO	400	gh	899	d	2,319	g
WP	675	bcde	1,928	b	5,316	ab
[CC+BC+Rad]	296	h	656	d	1,909	g
WB+WO	592	cdefg	1,667	bc	3,512	ef
WB+WP	915	a	2,427	a	5,890	a
WO+WP	661	cde	1,651	bc	4,485	bcde
WB+[CC+BC+Rad]	773	abc	1,760	bc	3,604	ef
WO+[CC+BC+Rad]	315	h	715	d	2,310	g
WP+[CC+BC+Rad]	459	fgh	1,419	c	4,141	cdeg
WB+WO+WP	557	defg	1,619	bc	4,824	bc
WB+WO+[CC+BC+Rad]	536	efg	1,472	bc	3,314	f
WB+WP+[CC+BC+Rad]	872	ab	1,648	bc	4,856	bc
WO+WP+[CC+BC+Rad]	547	efg	1,421	c	4,727	bcd
WB+WO+WP+[CC+BC+Rad]	755	abcd	1,851	bc	4,872	bc

[†] **Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.**

[§] **WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.**

Table 4.6. Dry matter production for all treatments at three different sampling times at St. John, WA averaged from 2019 and 2021.

Treatment	Early June		Mid-June		Early July	
			kg ha^{-1}			
WB[§]	1,296	c[†]	2,080	ab	2,338	c
WO	2,116	a	2,776	a	3,090	abc
WP	1,668	abc	2,368	ab	2,795	abc
[CC+BC+Rad]	1,448	bc	2,120	ab	2,669	abc
WB+WO	1,564	abc	2,332	ab	3,188	ab
WB+WP	1,644	abc	2,360	ab	2,793	abc
WO+WP	1,800	abc	2,664	ab	3,269	a
WB+[CC+BC+Rad]	1,576	abc	1,840	b	2,666	abc
WO+[CC+BC+Rad]	1,524	abc	2,432	ab	2,779	abc
WP+[CC+BC+Rad]	1,256	c	2,188	ab	2,437	bc
WB+WO+WP	1,688	abc	2,412	ab	2,783	abc
WB+WO+[CC+BC+Rad]	1,872	abc	2,748	a	2,741	abc
WB+WP+[CC+BC+Rad]	1,592	abc	2,156	ab	3,011	abc
WO+WP+[CC+BC+Rad]	1,876	abc	2,432	ab	3,032	abc
WB+WO+WP+[CC+BC+Rad]	1,940	abc	2,404	ab	2,888	abc

[†] **Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.**

[§] **WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.**

The dry weight of treatments was compared based on presence or absence of each individual component tested (Figure 4.5). At Genesee, the presence of WB in the mixture resulted in significantly higher dry weight compared to mixtures without WB. Similar results were observed for WP. However, the presence of small seed mix in the mixture had significantly lower dry weight compared to when absent, while the presence or absence of WO did not affect the dry weight of forage mixtures.

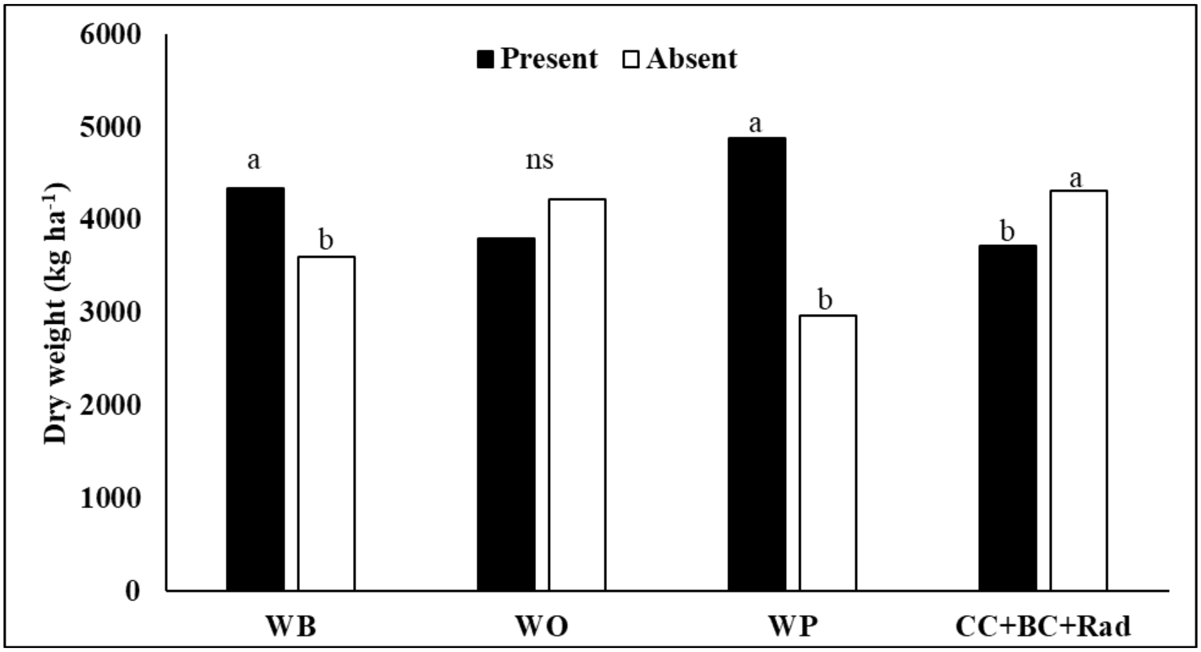

Figure 4.5. Comparison of dry matter production of mixtures when individual crops are either present or absent in the mixtures or monocropping at Genesee, ID from 2019 to 2021. WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish. Bars followed by different letters for a crop are statistically different using Fisher's LSD at *P* = 0.05.

At St. John, the dry matter production was not significantly affected by presence or absence of individual components (Figure 4.6). However, the presence of WP and WO tended to increase dry matter production compared to mixtures when these crops were absent. Conversely, the dry weight was usually lower when WB or CC+BC+Rad were present in the crop mix.

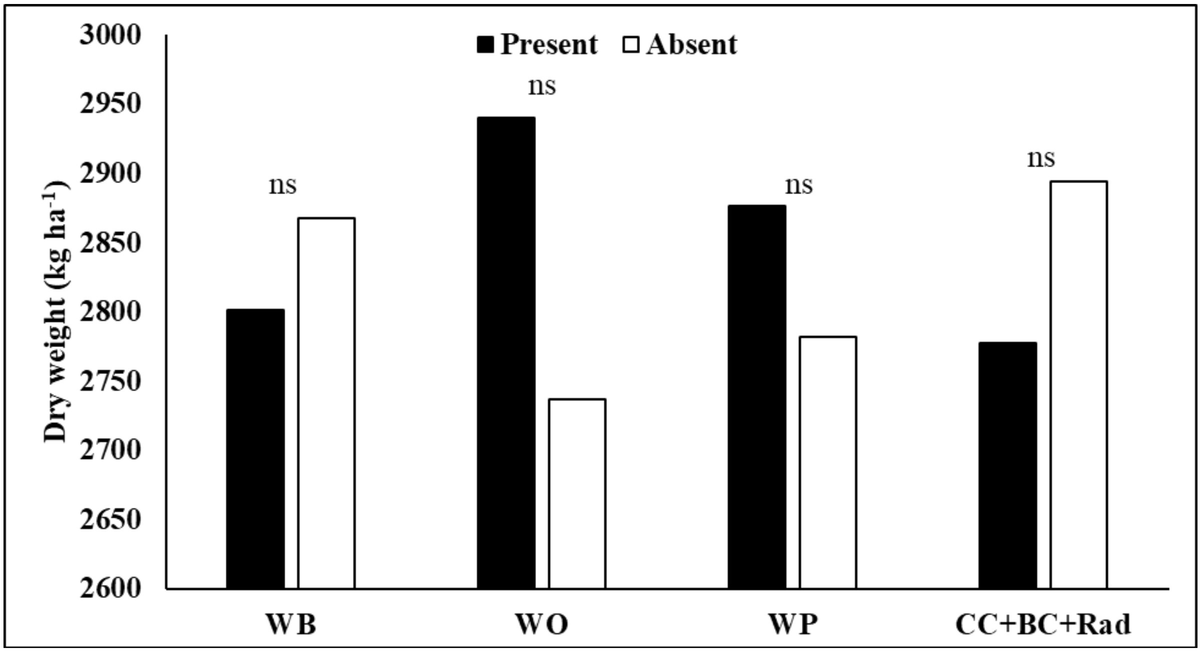

Figure 4.6. Comparison of dry matter production of mixtures when individual crops are either present or absent in the mixtures or monocropping at St. John, WA from 2019 and 2021. [WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish]. Bars followed by different letters for a crop are statistically different using Fisher's LSD at *P* = 0.05.

The terminal dry matter production of the treatments based on the number of crops in the mixture were compared (Figure 4.7). At Genesee the dry matter production was significantly lower for the monocrop compared to the mixtures, while there was no statistical difference between the two-way, three-way, and four-way mixtures. The monocrop treatments resulted in 30% less dry matter yield when compared to the four-way mix. At St. John, there was no difference between the number of crops in the mixtures.

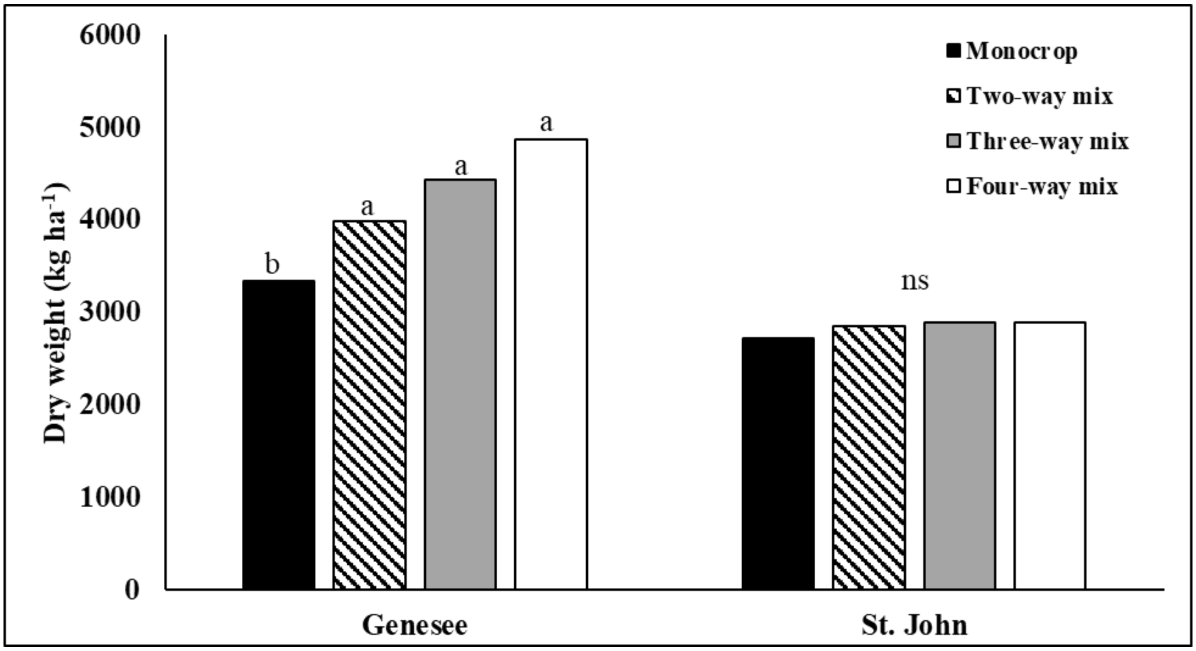

Figure 4.7. Dry matter yield comparing the treatment based on the number of crop types in the mixture at Genesee, ID and St. John, WA from 2019 to 2021. Bars followed by different letters for a crop are statistically different using Fisher's LSD at *P* = 0.05.

Forage Quality

The average CP at Genesee was 11.5 and ranged from 7.2 to 16.0% (Table 4.7). The mixture of WP and small seeded crops (i.e., volunteer barley) had the highest CP (16.0%), although not statistically higher than WO+WP+[CC+BC+Rad]. Monocrop WB had the lowest CP (7.7%) and was statistically similar to WB+[CC+BC+Rad] and WB+WO+[CC+BC+Rad]. At St. John the average CP was 8.1, ranging from 7.1 to 10.1% (Table 4.8). Monocrop WP had significantly highest CP (10.1%) than all other treatments except for WB+WP. The small seed mix (i.e., volunteer wheat) had the lowest CP (7.1%).

The NDF ranged from 48.3% to 58.2% at Genesee (Table 4.7). The treatments containing WB alone or in the mixture had higher in NDF content. The exception were those treatments with WB that also contained WP, in which case the NDF was lower. At St. John, the NDF ranged from 47.4% to 57.1% (Table 4.8). There were smaller differences between treatments, but WO+[CC+BC+Rad] had the highest NDF and WP monocropping had the lowest NDF across all treatments.

At Genesee, the ADF ranged from 29.2% to 32.5% (Table 4.7). The highest ADF was obtained from WB+WP+[CC+BC+Rad] but was statistically similar many of the other treatments. The lowest ADF was from the WO+[CC+BC+Rad] mixture. At St. John, the trend in ADF content was similar to the NDF content (Table 4.8). The highest ADF was with the mixture of WB+[CC+BC+Rad], while the lowest ADF was with WP.

Lignin content at Genesee was higher in the mixtures containing WP in the mixture and WP monocrop has the highest quantity of lignin (5.6%). The mixture with the lowest lignin content was WO+[CC+BC+Rad] but was not statistically lower than all other treatments lacking WP in the mixture. At St. John, the lignin content was similar between treatments. The highest lignin content was observed with the WO+WP+[CC+BC+Rad] but was only significantly higher than WB+WO+WP, WB+WO+[CC+BC+Rad] and WB+WO+WP+[CC+BC+Rad]. The lowest lignin content was in the mixture containing all six crops.

The RFV at Genesee ranged from 104 to 126 (Table 4.7) and from 107 to 133 at St. John (Table 4.8). The RFV was the highest for monocrop WP at both locations. The WB+WO mix at Genesee had the smallest RFV while the WO+[CC+BC+Rad] had the lowest RFV at St. John. Among all the mixtures at both locations, the top three mixtures with the highest RFV always had WP in the mixture.

Table 4.7. Forage quality parameters for fifteen different treatments at Genesee, ID averaged across three years from 2019 to 2021.

Treatment	CP[Φ] (%)		NDF (%)		ADF (%)		Lignin (%)		RFV	
WB[§]	7.2	j[†]	57.6	ab	31.0	abc	3.8	def	105	cd
WO	11.0	fg	54.5	de	29.9	bcd	3.5	f	114	bc
WP	14.4	bc	48.3	h	31.1	abc	5.6	a	126	a
[CC+BC+Rad]	14.2	bc	51.5	fg	29.7	cd	4.6	bcd	125	a
WB+WO	8.9	hi	58.2	a	31.0	abc	3.6	ef	104	d
WB+WP	11.6	ef	53.8	deg	32.0	a	4.9	abc	112	bcd
WO+WP	13.3	cd	51.8	fg	31.4	ab	5.2	ab	116	ab
WB+[CC+BC+Rad]	7.8	ij	56.4	abcd	30.0	bcd	3.3	f	108	bcd
WO+[CC+BC+Rad]	9.9	gh	53.4	ef	29.2	d	3.5	f	116	ab
WP+[CC+BC+Rad]	16.0	a	49.7	gh	30.8	abcd	4.9	abc	125	a
WB+WO+WP	12.4	de	53.4	ef	31.3	abc	4.7	abc	114	bcd
WB+WO+[CC+BC+Rad]	8.3	ij	57.2	abc	30.9	abcd	4.1	cdef	106	cd
WB+WP+[CC+BC+Rad]	11.8	ef	54.7	cde	32.5	a	4.5	bcde	109	bcd
WO+WP+[CC+BC+Rad]	14.9	ab	49.2	gh	31.0	abc	4.8	abc	124	a
WB+WO+WP+[CC+BC+Rad]	11.1	fg	55.0	bcde	32.1	a	4.6	bcd	109	bcd

[†] Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.

