Ecological Recovery Monitoring of Certified Reclaimed Wellsites in Alberta: Crop Harvest Mapping on Reclaimed Agricultural Sites

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EXECUTIVE SUMMARY

The intent of this project was to collaborate with the Alberta Biodiversity Monitoring Institute (ABMI) and Alberta Environment and Parks (formerly the Alberta Environmental Monitoring Evaluation and Reporting Agency) through the Ecological Recovery Monitoring (ERM) program to demonstrate whether crop yield maps can be used as a tool to inform on the assessment of ecological recovery at certified reclaimed wellsites in the cultivated areas of Alberta.

Crop harvest data from 4 farm operations were provided by ABMI for those certified reclaimed wellsites monitored as part of the 2015-2016 ERM pilot program. For individual sites, harvest data were collected between 2013 and 2015. Some reclaimed wellsites had 1 year of yield data, others had multiple years of yield data.

Upon receipt of the crop yield data, data files for each site were independently cleaned by removing data points that did not accurately represent crop yield (i.e., data artifacts) using crop flow rate and dry yield as indicators. Cleaned data were imported into a geographic information system (GIS) software package for data visualization. Map averaging was conducted to produce individual field maps through interpolation rasters using the Kriging method. Cleaned harvest data were tested for normality using the Shapiro-Wilk Normality Test. Statistical significance ($p < 0.05$) was assessed using one-way analysis of variance (ANOVA) tests for normal data and Kruskal-Wallis for non-normal data.

Key learnings from this study included the following:

- Wellsite and reference area comparisons, if analyzed alone, can provide very different results than a comparison between a wellsite and an entire field. Such analyses should be considered in future assessments, including the incorporation into a long-term monitoring project. The definition of a reference area, in terms of size and location, should also be considered.
- The statistical significance of average crop yield on a wellsite, in comparison to the prescribed reference area, may not be meaningful, in terms of the grand scheme of farming. A long-term monitoring plan should consider whether the assessment impacts, limits, changes, or influences the end land use.
- Many of the sites assessed exhibited data problems for a variety of reasons (i.e., the wellsite was too close to a road, the wellsite crossed over fields with different crop types, the combine harvest pattern was incomplete or inconsistent across the wellsite). As a result, the tool may not be reliable if sites are not selected appropriately for the tool, and communication is not conducted with the farmers to ensure that data is collected appropriately for the assessment.

This study showed that crop yield maps have the capacity to provide valuable information on annual crop yield at the field-scale. The accuracy of the maps will depend on the quality of the harvest data obtained in the field, especially over the wellsite and reference areas in question. Ideally, harvest data should be collected under uniform velocity in a continuous straight line, with an even swath width, and little overlapping between swaths. Experience in data cleaning and data interpretation was identified to be essential for analyzing and comparing crop yield data values across a site. To improve interpretation of crop yield data, it is recommended that

maps are incorporated, layered and/or placed side-by-side with environmental (e.g., soils, climate, elevation, etc.) and farm management data to ensure that conclusions are supported by other sources of information. Without this type of information, interpretation of ecological recovery should not be made, especially at smaller scales within the field (such as defined wellsite and reference site locations). Alone, crop yield maps can serve as an indicator of locations in the field that would warrant further investigation (or ground-truthing) with respect to crop yield variation.

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1.0 INTRODUCTION

1.1 CROP YIELD MAPPING

Crop yield maps, developed through the application of precision agriculture tools during crop harvest, are used to visually assess the spatial output of crop production. This georeferenced data can be used to complete the following:

(1) Identify areas of poor crop yield that warrant further investigation (i.e., landscape position, moisture variability, weeds, diseases and/or pests); and,
(2) Inform on the prescription and distribution of agricultural inputs (e.g., fertilizer application).