[§] WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.

[Φ] Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV).

Table 4.8. Forage quality parameters for fifteen different treatments at St. John. WA averaged across two years from 2019 and 2021.

Treatment	CP[Φ] (%)		NDF (%)		ADF (%)		Lignin (%)		RFV	
WB[§]	7.7	defg[†]	54.9	ab	28.9	ab	4.0	abc	113	bc
WO	7.7	defg	54.7	ab	29.0	ab	3.9	abc	115	bc
WP	10.1	a	47.4	d	28.0	b	4.3	ab	133	a
[CC+BC+Rad]	7.1	g	53.6	abc	29.0	ab	4.1	abc	117	bc
WB+WO	7.8	defg	55.9	ab	29.7	ab	3.9	abc	110	c
WB+WP	9.3	ab	53.8	abc	30.1	ab	4.2	abc	114	bc
WO+WP	7.5	efg	53.9	abc	29.8	ab	4.2	abc	114	bc
WB+[CC+BC+Rad]	7.9	cdefg	55.0	ab	29.1	ab	4.1	abc	114	bc
WO+[CC+BC+Rad]	7.6	efg	57.1	a	30.6	a	4.1	abc	107	c
WP+[CC+BC+Rad]	8.7	bc	50.6	cd	29.6	ab	4.3	ab	122	ab
WB+WO+WP	7.3	fg	52.8	bc	28.6	ab	3.9	bc	118	bc
WB+WO+[CC+BC+Rad]	8.1	cdef	56.2	ab	29.8	ab	3.9	bc	110	c
WB+WP+[CC+BC+Rad]	7.7	defg	53.3	bc	29.3	ab	4.2	abc	117	bc
WO+WP+[CC+BC+Rad]	8.5	bcd	53.6	abc	30.3	a	4.4	a	115	bc
WB+WO+WP+[CC+BC+Rad]	8.2	cde	53.3	bc	28.5	ab	3.7	c	118	bc

[†] Mean followed by different letters in a single column for a main effect are statistically different using Fisher's LSD at *P* = 0.05.

[§] WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.

[Φ] Crude protein (CP), Neutral detergent fiber (NDF), Acid detergent fiber (ADF), Lignin and relative feed value (RFV).

Economic Analysis

Economic analyses were conducted to determine average net return per hectare from each forage crop mixture at individual locations. Tables 4.9 and 4.10 show the average net return for the mixtures at Genesee and St. John, respectively. The total return is based on the forage production and the price was based on the hay price of \$0.17 kg^{-1} (USDA, 2020). Cost of chemicals, forage operations, planting, fuel, labor, and repairs used for all mixtures are assumed to be same. The only difference in cost is due to the change in various seed mixtures and their respective prices.

Cost of the mixtures used in this study differed markedly. The highest seed cost was for the monocrop WO (\$111.35 ha^{-1}). The lowest seed cost was \$28.58 for the monocrop WB. Genesee had higher yield and most of the mixtures had higher average net returns per hectare compared to St. John. At Genesee, the two-way mixture of WB+WP had the highest net return of \$702.88 ha^{-1}. Monocrop WO, the small seed mix and the two-way mix of WO and small seed mix had the lowest net returns of \$66.48, \$76.14 and \$104.04, respectively. Mixtures with WB and WP tended to have higher net returns. At St. John, the two-way mixture of WB+WO had the highest net return of \$256.18 ha^{-1} and lowest net return was from the two-way mixture of WP and small seed mix (\$125.37 ha^{-1}). Due to the abundance of volunteer wheat in the plots at St. John, there was far less variability in total returns between treatments as well as net return compared to Genesee.

Table 4.9. Average net return per hectare for various forage crop mixtures from 2019 to 2021 at Genesee.

	WB[§]	WO	WP	[CC+ BC+ Rad]	WB+ WO	WB+ WP	WO+ WP	WB+ [CC+ BC+ Rad]	WO+ [CC +BC +Rad]	WP+ [CC+ BC+ Rad]	WB+ WO+ WP	WB+ WO+ [CC+ BC+ Rad]	WB+ WP+ [CC+ BC+ Rad]	WO+ WP+ [CC+ BC+ Rad]	WB+ WO+ WP+ [CC+ BC+ Rad]
Hay yield (kg/ha)	3841	2319	5316	1909	3512	5890	4485	3604	2310	4141	4824	3314	4856	4727	4872
Hay price ($/kg)	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
Sale of forage hay	$635.11	$383.50	$879.04	$315.67	$580.67	$973.94	$741.55	$595.85	$382.00	$684.64	$797.69	$548.00	$802.95	$781.65	$805.65
Total Returns ($/ha)	**$635.11**	**$383.50**	**$879.04**	**$315.67**	**$580.67**	**$973.94**	**$741.55**	**$595.85**	**$382.00**	**$684.64**	**$797.69**	**$548.00**	**$802.95**	**$781.65**	**$805.65**
Seed cost	$28.58	$111.35	$110.01	$41.10	$69.58	$69.68	$110.41	$35.50	$75.94	$75.59	$84.18	$59.69	$60.82	$87.51	$73.52
Fertilizer cost	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82
Chemical cost	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Forage Operations	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47
Machine (Labor, Fuel and Repairs)	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99
Other Expenses (5%)	$9.14	$13.28	$13.21	$9.77	$11.19	$11.20	$13.23	$9.49	$11.51	$11.49	$11.92	$10.70	$10.76	$12.09	$11.39
Interest on operating inputs (6.75%)	$9.72	$14.12	$14.05	$10.39	$11.90	$11.91	$14.07	$10.09	$12.24	$12.22	$12.68	$11.37	$11.43	$12.85	$12.11
Crop Insurance	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Machine Replacement Costs	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99
Total Annual Costs	**$225.72**	**$317.02**	**$315.55**	**$239.53**	**$270.95**	**$271.06**	**$315.99**	**$233.36**	**$277.96**	**$277.58**	**$287.06**	**$260.04**	**$261.29**	**$290.73**	**$275.30**
Net Return ($/ha)	$409.39	$66.48	$563.49	$76.14	$309.73	$702.88	$425.56	$362.49	$104.04	$407.06	$510.63	$287.96	$541.66	$490.92	$530.35

[§] **WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.**

Table 4.10. Average net return per hectare for various forage crop mixtures in 2019 and 2021 at St John.

	WB§	**WO**	**WP**	**[CC+ BC+ Rad]**	**WB+ WO**	**WB+ WP**	**WO+ WP**	**WB+ [CC+ BC+ Rad]**	**WO+ [CC +BC +Rad]**	**WP+ [CC+ BC+ Rad]**	**WB+ WO+ WP**	**WB+ WO+ [CC+ BC+ Rad]**	**WB+ WP+ [CC+ BC+ Rad]**	**WO+ WP+ [CC+ BC+ Rad]**	**WB+ WO+ WP+ [CC+ BC+ Rad]**
Hay yield (kg/ha)	2338	3090	2795	2669	3188	2793	3269	2666	2779	2437	2783	2741	3011	3032	2888
Hay price ($/kg)	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
Sale of forage hay	$386.58	$510.92	$462.14	$441.31	$527.13	$461.81	$540.52	$440.81	$459.50	$402.95	$460.16	$453.22	$497.86	$501.33	$477.52
Total Returns ($/ha)	**$386.58**	**$510.92**	**$462.14**	**$441.31**	**$527.13**	**$461.81**	**$540.52**	**$440.81**	**$459.50**	**$402.95**	**$460.16**	**$453.22**	**$497.86**	**$501.33**	**$477.52**
Seed cost	$28.58	$111.35	$110.01	$41.10	$69.58	$69.68	$110.41	$35.50	$75.94	$75.59	$84.18	$59.69	$60.82	$87.51	$73.52
Fertilizer cost	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82	$11.82
Chemical cost	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Forage Operations	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47	$102.47
Machine (Labor, Fuel and Repairs)	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99	$39.99
Other Expenses (5%)	$9.14	$13.28	$13.21	$9.77	$11.19	$11.20	$13.23	$9.49	$11.51	$11.49	$11.92	$10.70	$10.76	$12.09	$11.39
Interest on operating inputs (6.75%)	$9.72	$14.12	$14.05	$10.39	$11.90	$11.91	$14.07	$10.09	$12.24	$12.22	$12.68	$11.37	$11.43	$12.85	$12.11
Crop Insurance	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Machine Replacement Costs	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99	$23.99
Total Annual Costs	**$225.72**	**$317.02**	**$315.55**	**$239.53**	**$270.95**	**$271.06**	**$315.99**	**$233.36**	**$277.96**	**$277.58**	**$287.06**	**$260.04**	**$261.29**	**$290.73**	**$275.30**
Net Return ($/ha)	$160.86	$193.90	$146.59	$201.78	$256.18	$190.75	$224.53	$207.46	$181.54	$125.37	$173.10	$193.17	$236.57	$210.60	$202.22

§WB, winter barley; WO, winter oat; WP, winter pea; CC, crimson clover; BC, balansa clover; Rad, radish.

Discussion

The concept of growing forage crops as part of the cereal-based cropping systems in the dryland regions of the IPNW is new and is gradually gaining popularity among growers. There has been little focus on fall seeded forage crops in the region, thus there is not much information on winter survivability, forage yield potential and forage quality of crops to use in mixes. In this study six different forage crops were tested in multiple combinations for their forage biomass production and forage nutritive value in the IPNW. Few forage crops are suitable for fall seeding in the intermediate and high rainfall regions of the IPNW due to their inability to survive winter conditions. However, WO, WP and WB are well adapted to the region and have high production potential.

The dry matter production was highly variable between years. Biomass production was greatest in 2019 which had suitable spring growing conditions with high precipitation. However, 2021 was one of the driest years on record for the region and there was a corresponding reduction in forage production at both locations. St. John had higher dry matter production earlier in the growing season (first and second sampling dates) in all years of the study compared to Genesee. This can be attributed to slightly warmer temperatures and a greater number of growing degree days earlier in the growing season at St. John which promoted the crop growth early in the spring. Crop maturity at each sampling date varied across locations, those at St. John were ahead in growth stage than crops at Genesee. However, the favorable growing conditions and higher precipitation in Genesee relative to St. John resulted in higher dry matter production at the final harvest in early July. The drier conditions at St. John resulted in earlier crop maturity and reduced yield potential.

Selection of proper crops and respective varieties along with planting at a proper depth are very important considerations for successful forage production. Selection of crops and varieties in this study was based on preliminary work at Pullman, WA to assess winter survival during 2015 to 2017 (Allen Casey, personal communication). Yet, small seed crops like CC, BC and radish did not emerge and rarely established in the field trials, while WB, WO and WP performed relatively good. Pavek (2014) reported biomass production of 37 different crop species where CC had low biomass production (less than 500 kg ha^{-1}), while Rad did not survive the winter. The same study showed higher biomass production with crops like triticale, barley, wheat, winter peas and turnip. In a separate study conducted in Maryland, CC, BC and Rad, were observed to have poor winter survival and biomass production (Ugiansky, 2020). An additional possibility for the failure of the small seed crops was the planting depth. In this study, to best accommodate all crops in the mix, all crops were seeded at the same time at a depth of 2.5 to 3.5 cm which was likely too deep for the smaller seed crops. White and Barbercheck (2017) indicated that if a single depth was chosen for a mixture, the small seed crops had sub-optimal establishment, which is similar to what we observed in this study. White and Barbercheck (2017) further suggested different planting methods for successful production of crop mixtures. Some potential solutions to overcome the seeding depth issues are to use specialized equipment capable of planting at different depths or conducting two planting operations where larger seeds are planted deeper and small seeds are planted shallower. Broadcasting of small seeds followed by a harrow might be other options for seeding these crops.

Biomass production of the mixtures was comparable to yields reported in studies from other dryland growing areas of the U.S. In the current study, the dry matter yield ranged from

1,909 to 5,890 kg ha^{-1} at Genesee and 2,338 to 3,269 kg ha^{-1} at St. John. Holman et al. (2018) reported forage dry matter yield ranging from 622 to 4,209 kg ha^{-1} in a study in Kansas, which included fall seeded forage crops such as hairy vetch, winter triticale, winter lentil and winter pea in different combinations over three years from 2008 to 2011. A study conducted in Tennessee by Bracey et al. (2022) had biomass production ranging from 475 to 4,282 kg ha^{-1} with fall seeded cool season crops. In the Tennessee study, higher dry matter production was obtained with crimson clover, winter pea, oat, wheat, vetch, and canola. Compared to our region, the sites in Tennessee and Kansas receive precipitation during the fall which allows for earlier seeding and improved establishment. Unfortunately, the fall in the IPNW is very irregular in terms of precipitation which might result in poor establishment of certain species (Pavek, 2014). All crops in the mixtures in our study did not contribute towards the biomass due to lack of germination and/or poor establishment. Improved and adapted cultivars or modified agronomic practices might help in increasing the overall yield of the mixtures.

Composition of forage crop mixtures is an important component in forage production. In this study, the smaller seed crops CC, BC and Rad rarely established. However, due to the contributions of seeded WB, WO and WP along with volunteer cereals at both locations, most plots had sufficient crop stands to compete with weeds and produce adequate forage yields. Mixtures containing WB and WP had higher dry matter production at Genesee, however, at St. John, higher production was from mixtures containing WO and WP. WB had problems establishing in St. John and WO did not establish well in Genesee. A study in Kansas by Farney et al. (2018) compared the composition and production of fall planted forage crops that included barley, radish, clover, pea, turnip, oat, rye and radish in various combinations. Results showed that WO, WB and WP performed well in cooler and dryer environments, where WO and WB had higher biomass production. In the same study, radish had higher biomass production than turnip and WP had higher production than clover. Cereals crops often are major contributors to dry matter production (Adesogan et al., 2012). Legumes, on the other hand, have higher nutritive value and can contribute to improve nutritive value of the mixture (Ball et al., 2001). Brassica crops could be an excellent source of forage biomass with higher nutritive value, but these crops are sensitive to environmental conditions, especially to low temperature and moisture (Farney et al., 2018). In this study, when comparing treatments based on the number of species in the mixture, we observed that the dry matter production increased as the number of components in the mixture increased. Wortman et al. (2012) also reported that a higher number of crops in the mixture produced higher biomass compared to a monocrop.

Volunteer crops played a significant role in the forage production in terms of forage yield and quality. While the impact of spring wheat was significant at St. John, the volunteer spring barley at Genesee had minimum influence. In every treatment in the St. John site in all years, volunteer spring wheat contributed at least 50% to the total plant population. Due to this reason, the composition of the mixtures at St. John was dominated mostly by cereals and difference between the treatments were difficult to discern. Similar results were observed for forage quality as well. As discussed above, due to heavy concentration of cereals, the CP content of mixtures at St. John was poor and the treatments also did not differ greatly among each other as compared to the treatments at Genesee. A potential solution to solve the impact of volunteer crop is anticipating their emergence based on experience and history of the land and preparing the mixture accordingly.

When selecting a crop mix that will be used for grazing or haying, the crop mixture must have an adequate forage nutritive value. Upon examining the treatment combinations in this study, it was observed that CP was higher in the treatment that had WP as part of the mixture, while the CP was lower with WB and WO in the mixture. The NDF and ADF was comparatively lower in mixtures with WP and were higher for mixtures with barley and/or oat. Relative feed values were also higher for mixtures with WP in them. A study in Tennessee by Bracey et al. (2022) reported forage nutritive values of numerous crop species including legumes, brassicas, and cereals in a monocrop setting. The forage quality of the crops in this study was superior [barley (4.2% lignin, 52.3% NDF, 30.4% ADF, 11% CP), oat (3.9% lignin, 44.9% NDF, 25% ADF, 10.1% CP), crimson clover (5.6% lignin, 39.3% NDF, 29.8% ADF, 20.1% CP), forage radish (6.9% lignin, 46.2% NDF, 32.5% ADF, 15.6% CP), winter peas (5.6% lignin, 42.7% NDF, 27.1% ADF, 20.7% CP)] than the values obtained in the current IPNW studies. USDA has hay quality designation guidelines to distinguish different grades of alfalfa hay as shown in Table 4.11 (USDA, Hay Quality Designation Guidelines). When compared to the alfalfa guidelines for forage nutritive value, most of the forage crop treatments from this study are equivalent to utility grade alfalfa hay.

Table 4.11. Alfalfa guidelines (domestic livestock use and not more than 10% grass) (USDA Hay Quality Designation Guidelines).

Quality	CP (%)	NDF (%)	ADF (%)	RFV
Supreme	>22	<34	<27	>185
Premium	20-22	34-36	27-29	170-185
Good	18-20	36-40	29-32	150-170
Fair	16-18	40-44	32-35	130-150
Utility	<16	>44	>35	<130

Although the forage crop mixture from this study can be used as hay to feed farm animals, the forage quality of the mixtures is not high enough to be considered a good quality hay. Numerous factors could have played a role in the low forage nutritive value of the crops.

Crop maturity plays a vital role in determining the forage nutritive value. These forage quality parameters were measured only in the samples that were harvested at early July. Had the samples from early June and mid-June been evaluated, the quality parameters measured would have improved. As seen in Chapter 2, the CP content and RFV of the forage mixtures declined as plant matured and ADF, NDF and lignin increased as plant matured in the winter forage crop mixtures at Genesee. Within 40 to 45 days between late May and early July, there was a significant reduction in the forage quality of the winter forage mix at Genesee. As plants mature and reach reproductive maturity, the quality of the forage will decrease (Ball et al., 2001; Coleman et al., 2004; Wyffels et al., 2022). However, harvest date should be properly selected to balance forage yield with forage quality. Failure of CC, BC and Rad to establish in the mixtures in the study almost certainly contributed to lower nutritive value. Bracey et al. (2022) reported forage nutritive values for forage radish and crimson clover. These crops, if established in the mixture would contribute towards improving nutritive value of the mixture. Lastly, temperature also plays a role in determining forage quality as higher temperature seem to decrease the forage nutritive value of crops (Ford et al., 1979; Fick et al., 1988). This phenomenon was observed in the forage quality of 2021, where higher temperature reduced forage yield as well as forage quality.

Fall seeded forage crops could be an excellent source of income for growers either replacing fallow or even replacing a cash crop if used as hay or for grazing. Economic analyses from this study show a net return as high as \$700 ha^{-1} at Genesee and \$250 ha^{-1} at St. John. Generally, mixtures containing WB and WP had higher net return at Genesee and mixtures containing WO had higher return at St. John. Net return of these forage crop mixtures highly depends on the crop composition, seed price, forage production and price of hay in a particular year. Regardless, grazing or haying of forage crops would be a potential source of profit for the growers compared to leaving the land fallow or planting a multispecies cover crop (Schomberg et al., 2014; Plastina et al., 2018).

Conclusion

The results from the study suggest that fall seeded forage crops can be successfully grown in the IPNW with adequate dry matter production along with acceptable forage quality. WP, WB and WO are best adapted to the region and performed better in monocrop and mixtures. However, crops like crimson clover, balansa clover and radish did not perform well at either location in all years, demonstrating the challenges in establishing these crops and their potential unsuitability in the region. Seeding depth likely played a role in the unsuccessful growth of these crops and future work may consider a different strategy for seeding these smaller seed crops to improve establishment.

Winter pea, winter oat and winter barley proved to be suitable components as part of a forage crop in the region, provided they are timely harvested to attain the highest dry matter production with higher forage nutritive value. Future research should focus on developing crops and cultivars that are locally adapted, have high forage yield and quality, and have compatibility to grow in mixture with other crops. Furthermore, management strategies for these forage crops such as seeding depth, seeding rate, proportions of each crop, termination dates, and planting dates should be studies if we are to successfully establish annual forage crops as part of the cereal-based cropping system in the IPNW.

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Chapter 5: Summary and Conclusion

The cereal based cropping systems in the IPNW will face unique challenges in the near future associated with the eminent climate change. Precipitation patterns and temperatures are expected to change, distinctively impacting each cropping system in the region. Due to this climatic variability, the intermediate cropping region of the IPNW will face increased fallowing where fallow will occur every 2 years compared to every 3 years in parts of the region with an increased vulnerability to soil erosion. Similarly, the acreage of annual cropping will decline with fallow being practiced. The region will likely deal with delayed planting, erosion and compaction due to excessive moisture in the spring as well as hotter and dryer than normal summers. Diversification of the existing cropping system with the integration of additional fall seeded crop options may contribute to a solution to manage climate change and bolster the cropping system to be more resilient to climate variability. With limited annual precipitation and cold winters, there are very few options to diversify the cropping system. Winter pea and forage crops are two alternatives that could potentially be incorporated into the dryland cropping system of the IPNW. Three different experiments were conducted in the intermediate and annual cropping region of the IPNW to study the rotational impacts and production potential of these alternative crops.

The first was a 4-year study started in the fall of 2017 where winter pea and forage crops were incorporated in place of fallow in the transitional cropping region (traditional rotation of winter wheat - spring wheat - fallow) or spring planted crops in the annual cropping region (traditional rotation of winter wheat - spring cereal - spring legume/canola) of the IPNW. The second was a 3-year study to optimize the production of winter peas with regard to seeding date, seeding rate, and phosphorus and sulfur application. The third was a 3-year study started in the fall of 2018 where winter barley, winter oat, winter pea, radish, crimson clover and balansa clover were evaluated for forage yield and quality in various combinations.

Winter pea and forage crop mixtures were successfully incorporated into the existing cropping system of the IPNW. Fallow in the intermediate precipitation region was replaced by winter pea or spring forage. In the annual cropping region, spring wheat was replaced by winter forage crop or chickpea was replaced with winter pea. The new alternative crops had higher productivity compared to crops they replaced in the traditional rotation. With forage crops in the rotation, there was a significant reduction in use of chemical pesticides. The new cropping systems with these alternative crops had higher productivity and farm profitability compared to the traditional cropping system.

Winter pea yield was improved with optimization of agronomic management. Earlier seeding of winter pea consistently produced higher yields, while the seeding rate of 130 seeds m^{-2} was the most productive and had the highest net return. However, the application of phosphorus and sulfur fertilizer was insignificant and did not impact winter pea production. These results were at odds with previous work on phosphorus and sulfur application and may warrant additional work in the future. The fall seeded forage mixtures had varying success and even failed to establish during one season in St. John, pointing out a potential risk of fall seeded forage crops in this region if there is not adequate moisture for fall establishment. Winter barley, winter oat and winter pea were the most well adapted crops among those tested. The small-seeded crops such as clovers and radish were likely seeded too deep, impacting emergence. Other planting strategies should be explored to improve the success of a more diverse forage mix. The forage quality of the mixtures tested was not extraordinary but was acceptable.

Winter pea and forage crops can be successfully grown in the IPNW provided that appropriate management practices are adopted, and proper forage crop mixes are selected. Future research should focus on developing superior food grade cultivars. Additional work is needed to improve the success of forages and future research should focus on seeding depth, seeding rate, termination dates, seeding dates, and identification of proper crop ratios in the mix. Strategies to improve market access for winter peas and forage crops will also be required to expand the use of these crops to larger areas of land. The research outlined in this dissertation will help establish winter peas and forge crops as prospective and integral part of the IPNW cropping systems in the coming years.

Appendix A

Various assumptions were made while conducting the economic analysis. Table A.1 list all the pesticides, used application rates and price of the pesticides for respective crops at both locations. Table A.2 consists of the list of field operations done for each crops including seeding, spraying, harvesting, mowing, raking, and baling.

Table A. 3 consists of list of machines used for the field operations such as tractors, combine harvester, tillage operations, trucks, fertilizer applicators, etc. The table also includes the price, life of the equipment, fuel use and equipment efficiency. Table A.4 includes assumption rates for interest rate, fuel and labor prices for the analyses conducted.

Table A.1. Summary of application of pesticides to each crop in all rotations along with the application rate as well as price of each chemical.

Crop	Chemicals	Rate	Price per unit
Winter pea	**Assure**	0.58 L ha^{-1}	\$33.48 L^{-1}
	crop oil	1.17 L ha^{-1}	\$3.51 L^{-1}
	Diurex 4L	2.34 L ha^{-1}	\$7.10 L^{-1}
	Spartan	0.58 L ha^{-1}	\$69.32 L^{-1}
	Glyphosate	2.34 L ha^{-1}	\$5.07 L^{-1}
	Asana XL	0.70 L ha^{-1}	\$21.98 L^{-1}
Winter wheat	**Huskie**	0.99 L ha^{-1}	\$30.09 L^{-1}
	Osprey Xtra	0.34 kg ha^{-1}	\$178.13 kg^{-1}
	NIS (R11)	0.58 L ha^{-1}	\$8.79 L^{-1}
	AMS	0.21 kg ha^{-1}	\$1.57 kg^{-1}
	Strarane Ultra	0.03 L ha^{-1}	\$26.04 L^{-1}
	Glyphosate	2.34 L ha^{-1}	\$5.07 L^{-1}
	Affinity	0.06 kg ha^{-1}	\$316.41 kg^{-1}
Spring wheat	**Huskie**	0.88 L ha^{-1}	\$30.09 L^{-1}
	Axial Star	1.20 L ha^{-1}	\$44.63 L^{-1}
	NIS (R11)	0.58 L ha^{-1}	\$8.79 L^{-1}
	AMS	0.21 kg ha^{-1}	\$1.57 kg^{-1}
	Strarane Ultra	0.48 L ha^{-1}	\$26.04 L^{-1}
	Glyphosate	2.34 L ha^{-1}	\$5.07 L^{-1}
Chickpea	**Spartan**	0.58 L ha^{-1}	\$69.32 L^{-1}
	Diurex 4L	2.34 L ha^{-1}	\$7.10 L^{-1}
	Assure	0.58 L ha^{-1}	\$33.48 L^{-1}
	Crop Oil	1.17 L ha^{-1}	\$3.51 L^{-1}
	Priaxor	0.58 L ha^{-1}	\$149.80 L^{-1}
	Glyphosate	2.34 L ha^{-1}	\$5.07 L^{-1}
Forage crops	**Glyphosate**	2.34 L ha^{-1}	\$5.07 L^{-1}
Fallow	**Glyphosate**	2.34 L ha^{-1}	\$5.07 L^{-1}

Table A.2. Assumption of field operations and number of each field operation performed for each crop in the rotations.

Crops	Seeding	Spraying	Harvesting	Mowing	Raking	Baling
Winter pea	1	5	1			
Winter wheat	1	2	1			
Spring wheat	1	2	1			
Chickpea	1	3	1			
Forage crops	1	1		1	1	1
Fallow		2				

Table A.3. List of Power Units and Machinery Values, Years of Life, Width and Speed of Operations.

Power Units and Machinery	Purchase Price ($)	Useful Life (Years)	Fuel Use/Hour (gallon/hour)	Width (inch)	Speed (mph)	Field Efficiency
450 HP tractor	$180,000	10	20	-	-	-
200 HP Trac	$180,000	10	20	-	-	-
Shredder	$30,000	10	-	30	4.89	90
Harrow	$12,000	15	-	60	5.99	85
Chisel plow	$45,000	15	-	35	6	85
Moldboard plow	$55,000	15	-	25	3.4	85
Cultivator	$20,000	15	-	36	5	85
Cultiweeder	$25,000	15	-	36	5	85
Drill	150,000	10	-	36	4.9	70
Combine w/ 36' header	$300,000	10	14	36	4.6	65
Bankout Wagon	$18,000	15	-	-	-	-
Fertilizer Spreader	$25,000	20	-	40	6	70
Fertilizer tanks and pump	$30,000	20	-	16.5	7	70
Boom sprayer	$42,000	20	-	100	6.47	65
Tandem Axle Truck	$40,000	10	6	-	-	-
Tandem Axle Truck	$40,000	10	6	-	-	-

Table A.4. Assumptions of interest rates, fuel prices and labor rates used for the economic analyses.

	Unit	$/Unit
Other Expenses	Percent	5.00%
Operating Interest Rate	Percent	6.75%
Months of Operating Loan	Months	9
Gas	Gallon	$4.00
Diesel	Gallon	$4.00
Machine Labor Rates	Hour	$20.00

Appendix B

Table B.1. Analysis of variance (sources were similar crops in different rotations) and p-values of crop growth parameters at Genesee from 2018 to 2021.

	2017-18			2018-19			2019-20			2020-21		
	Chickpea	Spring wheat	Winter wheat	Chickpea	Spring wheat	Winter wheat	Chickpea	Spring wheat	Winter wheat	Chickpea	Spring wheat	Winter wheat
Plant height	0.885	0.223	0.358	1.000	0.032	0.098	0.729	0.120	0.735	0.816	0.455	0.965
Yield	0.121	0.040	0.876	0.767	0.144	0.751	0.233	0.465	0.455	0.878	0.316	0.372
Grain protein	0.298	0.900	0.303	0.370	0.201	0.013	0.436	0.143	0.386	0.805	0.372	0.449
Seed weight	0.214	0.488	0.959	0.511	0.709	0.421	0.490	0.928	0.219	0.161	0.792	0.406
Test weight		0.844	0.627		0.047	0.117		0.118	0.317		0.462	0.310
Flour protein		0.417	0.940		0.210	0.132		0.206	0.688		0.125	0.692
Flour yield		0.591	0.276		0.476	0.051		0.816	0.806		0.527	0.259
Flour ash		0.172	0.262		0.172	0.578		0.694	0.974		0.572	0.409
Break flour		0.819	0.670		0.458	0.486		0.480	0.955		0.598	0.841

Table B.2. Analysis of variance (sources were similar crops in different rotations) and p-values of crop growth parameters at St. John from 2018 to 2021.