This technology may be applicable for reclamation monitoring at cultivated sites, to provide information on whether previous industrial disturbance has affected crop yield (as it compares to non-disturbed areas within the same field and same management regime). If variability in crop yield is identified between reclaimed and reference areas, further investigation on the physical, chemical and/or biological conditions of the soil is needed to determine the cause of the change in crop performance. Natural variability can be observed in the larger mapping area and must be considered when evaluating yield data at smaller scales. Therefore, crop yield maps may be used as an additional indicator of vegetative productivity[1] on reclaimed areas at cultivated sites.

1.2 ECOLOGICAL RECOVERY MONITORING (ERM) PROGRAM

The Ecological Recovery Monitoring (ERM) program is based on developing an integrated, scientifically robust and financially sustainable monitoring program to enable the assessment of ecological recovery of physical, chemical and biological indicators at certified and reclaimed industrial sites across Alberta. The goal of the long-term program is to monitor, evaluate and inform Albertans on the state/direction of landscape health and recovery at reclaimed and certified industrial human footprints in Alberta. To do this, a variety of tools have been investigated to determine the most optimal methods and protocols to incorporate into a long-term monitoring program assessing ecological recovery at reclaimed sites.

[1]It is important to note that productivity is not only influenced by soil disturbance, but also natural (e.g., climate, insect infestation, disease) and anthropogenic (e.g., fertilization, herbicides) causes (Powter et al., 2012). Therefore, management history in addition to soil characterization is required prior to drawing conclusions that may be affected by natural and anthropogenic causes.

2.0 PROJECT GOAL

The goal of the project was to demonstrate whether crop yield maps can be used as a tool to inform the assessment of ecological recovery at certified reclaimed wellsites in cultivated lands in Alberta.

The intent of this project was to collaborate with the Alberta Biodiversity Monitoring Institute (ABMI) and Alberta Environment and Parks (formerly the Alberta Environmental Monitoring Evaluation and Reporting Agency) through the ERM program to evaluate the appropriateness of precision agriculture tools for reclamation monitoring. More specifically, this project aimed to demonstrate the application of crop yield maps for long-term monitoring of certified reclaimed wellsites in cultivated lands.

3.0 METHODOLOGY

3.1 DATA COLLECTION

Crop harvest data were provided directly by ABMI for certified reclaimed wellsites in cultivated lands belonging to 4 farm operations, as part of the 2015-2016 ERM pilot program (see Degenhardt et al., 2016 for further detail on the individual sites; Figure 1). Table 1 provides detail on the years of data available for those sites. Data were collected between 2013 and 2015. Some sites had 1 year of data, others had multiple years of data.

Table 1: ERM site number and associated data available for assessment within the project.

ERM Certified Reclaimed Site	Year(s) of Data Available
1	2015
2	2014, 2015
3	None
4	2015
5	2015
6	2013*, 2015
7	2014, 2015
8	2014, 2015
9	2013
10	2013, 2015
11	2013, 2015
12	2013, 2015
13	None
14	None
15	2014, 2015
16	2013, 2015
17	2014**, 2015
18	None
19	None
20	None
21	2013
22	2015
23	None
24	2013
25	None
26	None
27	None

Note: Sites without data are not included in Figure 1.

*Data were not included in the report since no harvest data was available on the wellsite. For this site specifically, data were only available for an area north of the wellsite.

**Data were not included in the report since there were no usable data after data cleaning (See *Section 3.2* for further detail on data cleaning procedures).