	2017-18		2018-19		2019-20		2020-21	
	Spring wheat	Winter wheat	Spring wheat	Winter wheat	Spring wheat	Winter wheat	Spring wheat	Winter wheat
Plant height	0.891	0.650	0.780	0.505	0.454	0.883	0.556	0.119
Yield	0.777	0.927	0.876	0.224	0.855	0.871	0.362	0.110
Grain protein	0.864	0.876	0.885	0.266	0.403	0.725	0.779	0.319
Seed weight	0.533	0.430	0.941	0.700	0.508	0.426	0.803	0.653
Test weight	0.582	0.516	0.727	0.462	0.350	0.010	0.425	0.336
Flour protein	0.743	0.956	0.582	0.597	0.960	0.845	0.869	0.513
Flour yield	0.737	0.853	0.674	0.421	0.918	0.001	0.587	0.424
Flour ash	0.455	0.656	0.848	0.309	0.462	0.371	0.773	0.666
Break flour	0.497	0.941	0.924	0.235	0.733	0.815	0.837	0.298

Table B.3. Analysis of variance (sources were harvest dates and crops) and p-values of forage yield and forage nutritive values of winter forage mixes at Genesee from 2018 to 2021.

	2017-18		2018-19		2019-20		2020-21	
	Harvest date	**Crops**	**Harvest date**	**Crops**	**Harvest date**	**Crops**	**Harvest date**	**Crops**
Dry matter	<0.0001		<0.0001		<0.0001		0.0017	
NDF	<0.0001	<0.0001	0.0339	<0.0001	0.0173	<0.0001	<0.0001	<0.0001
ADF	<0.0001	0.2023	0.0016	<0.0001	0.1375	<0.0001	<0.0001	0.0064
Lignin	0.0108	<0.0001	0.0195	<0.0001	0.0096	<0.0001	0.0020	0.0009
CP	<0.0001	<0.0001	0.0041	<0.0001	0.1471	<0.0001	<0.0001	<0.0001
RFV	<0.0001	0.0066	0.0096	<0.0001	0.0473	<0.0001	<0.0001	<0.0001

Table B.4. Analysis of variance (sources were harvest dates and crops) and p-values of forage yield and forage nutritive value of spring forage mixes at St. John from 2018 to 2021.

	2017-18		2018-19		2019-20		2020-21	
	Harvest date	**Crops**	**Harvest date**	**Crops**	**Harvest date**	**Crops**	**Harvest date**	**Crops**
Dry matter	<0.0001		<0.0001		<0.0001		0.0012	
NDF	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
ADF	0.0004	<0.0001	0.0011	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lignin	0.0529	0.0002	0.4254	0.0019	0.4975	<0.0001	0.5248	0.0001
CP	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	<0.0001
RFV	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Appendix C

Table C.1. Plant height or vine length of crops in the rotation at Genesee, ID from 2017 to 2021.

		WP[†]	**CP**	**WW**	**SW**
Year	**Rotation**	Plant Height or Vine Length (cm)			
2017-18	**Incremental (WP)**	81		101	77
	Aspirational (WFC)		60	100	
	Business as Usual (CP/SW)		61	98	78
2018-19	**Incremental (WP)**	54		82	79 a[§]
	Aspirational (WFC)		38	88	
	Business as Usual (CP/SW)		38	79	75 b
2019-20	**Incremental (WP)**	90		93	74
	Aspirational (WFC)		61	95	
	Business as Usual (CP/SW)		62	96	78
2020-21	**Incremental (WP)**	41		76	58
	Aspirational (WFC)		38	77	
	Business as Usual (CP/SW)		38	77	56

[†] WP-winter pea; CP-chickpea; WFC-winter forage crop; SW- spring wheat; and WW- winter wheat.

[§] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P*= 0.05.

Table C.2. Plant height or vine length of crops in the rotation at St. John, WA from 2017 to 2021.

		WP[†]	**WW**	**SW**
Year	**Rotation**	Plant Height or Vine Length (cm)		
2017-18	**Incremental (WP)**	85	85	74
	Aspirational (SFC)		88	75
	Business as Usual (Fallow)		85	74
2018-19	**Incremental (WP)**	57	76	68
	Aspirational (SFC)		70	69
	Business as Usual (Fallow)		79	66
2019-20	**Incremental (WP)**	74	91	64
	Aspirational (SFC)		90	60
	Business as Usual (Fallow)		91	59
2020-21	**Incremental (WP)**	36	76	53
	Aspirational (SFC)		75	51
	Business as Usual (Fallow)		80	49

[†] **WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.**

Table C.3. Grain protein of all crops in three different rotations at Genesee from 2017 to 2021.

Year	Rotation	WP[†]	CP	WW	SW
		Grain Protein (%)			
2017-18	**Incremental (WP)**	9.8		9.1	14.3
	Aspirational (WFC)		20.5	9.0	
	Business as Usual (CP/SW)		20.0	8.8	14.3
2018-19	**Incremental (WP)**	18.8		9.9 b[§]	13.4
	Aspirational (WFC)		18.6	10.3 a	
	Business as Usual (CP/SW)		19.0	10.1 ab	13.6
2019-20	**Incremental (WP)**	16.8		9.2	13.3
	Aspirational (WFC)		20.3	8.7	
	Business as Usual (CP/SW)		19.9	8.9	13.7
2020-21	**Incremental (WP)**	14.2		14.2	17.6
	Aspirational (WFC)		18.1	14.3	
	Business as Usual (CP/SW)		18.2	13.9	17.5

[†] WP-winter pea; CP-chickpea; WFC-winter forage crop; SW- spring wheat; and WW- winter wheat.

[§] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table C.4. Grain protein of all crops in three different rotations at St. John from 2017 to 2021.

Year	Rotation	WP†	WW	SW
			Grain Protein (%)	
2017-18	**Incremental (WP)**	12.0	11.8	16.2
	Aspirational (SFC)		11.6	16.1
	Business as Usual (Fallow)		11.7	16.1
2018-19	**Incremental (WP)**	16.8	12.2	14.0
	Aspirational (SFC)		10.7	14.2
	Business as Usual (Fallow)		10.8	13.9
2019-20	**Incremental (WP)**	15.8	9.9	15.1
	Aspirational (SFC)		10.0	13.1
	Business as Usual (Fallow)		9.7	15.2
2020-21	**Incremental (WP)**	14.8	12.1	17.3
	Aspirational (SFC)		12.1	17.7
	Business as Usual (Fallow)		11.5	17.4

†WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.

Table C.5. Thousand seed weight of all crops in three different rotations at Genesee from 2017 to 2021.

Year	Rotation	WP	CP	WW	SW
		Thousand Seed Weight (g)			
2017-18	**Incremental (WP)** [§]	151.8		44.7	35.7
	Aspirational (WFC)		292.0	44.8	
	Business as Usual (CP/SW)		297.4	44.6	35.4
2018-19	**Incremental (WP)**	159.4		42.0	33.5
	Aspirational (WFC)		297.8	42.6	
	Business as Usual (CP/SW)		304.3	43.2	33.4
2019-20	**Incremental (WP)**	139.3		39.6	31.6
	Aspirational (WFC)		292.3	41.0	
	Business as Usual (CP/SW)		289.8	40.3	31.6
2020-21	**Incremental (WP)**	121.4		21.9	27.4
	Aspirational (WFC)		285.1	21.8	
	Business as Usual (CP/SW)		288.9	23.0	27.6

[§] **WP-winter pea; CP-chickpea; WFC-winter forage crop; SW- spring wheat; and WW- winter wheat.**

Table C.6. Thousand seed weight of all crops in three different rotations at St. John from 2017 to 2021.

Year	Rotation	WP	WW	SW
		Thousand Seed Weight (g)		
2017-18	**Incremental (WP)** [§]	150.7	41.5	34.7
	Aspirational (SFC)		45.0	35.0
	Business as Usual (Fallow)		42.8	33.1
2018-19	**Incremental (WP)**	151.7	46.8	35.7
	Aspirational (SFC)		46.1	36.2
	Business as Usual (Fallow)		47.8	35.8
2019-20	**Incremental (WP)**	132.0	42.0	35.1
	Aspirational (SFC)		49.8	34.1
	Business as Usual (Fallow)		42.8	34.7
2020-21	**Incremental (WP)**	117.3	31.2	29.5
	Aspirational (SFC)		29.7	30.8
	Business as Usual (Fallow)		32.0	30.5

[§] WP-winter pea; SFC-spring forage crop; SW- spring wheat; and WW- winter wheat.

Table C.7: Test weight and flour qualities of winter wheat in three different rotations at Genesee from 2017 to 2021.

Year	Rotation	Test weight	Flour Protein	Flour Yield	Flour Ash	Break Flour
		(g)	%	%	%	%
	Incremental	430	7.1	71.3	0.4	42.4
2017-18	**Aspirational**	431	7.2	71.2	0.4	42.1
	Business as usual	429	7.1	71.0	0.4	42.0
	Incremental	435	10.1	77.8 ab[†]	0.4	55.0
2018-19	**Aspirational**	434	10.3	77.6 b	0.4	54.6
	Business as usual	436	10.0	78.2 a	0.4	55.1
	Incremental	439	9.0	78.4	0.4	53.7
2019-20	**Aspirational**	438	8.6	78.8	0.4	53.4
	Business as usual	439	8.7	78.9	0.4	53.8
	Incremental	355	12.7	68.2	0.3	48.1
2020-21	**Aspirational**	352	12.9	67.6	0.3	48.0
	Business as usual	361	12.9	69.1	0.3	48.4

[†] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table C.8: Test weight and flour qualities of spring wheat in two different rotations at Genesee from 2017 to 2021.

Year	Rotation	Test weight	Flour Protein	Flour Yield	Flour Ash	Break Flour
		(g)	%	%	%	%
2017-18	**Incremental**	435	13.0	54.5	0.4	24.5
	Business as usual	435	13.0	54.1	0.4	24.6
2018-19	**Incremental**	435 a[†]	11.9	71.3	0.5	38.5
	Business as usual	433 b	12.4	71.7	0.5	39.3
2019-20	**Incremental**	438	12.0	71.7	0.5	37.7
	Business as usual	435	12.5	71.8	0.5	38.43
2020-21	**Incremental**	404	17.8	69.9	0.4	37.6
	Business as usual	403	17.4	70.2	0.4	37.9

[†] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table C.9: Test weight and flour qualities of winter wheat in three different rotations at St. John from 2017 to 2021.

Year	Rotation	Test weight	Flour Protein	Flour Yield	Flour Ash	Break Flour
		(g)	%	%	%	%
	Incremental	401	10.3	63.3	0.4	37.6
2017-18	**Aspirational**	412	10.1	64.3	0.4	37.5
	Business as usual	404	10.2	64.2	0.4	37.7
	Incremental	427	10.6	77.1	0.4	53.0
2018-19	**Aspirational**	426	10.2	76.9	0.4	53.5
	Business as usual	432	10.2	77.7	0.4	54.1
	Incremental	430 b[†]	9.4	77.36 b	0.4	51.3
2019-20	**Aspirational**	432 b	9.3	77.74 b	0.4	51.6
	Business as usual	437 a	9.1	78.39 a	0.4	51.6
	Incremental	388	11.1	71.9	0.3	48.2
2020-21	**Aspirational**	384	11.0	71.3	0.3	47.6
	Business as usual	401	10.6	73.3	0.3	48.8

[†] Mean followed by different letters in a single column and year are statistically different using Fishers LSD at *P* = 0.05.

Table C.10: Test weight and flour qualities of spring wheat in three different rotations at St. John from 2017 to 2021.

Year	Rotation	Test weight (g)	Flour Protein %	Flour Yield %	Flour Ash %	Break Flour %
2017-18	**Incremental**	407	14.6	50.8	0.4	22.1
	Aspirational	414	14.6	50.4	0.4	22.0
	Business as usual	406	14.4	50.1	0.4	21.6
2018-19	**Incremental**	429	12.8	69.2	0.5	34.4
	Aspirational	431	13.4	70.0	0.5	34.8
	Business as usual	429	12.8	69.8	0.5	34.7
2019-20	**Incremental**	436	13.9	68.5	0.5	32.8
	Aspirational	413	13.9	68.4	0.5	33.1
	Business as usual	435	14.0	68.4	0.5	33.1
2020-21	**Incremental**	409	17.0	68.8	0.4	32.5
	Aspirational	402	17.2	68.7	0.4	32.1
	Business as usual	400	17.2	68.3	0.4	32.4

Appendix D

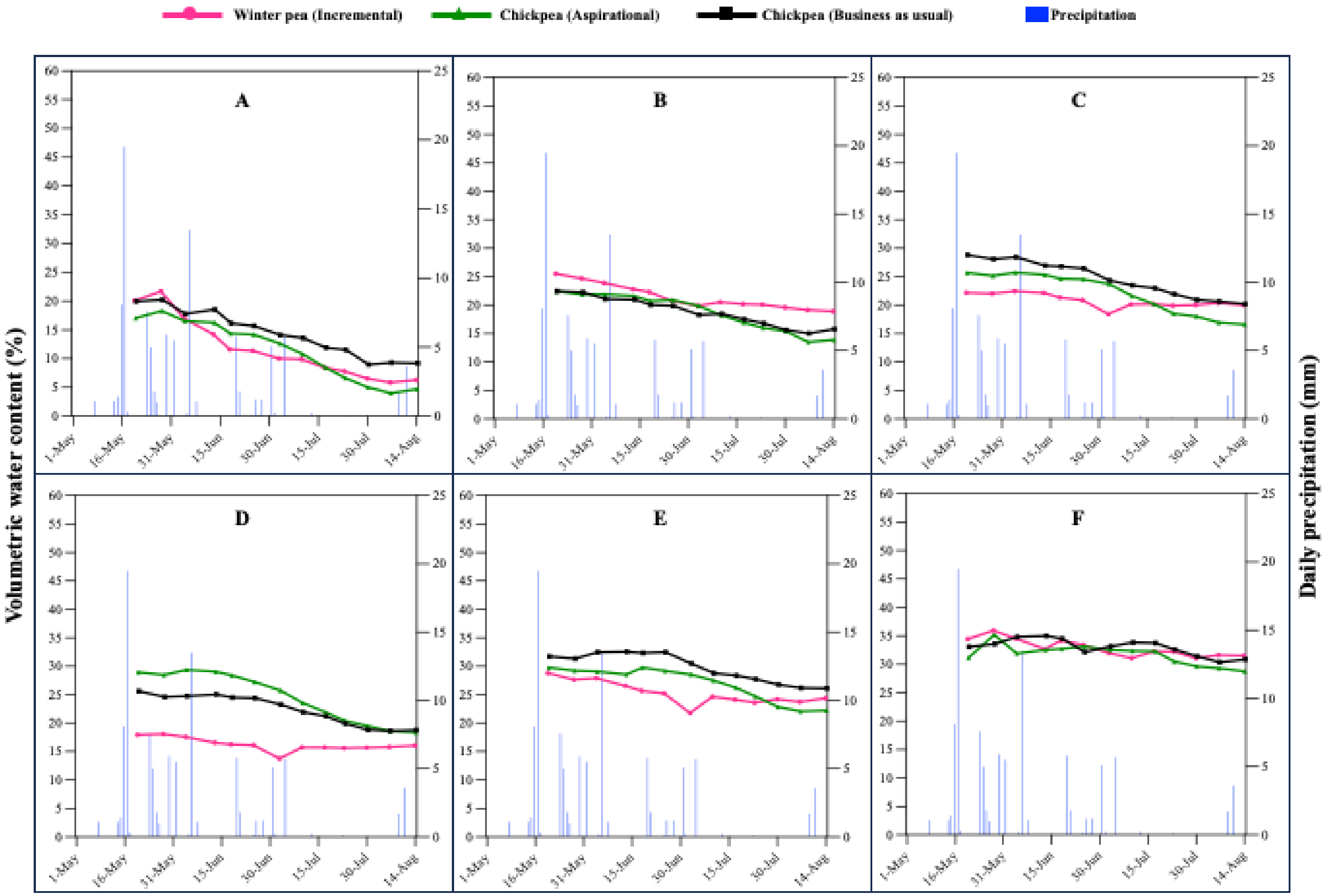

Figure D.1. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019.