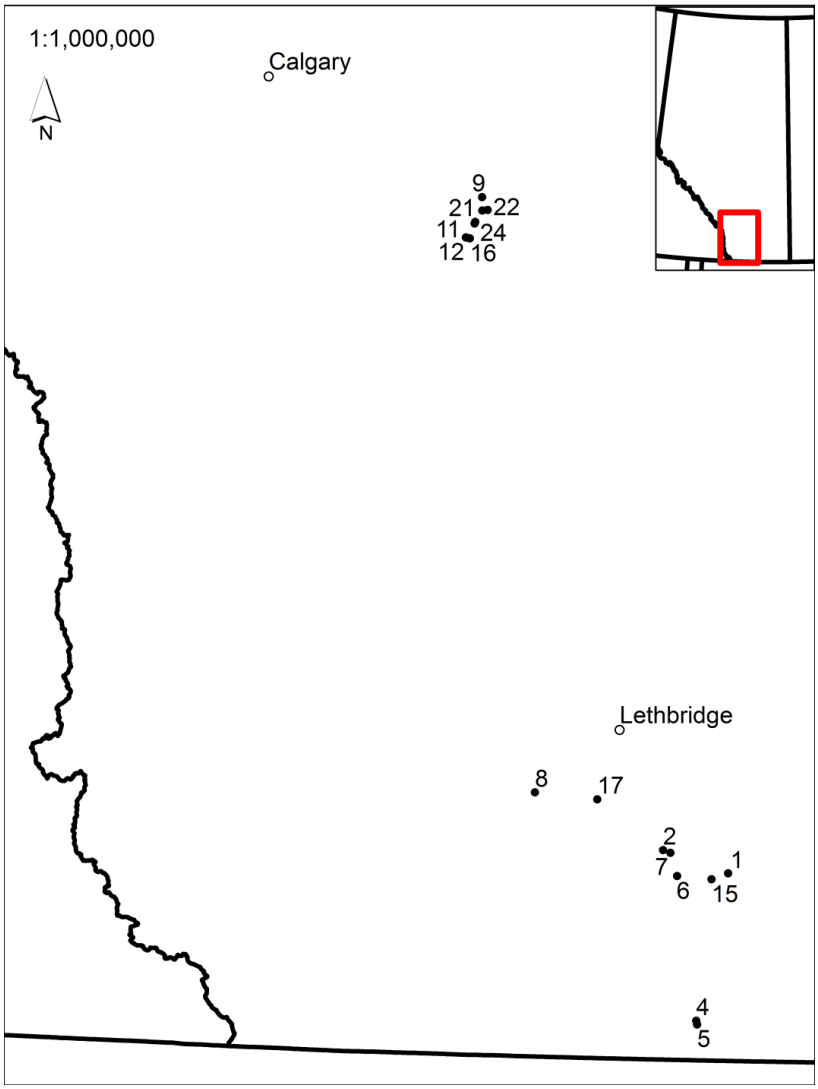

Figure 1: Location of the certified reclaimed cultivated sites with crop yield data, used for the study (Alberta, Canada).

3.2 DATA CLEANING

Once received, data were exported as comma separated values (.csv) after coordinates were added to the individual shapefiles. The comma separated values were imported into Microsoft Excel (2010) for data cleaning. Raw data were provided as dry yield per area (i.e., bushels per acre) values[2]. Individual data files, for each site, were cleaned by removing data points that did not accurately represent crop yield (i.e., data artifacts) at a corresponding location. This included the following:

1. Data points at the beginning and end of measurement transects accounting for start- and end-pass delay (this occurs when the combine grain elevator is initially filling or gradually emptying at the start and end of each crop harvest pass);

[2]Dry yield is calculated by the harvesting machine (e.g., combine) from the distance travelled, swath width, crop flow rate, and in-field moisture content.

2. Data points corresponding to when the harvest combine stopped, slowed down, or changed direction;
3. Unrealistically low and high dry yield volumes observed as major outliers in the data; and,
4. Data points that were more than 30% higher than the average of 6 surrounding data points (based on the normalized yield or ratio of the actual yield to the surrounding yield average).

To identify artifacts, crop flow rate and dry yield were used as indicators.

3.3 DATA PROCESSING AND MAP DEVELOPMENT

Cleaned data were imported to ESRI ArcMap 10.3.1, a geographic information system (GIS) software package, for data visualization. Map averaging or smoothing was conducted to produce individual field maps through interpolation rasters using the Kriging method, clipped to the extent of the available harvest data.

The wellsite was identified, based on the locations provided from the 2015-2016 ERM program (Degenhardt et al., 2016). For this, the wellsite was 100 m x 100 m, centered on the wellsite center. The reference area was defined as an additional 25 m buffer past the wellsite area (Degenhardt et al., 2016; Faechner, 2008).

Dry yield was visually represented by 3 different maps for each site, including *Field View*, *Grid with Dry Yield View*, and *Data Collection Points over Wellsite and Reference Areas View*. A further description of each map type is provided.

Field View – Map includes the interpolated data layer over satellite imagery, showcasing the location of the wellsite and reference area, indicated as red and green squares, respectively.

Grid with Dry Yield View – A 6 x 6 grid pattern was placed over both the wellsite and reference area, resulting in 25 m x 25 m grid squares (Faechner, 2008). The wellsite and reference area contain 16 and 20 grid squares, respectively. Data points within each grid square were averaged and labelled in the center of each grid square. The locations of the wellsite and reference area are indicated by red and green squares, respectively. This map was layered over the *Field View* map.

Data Collection Points over Wellsite and Reference Areas View– Individual cleaned dry crop yield data collection points (See *Section 3.2* for further detail) were indicated across both the wellsite and reference area, in terms of a gradient. Red, yellow and green data points referred to low, medium, and high crop yields, in terms of bushels per acre. This map was layered over the *Field View* map.

3.4 STATISTICS

Since each site had undergone different farming and tilling practices, were planted with different crops, and crops were harvested with different equipment, sites were not treated as replicates (i.e., data from individual sites were assessed separately). For sites with data from multiple years, data from each year were assessed separately (multiple years of data were not always planted with the same crop and harvest patterns were not similar across years).

All statistical analyses were done in R 3.3.2 (R Core Team 2016). Cleaned harvest data were tested for normality using the Shapiro-Wilk Normality Test. Statistical significance ($p < 0.05$) was assessed using one-way analysis of variance (ANOVA) tests for normal data and Kruskal-Wallis for non-normal data.

For each individual site, comparisons in crop yield were made between the wellsite and reference area at a high-level (environmental and farm management data were not used to inform comparisons).

4.0 RESULTS

4.1 SITE 1 – 2015

A summary of the crop yield data, collected in 2015, for Site 1, including the wellsite and reference area is provided in Figure 2. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 2.

4.1.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 4.1 \times 10^{-2}$). Comparisons were not made between the wellsite and the entire field.

The area showing the lowest yield on the wellsite was observed to be roughly within the center of the 1 ha wellsite (Figure 2a); however, these values were still within the range of those observed across the entire field. The lowest average crop yield on the wellsite and reference area was 45.6 and 48.3 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 87.9 and 87.3 bu/acre, respectively (Figure 2b).