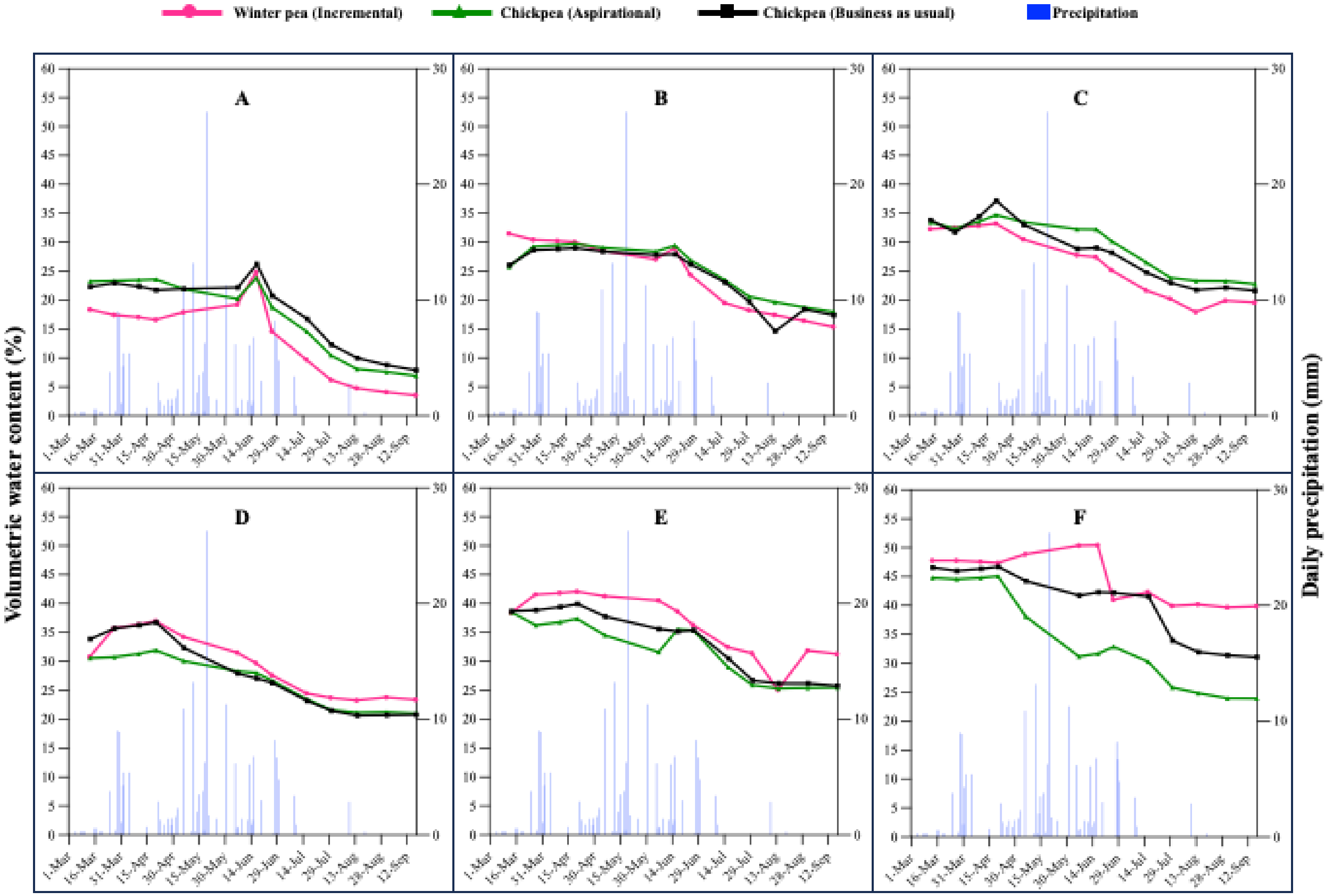

Figure D.2. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020.

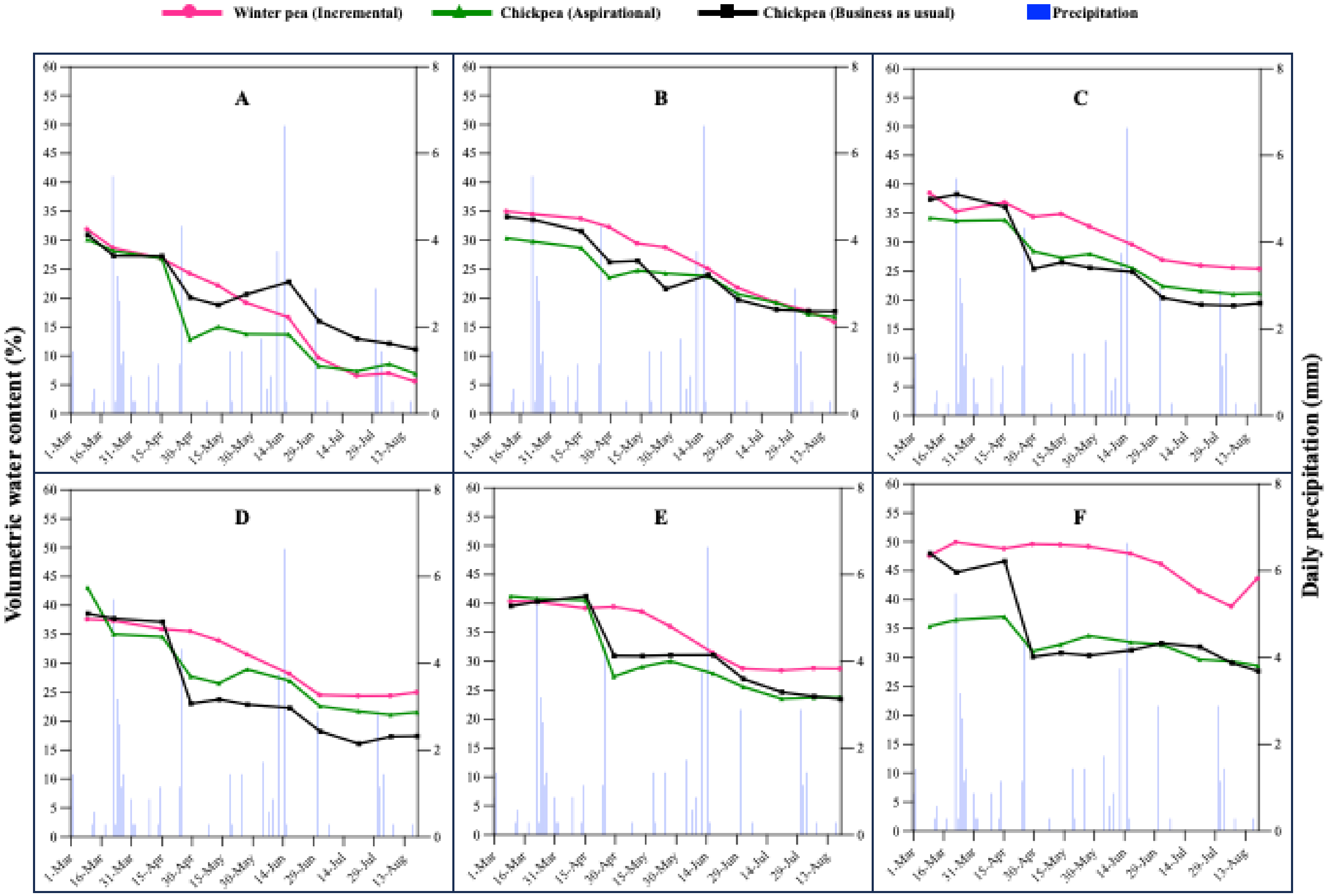

Figure D.3. Daily precipitation during growing season and volumetric water content of winter pea (WP) and chickpea (CP) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021.

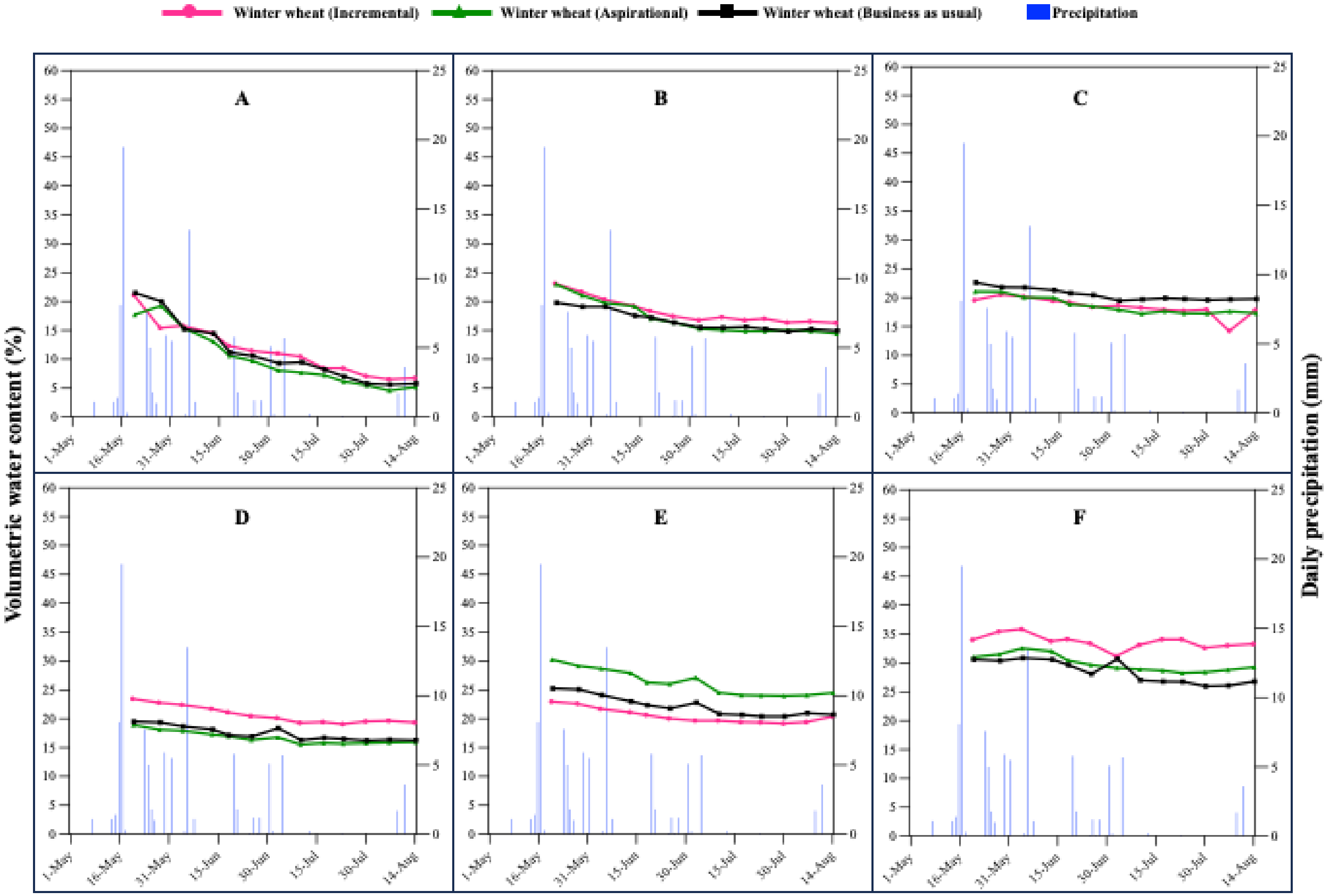

Figure D.4. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019.

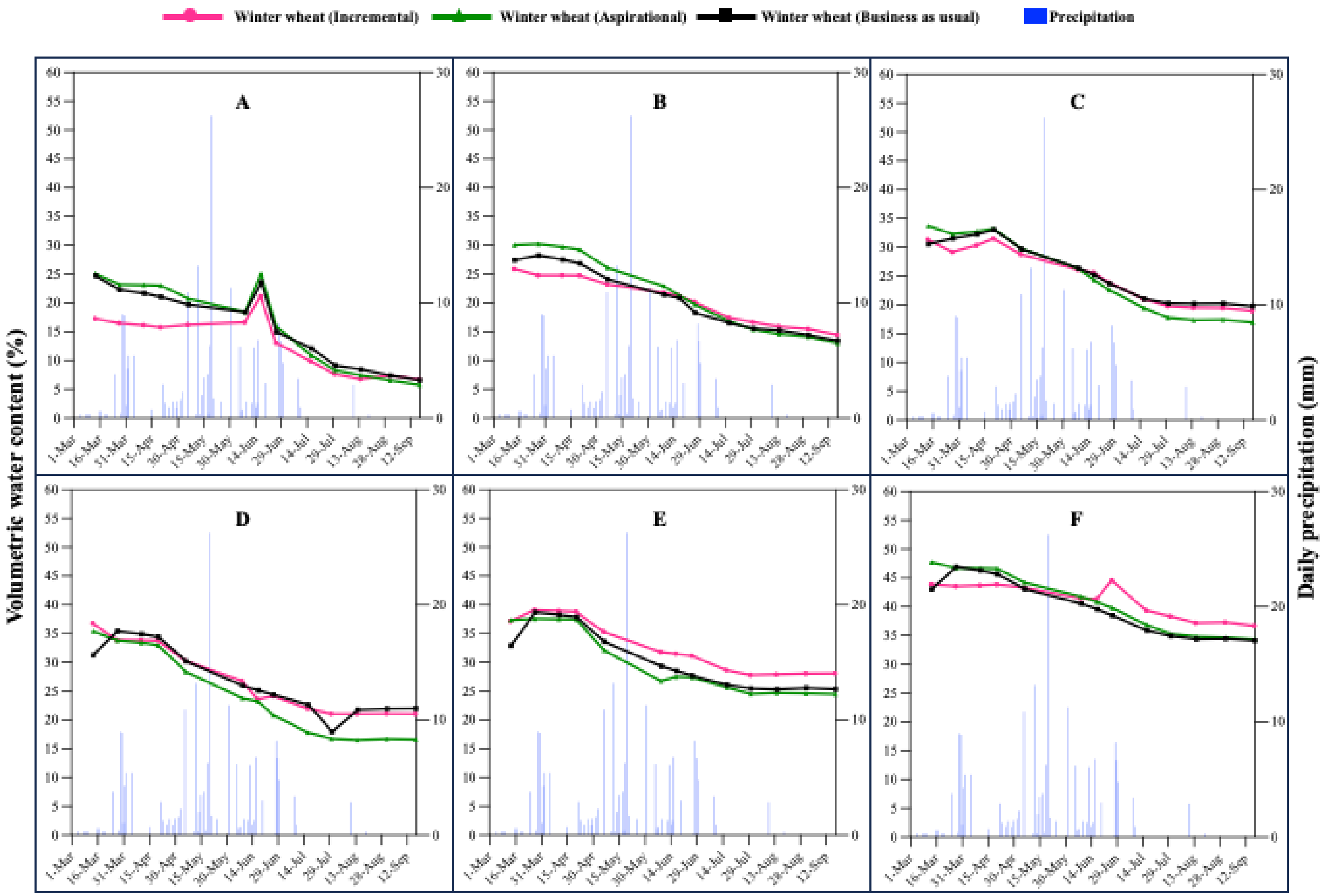

Figure D.5. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020.