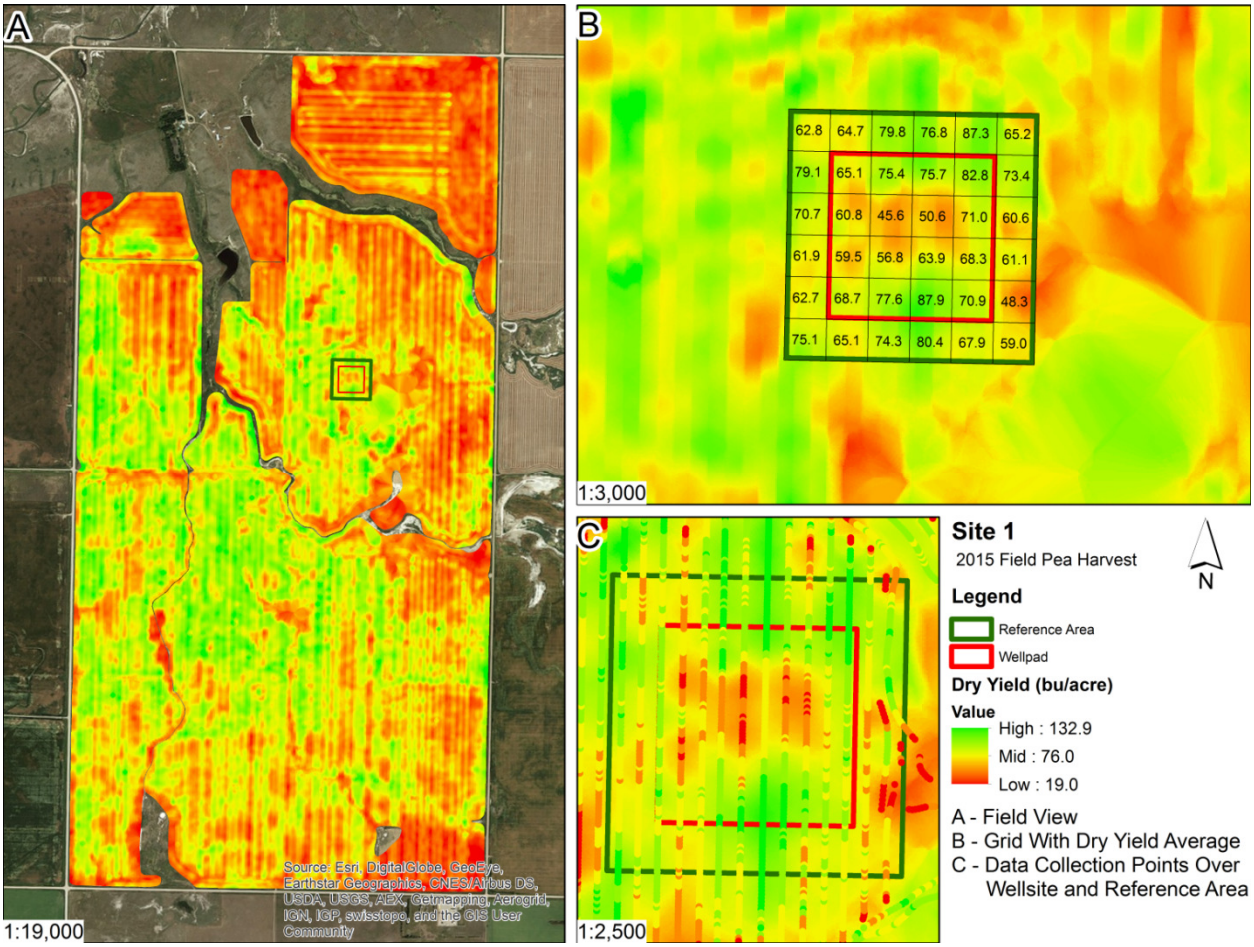

Figure 2: Site 1 dry yield field pea harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 2: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 1 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Field Pea	Wellsite	1.0	67.3	14.9	599	4.1×10^{-2}
		Reference Area	1.3	69.0	14.3	674	
		Entire Field	448.0	58.3	19.9	243,558	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.2 SITE 2 – 2014

A summary of the crop yield data, collected in 2014, for Site 2 including the wellsite and reference area is provided in Figure 3. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 3.

4.2.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 1.7 \times 10^{-9}$). Comparisons were not made between the wellsite and the entire field.

The lowest yields on the wellsite were found in the northern and southern edges of the wellsite; however, these values were still within the range of those observed across the entire field (Figure 3a). The lowest average crop yield on the wellsite and reference area was 44.2 and 45.1 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 55.5 and 64.4 bu/acre, respectively (Figure 3b).