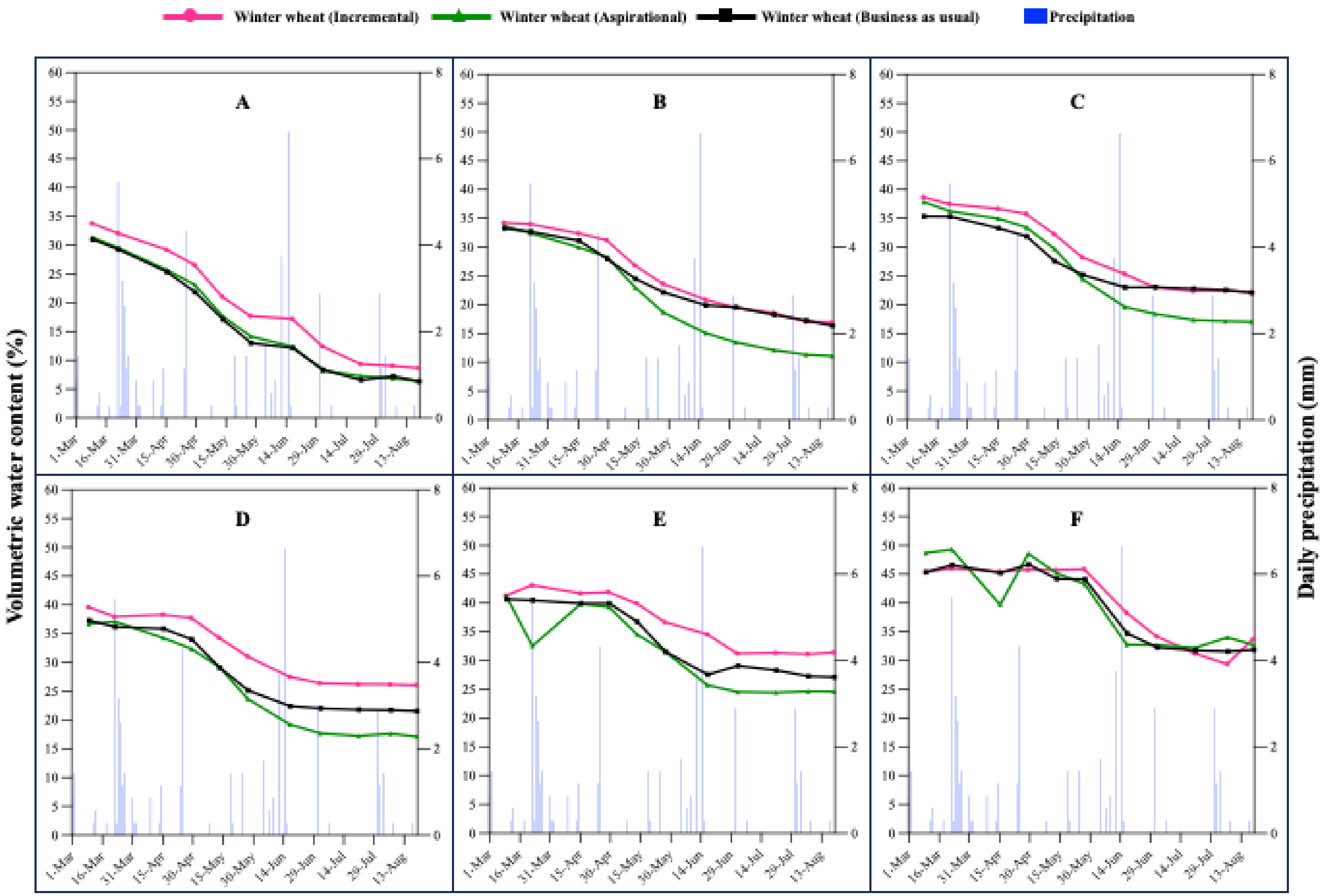

Figure D.6. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021.

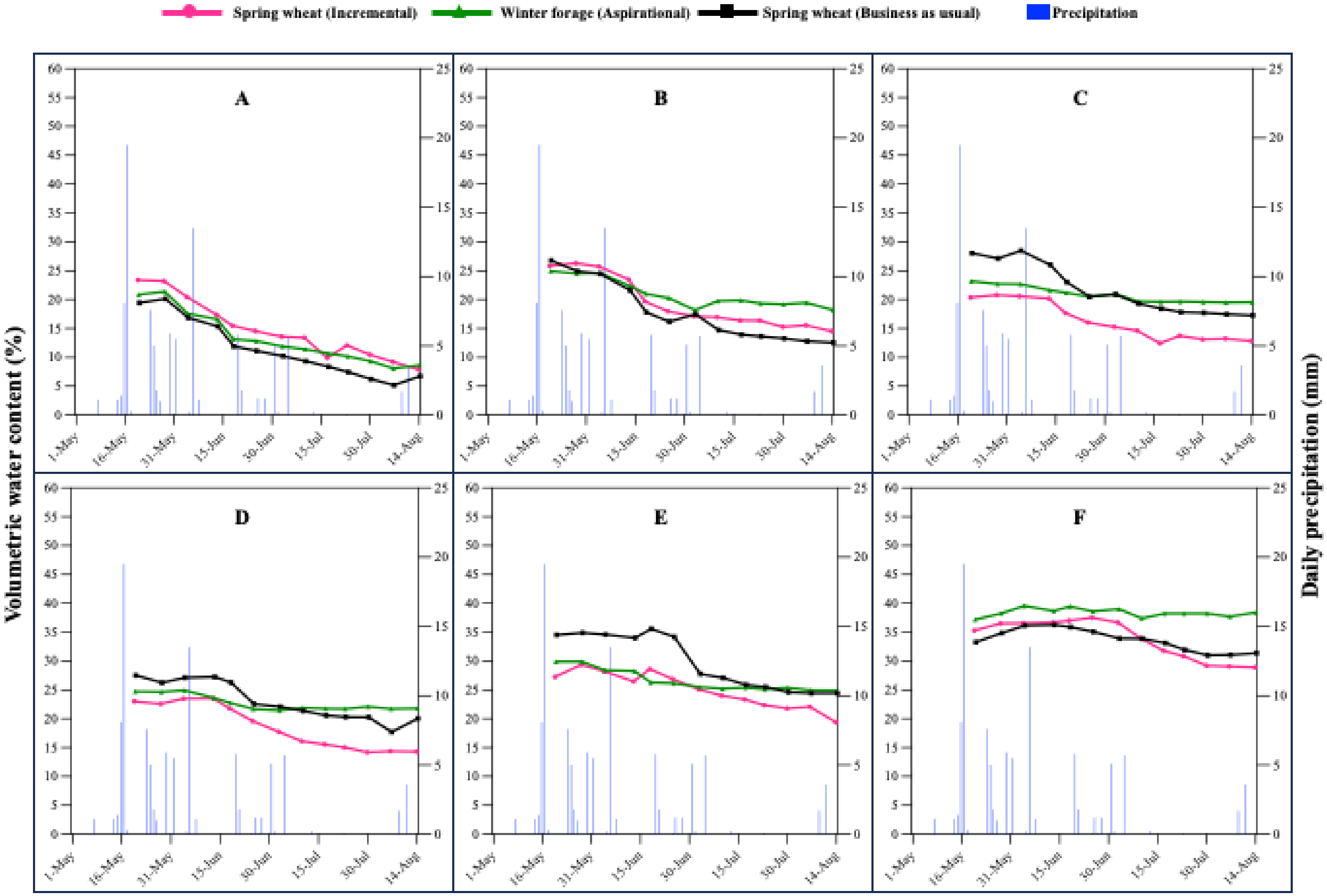

Figure D.7. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2019.

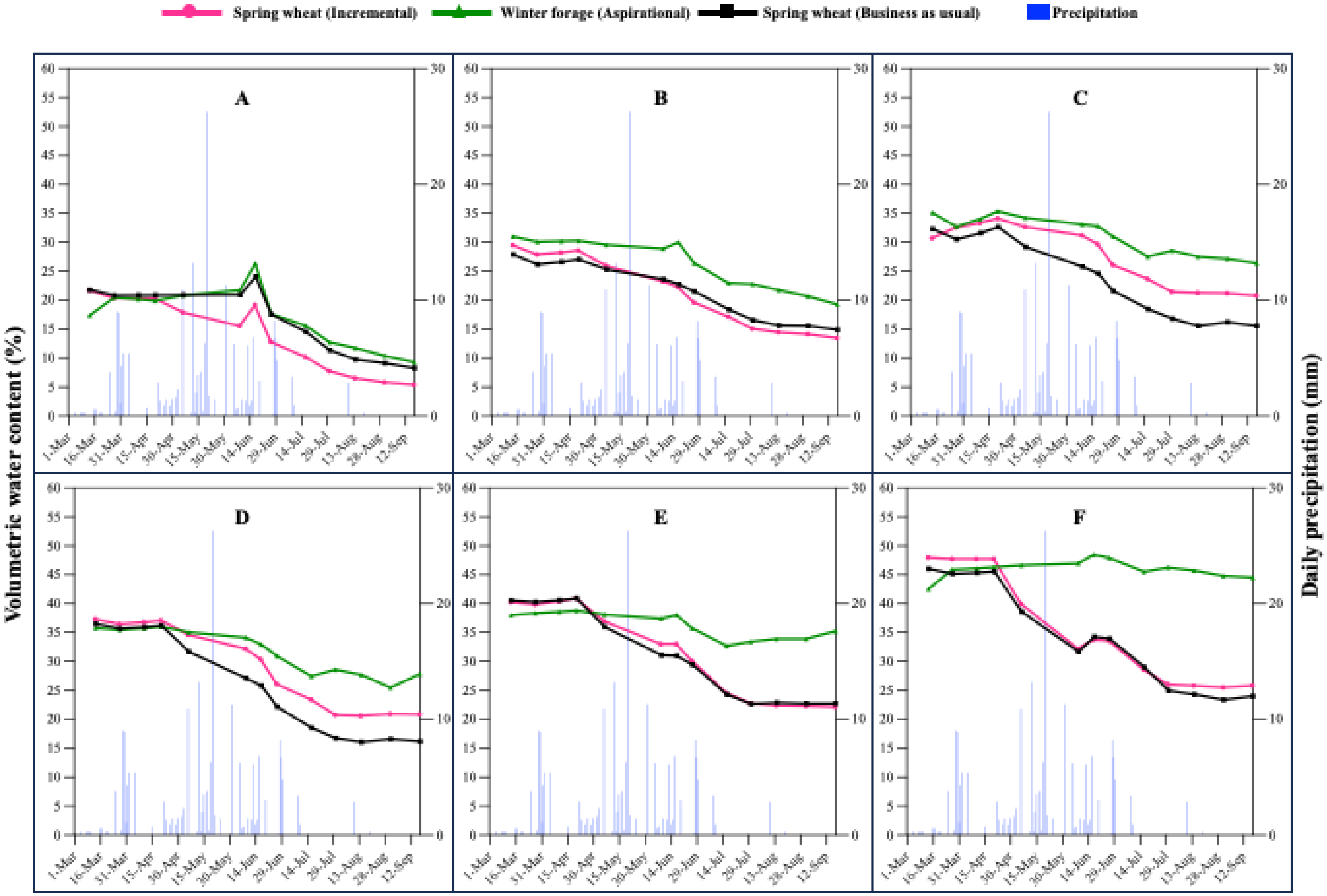

Figure D.8. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2020.

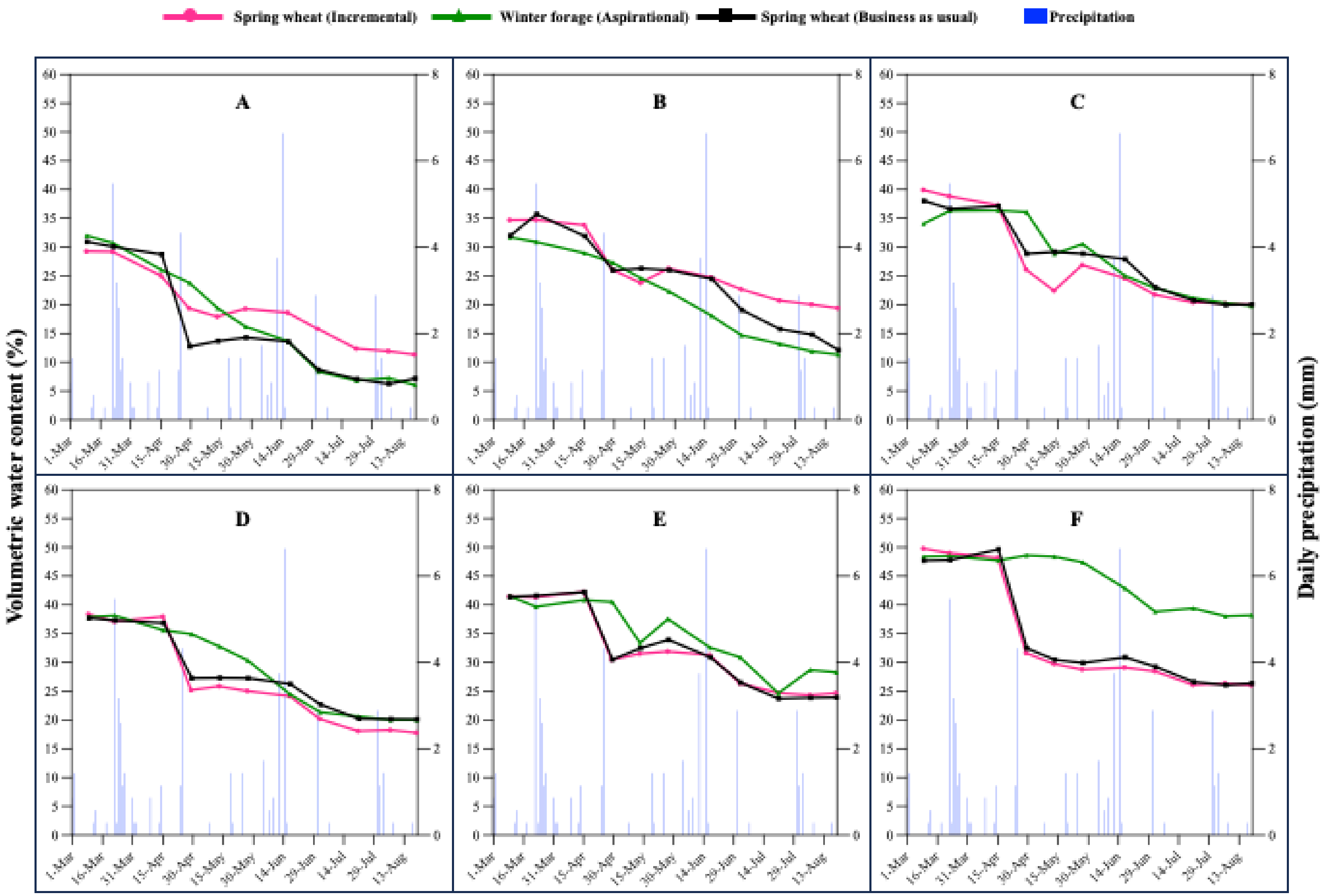

Figure D.9. Daily precipitation during growing season and volumetric water content of spring wheat (SW) and winter forage crop (WFC) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in Genesee during 2021.

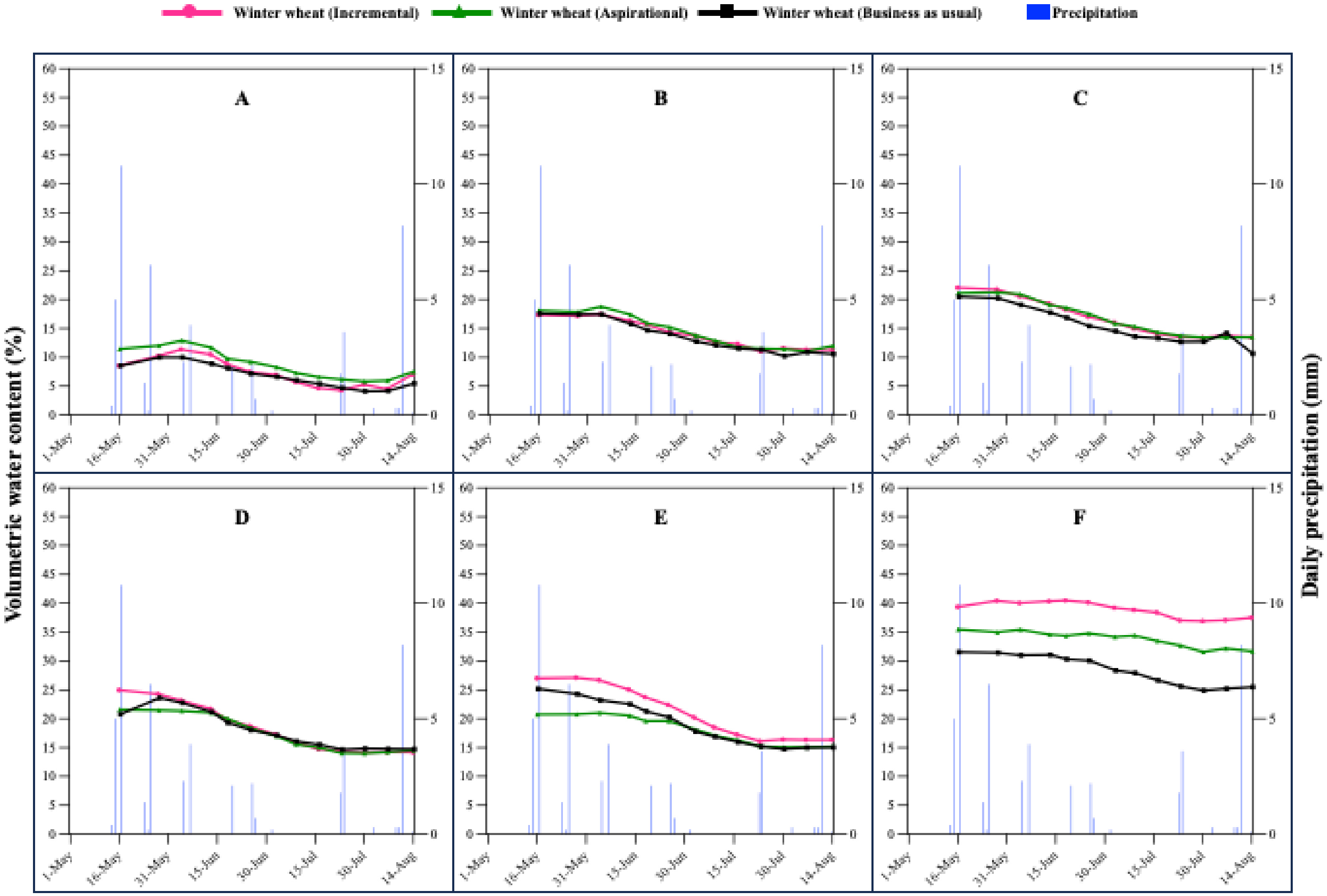

Figure D.10. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019.

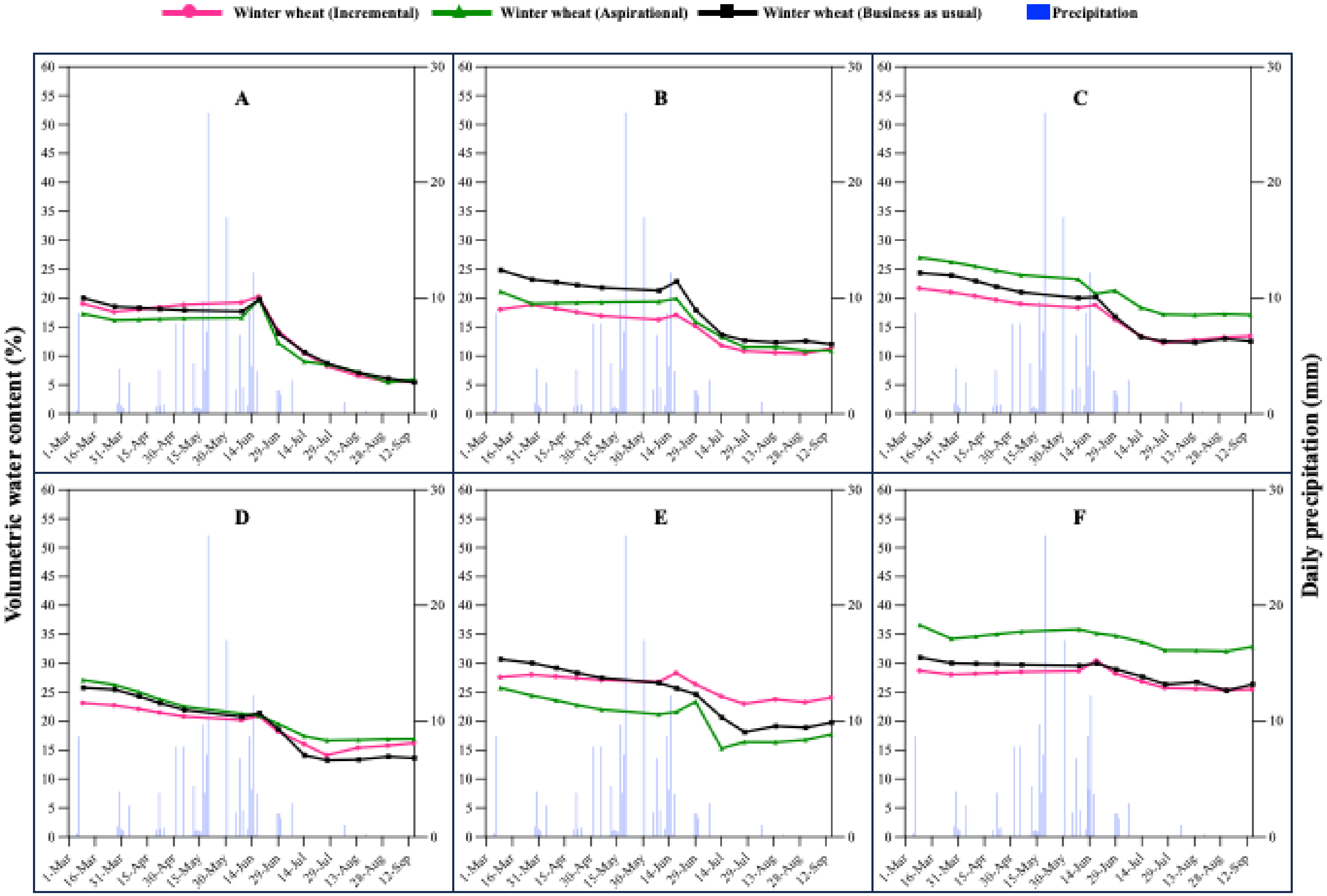

Figure D.11. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020.

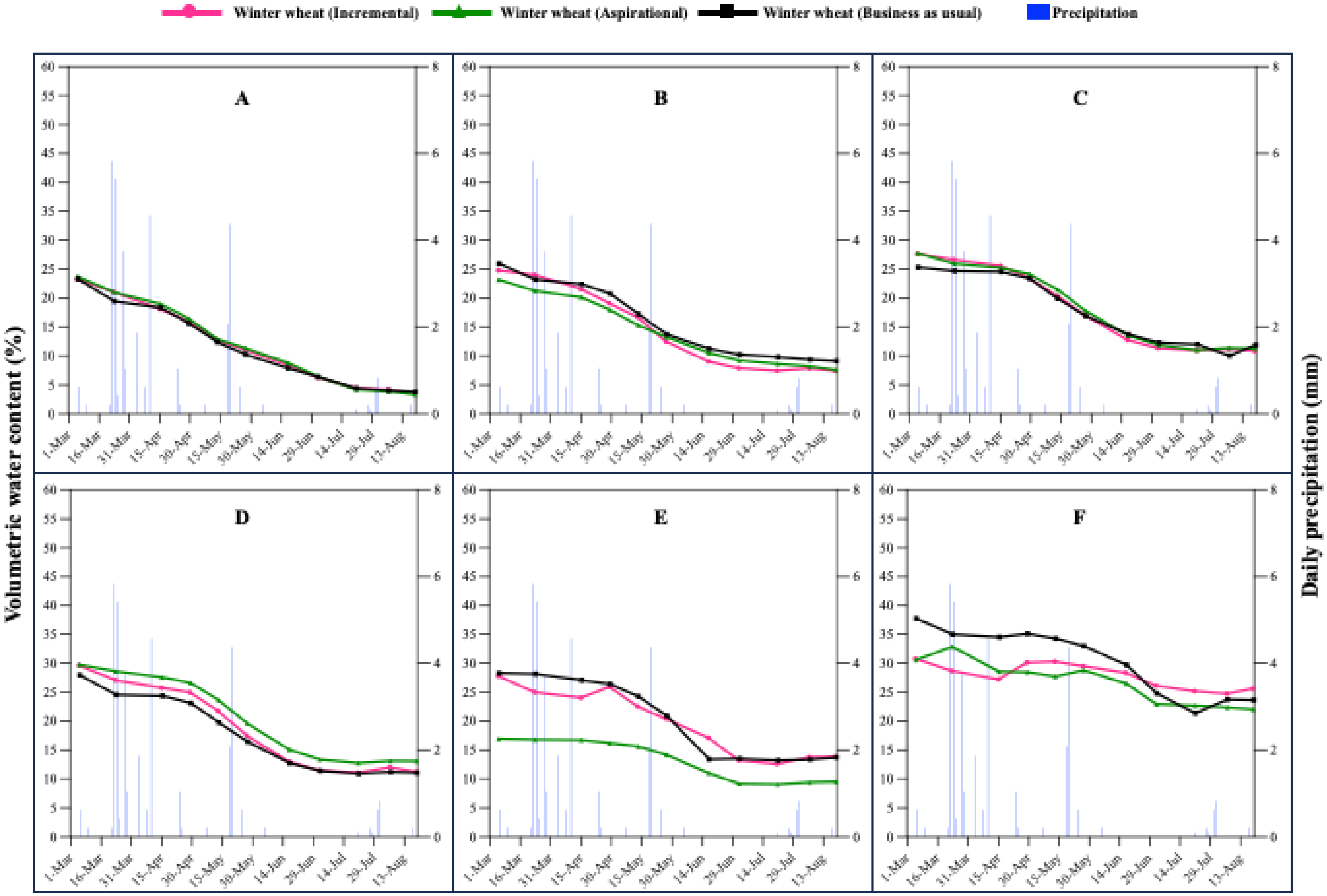

Figure D.12. Daily precipitation during growing season and volumetric water content of winter wheat (WW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021.

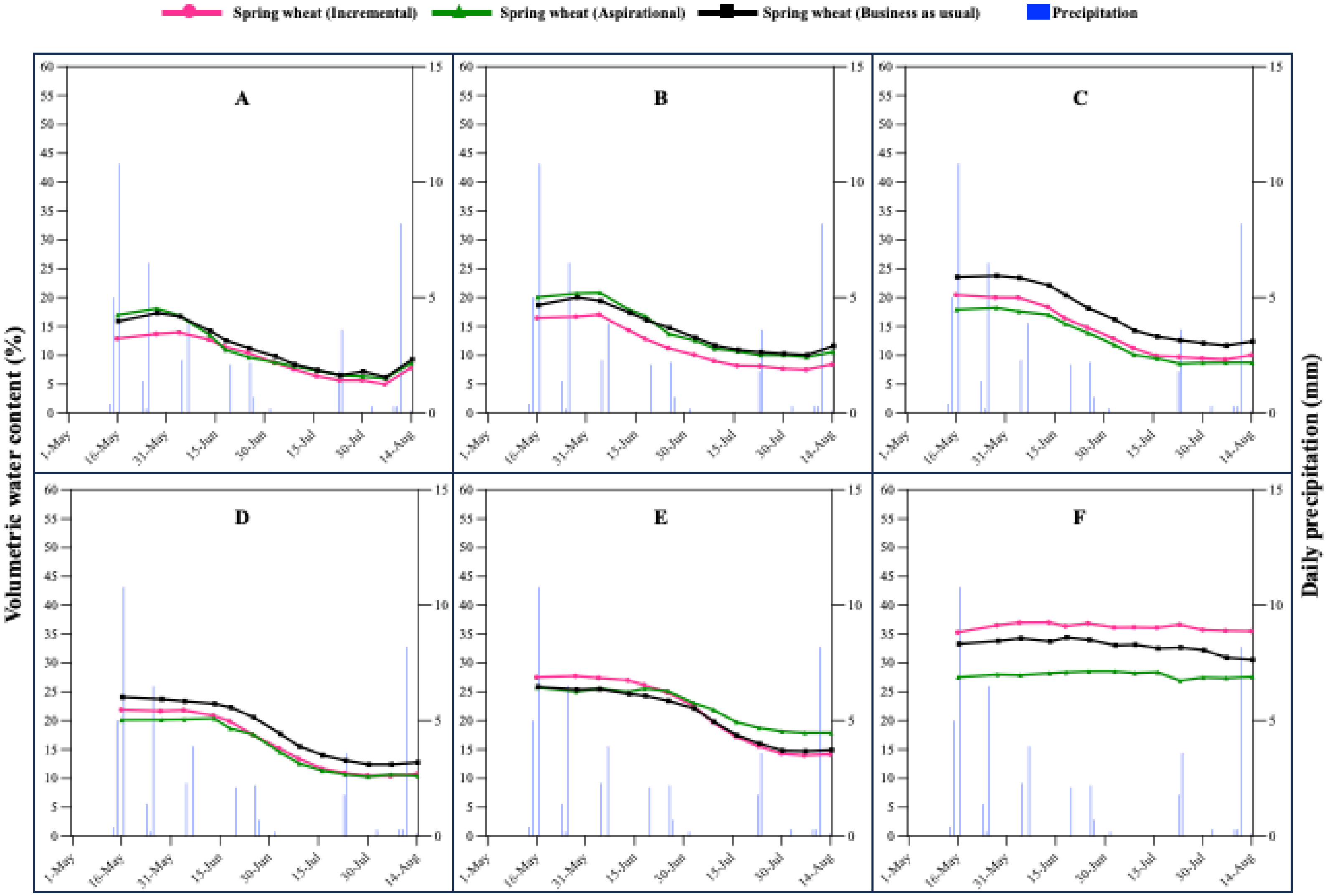

Figure D.13. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2019.

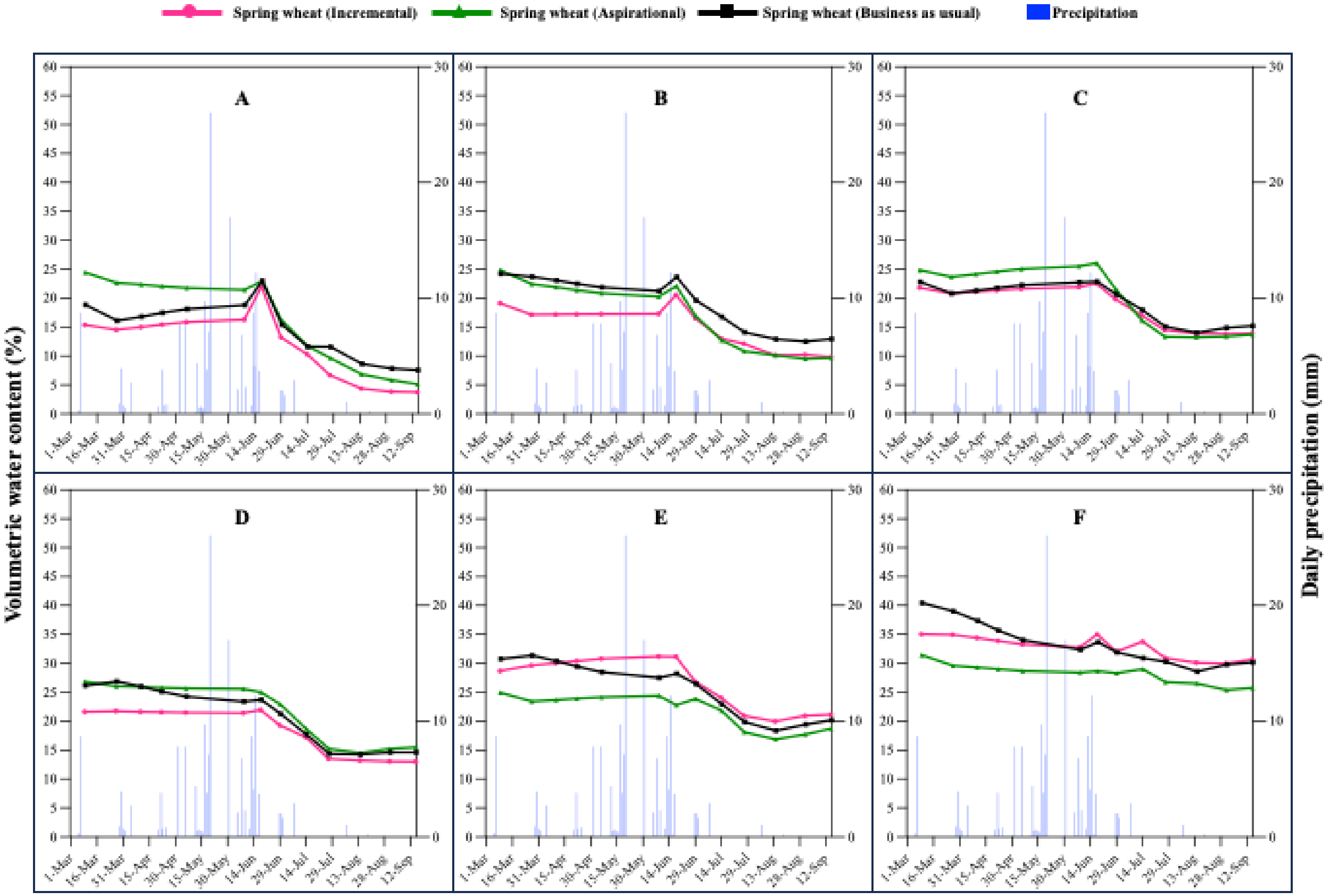

Figure D.14. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2020.

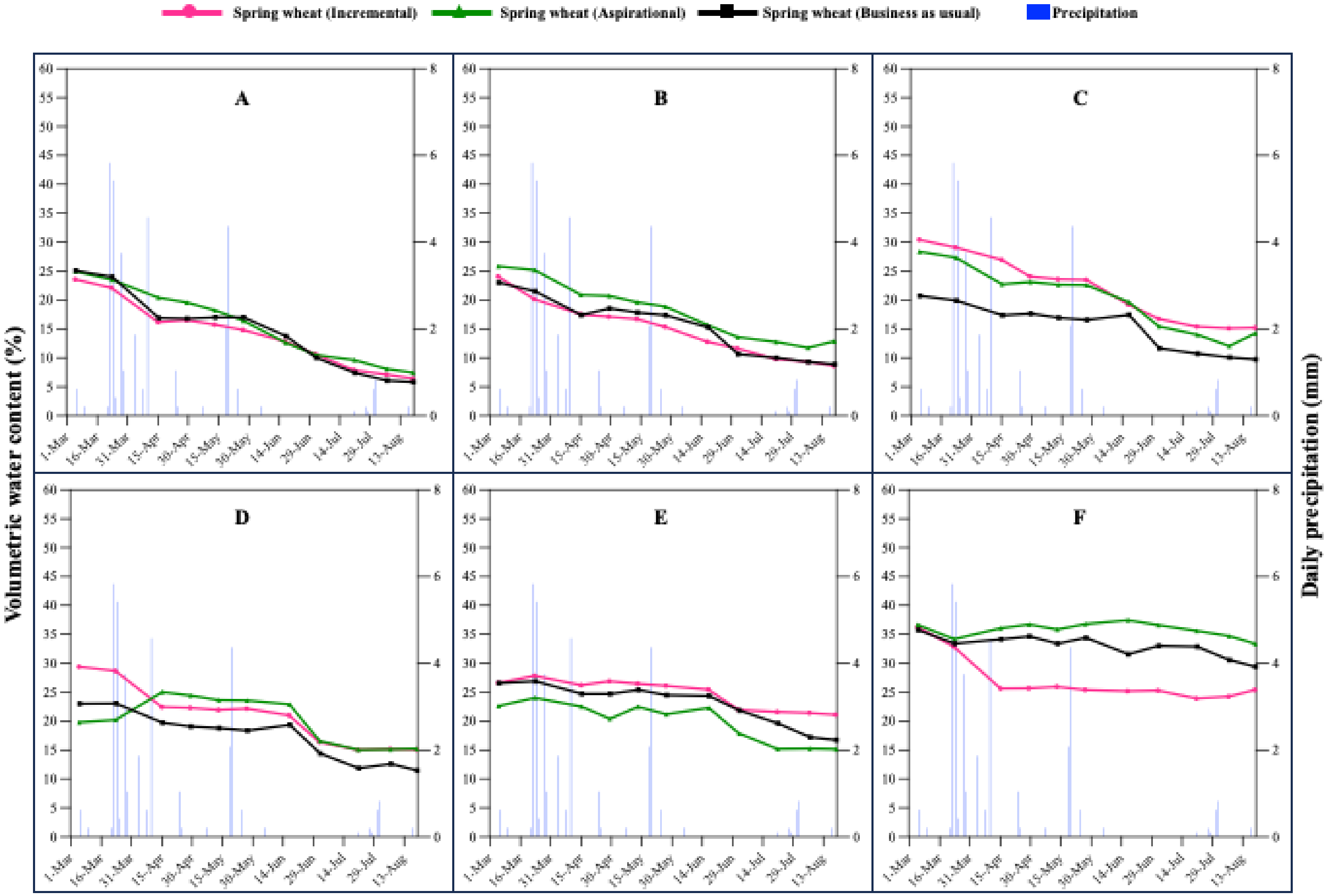

Figure D.15. Daily precipitation during growing season and volumetric water content of spring wheat (SW) in incremental, aspirational, and business-as-usual rotation at different depths of 10 cm (A), 20 cm (B), 30 cm (C), 40 cm (D), 60 cm (E) and 100 cm (F) in St. John during 2021.

Appendix E

Table E.1. Analysis of variance (Sources: Y- Year, P-Planting date, F-Fertilization, R-Seeding rate, and C- Cultivar) including F-value and level of significance of winter pea growth, yield and quality parameters at Genesee, ID from 2018 to 2020.

Source	df	Plant population	Plant height	Canopy height	Yield	Protein	100 seed weight
Y	2	30.2***	16.16**	252.18***	213.0***	569.06***	1033.35***
P	2	16.77***	9.17**	7.82**	45.75***	13.24***	57.64***
Y×P	4	21.21***	13.58**	4.25*	17.05***	11.40***	41.35***
F	1	0.02	1.99	0.83	2.15	0.02	0.88
Y×F	2	1.34	0.21	0.77	3.49*	2.53	0.52
P×F	2	1.22	0.47	0.02	0.52	0.63	0.07
Y×P×F	4	0.59	0.22	0.68	1.77	0.75	0.43
R	3	98.34***	1.29	1.53	19.57***	1.55	0.35
C	1	27.73***	29.87**	102.08***	10.27**	3.88*	5299.24***
Y×R	5	4.43***	2.86*	0.96	15.17***	9.17***	1.77
Y×C	2	1.4	7.02**	1.87	7.05**	10.35***	15.43***
P×R	6	0.51	0.7	2.89**	1.03	1.58	1.02
P×C	2	1.2	2.46	7.39**	18.14***	13.82***	2.59
F×R	3	1.19	0.56	1.59	1.05	0.24	0.09
F×C	1	0.15	0.08	1.5	1.71	0.06	0.09
R×C	3	0.64	2.68*	1.75	0.36	1	0.28
Y×P×R	10	1.73	1.38	1.32	0.82	1.27	0.46
Y×P×C	3	2.76*	2.1	1.01	1.86	8.59***	6.16***
Y×F×R	5	0.5	0.66	0.78	1.44	1.06	0.63
Y×F×C	2	1.55	1.43	2.18	0.04	2.77	3.33*
Y×R×C	5	0.91	1.85	1.3	0.74	1.02	0.86
P×F×R	6	0.52	0.44	1.26	0.39	0.46	0.42
P×F×C	2	5.81**	0.35	2.22	0.65	0.51	1.4
P×R×C	6	0.5	4.09***	1.88	1.05	0.38	1.18
F×R×C	3	0.28	0.59	0.45	0.42	0.72	0.31
Y×P×F×R	10	0.91	0.56	0.81	0.82	1.02	0.64
Y×P×F×C	3	3.14*	0.69	5.45**	2.95*	0.72	1.19
Y×P×R×C	7	1.98	1.47	0.45	0.76	1.66	0.4
Y×F×R×C	5	1.43	1.1	1.47	0.86	0.34	0.1
P×F×R×C	6	1.7	2.44*	1.44	2.17*	0.65	0.47
Y×P×F×R×C	7	0.62	0.72	1.08	0.34	1.39	0.77

†* Significant at $p<0.05$, ** Significant at $p<0.01$ and *** Significant at $p<0.001$.

Table E.2. Analysis of variance (Sources: Y- Year, P-Planting date, F-Fertilization, R-Seeding rate, and C- Cultivar) including F-value and level of significance of winter pea growth, yield and quality parameters at St. John, WA from 2017 to 2020.

Source	df	Plant population	Plant height	Canopy height	Yield	Protein	100 seed weight
Y	2	109.44***	122.19***	3.75	13.32**	506.46***	213.11***
P	2	26.82***	2.21	2.66	33.13***	10.90***	1.44
Y×P	4	17.42***	12.89***	16.75***	29.81***	5.47**	2.63
F	1	0.04	2.22	0.07	4.69*	3.73	0.03
Y×F	2	2.05	2.55	0.3	0.43	1.5	0.23
P×F	2	1.86	0.78	0.52	0.13	1.87	2.65
Y×P×F	4	0.71	0.77	0.47	1.13	1.4	0.27
R	3	152.16***	1.14	0.8	17.76***	4.30**	8.38***
C	1	7.63**	20.58***	7.04**	39.23***	165.62***	6112.22***
Y×R	5	17.08***	1.65	0.95	1.54	0.18	5.43***
Y×C	2	2.04	8.36***	1.87	118.81***	1.65	6.69**
P×R	6	0.9	1.44	0.36	0.85	0.74	0.34
P×C	2	3.91*	3.18*	0.12	2.12	1.33	17.46***
F×R	3	1.01	0.2	0.94	0.11	0.87	0.65
F×C	1	1.81	0.06	0.32	3.27	0.28	0.24
R×C	3	0.38	1.21	0.54	3.30*	2.42	2.95*
Y×P×R	10	2.98**	0.83	1.57	2.26*	0.62	0.46
Y×P×C	3	1.08	5.39**	0.45	6.52***	0.15	12.80***
Y×F×R	5	0.37	0.5	0.32	2.78*	1.66	1.57
Y×F×C	2	0.47	0.87	0.57	0.49	3.15*	0.12
Y×R×C	5	1.87	0.51	1.94	0.88	1.85	0.71
P×F×R	6	0.33	1.71	1.19	0.9	1.37	1.1
P×F×C	2	1.19	0.56	0.38	0.16	1	1.72
P×R×C	6	5.32***	0.29	0.55	1.26	1.35	0.6
F×R×C	3	0.24	0.96	0.42	0.69	0.63	0.54
Y×P×F×R	10	1.34	0.48	0.69	1.09	1	0.61
Y×P×F×C	3	2.31	0.17	0.36	1.12	3.55	0.49
Y×P×R×C	7	0.46	0.37	0.74	1.2	0.61	0.54
Y×F×R×C	5	0.25	0.38	1.27	0.81	0.54	0.47
P×F×R×C	6	0.34	0.68	0.15	0.28	0.76	0.37
Y×P×F×R×C	7	0.34	1.31	1.37	0.9	1.37	0.57

[†] *** Significant at $p<0.05$, ** Significant at $p<0.01$ and *** Significant at $p<0.001$.**

Appendix F

Table F.1. Analysis of variance including F-value and level of significance of yield and quality of winter forage mixes at Genesee, ID from 2019 to 2021.

	df	Plant pop	FW1	DW1	FW2	DW2	FW3	DW3	CP	NDF	ADF	Lignin	RFV
Year	2	6.2*†	9.72**	24.58***	12.54**	4.51*	47.05***	53.64***	42.22***	18.76***	17.45***	4.56*	9.53**
Treatment	14	8.68***	8.11***	6.64***	10.91***	7.57***	15.68***	11.28***	39.09***	10.31***	2.17*	4.10***	4.93***
Year*Treatment	28	1.43	3.06***	2.61***	3.64***	2.6***	5.48***	5.33***	17.70***	4.41***	2.14**	1.56*	3.25***

†* Significant at $p<0.05$, ** Significant at $p<0.01$ and * Significant at $p<0.001$.**

Table F.2. Analysis of variance including F-value and level of significance of yield and quality of winter forage mixes at St. John, WA from 2019 and 2021.

	df	Plant pop	FW1	DW1	FW2	DW2	FW3	DW3	CP	NDF	ADF	Lignin	RFV
Year	1	7.56*†	0.9	1.08	3.84	1.16	41.01	5.80*	12.08**	6.20*	0.45	0.01	4.09
Treatment	14	3.78***	2.25*	2.36*	3.01*	2.25*	3.2*	2.71*	7.01***	3.04***	2.26*	2.44*	2.24*
Year*Treatment	14	1.83*	1.03	0.91	1.35	1.17	0.8	0.86	0.86	1.33	1.68	1.83*	1.45

†* Significant at $p<0.05$, ** Significant at $p<0.01$ and * Significant at $p<0.001$.**