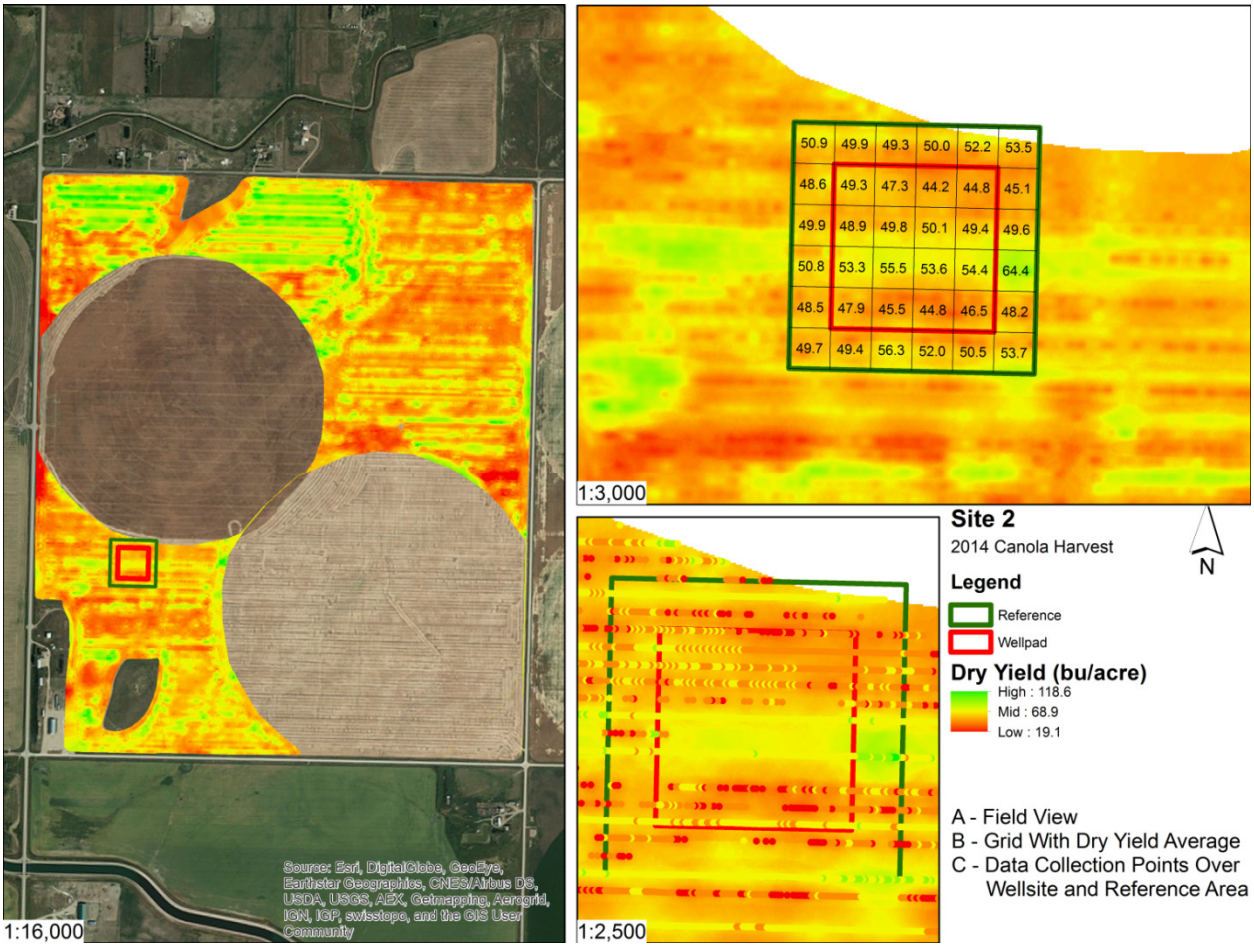

Figure 3: Site 2 dry yield canola harvest data from 2014. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 3: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 2 in 2014. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2014	Canola	Wellsite	1.0	48.2	5.6	547	1.7×10^{-9}
		Reference Area	1.3	50.4	7.1	602	
		Entire Field	148.5	51.0	10.2	66,044	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.3 SITE 2 – 2015

A summary of the crop yield data, collected in 2015, for Site 2 including the wellsite and reference area is provided in Figure 4. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 4.

4.3.1 Wellsite and Reference Area Comparison

Unlike the previous year, average crop yield was not found to be statistically different between the wellsite and reference area ($p = 8.4x10^{-1}$). Comparisons were not made between the wellsite and the entire field.

The area showing the lowest yield on the wellsite was roughly the north and center of the wellsite, likely due to the combine beginning or ending a harvest transect; however, these values were still within the range of those observed within the reference area as well as across the entire field (Figure 4a). The lowest average crop yield on the wellsite and reference area was 53.9 and 52.9 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 89.7 and 91.8 bu/acre, respectively (Figure 4b).

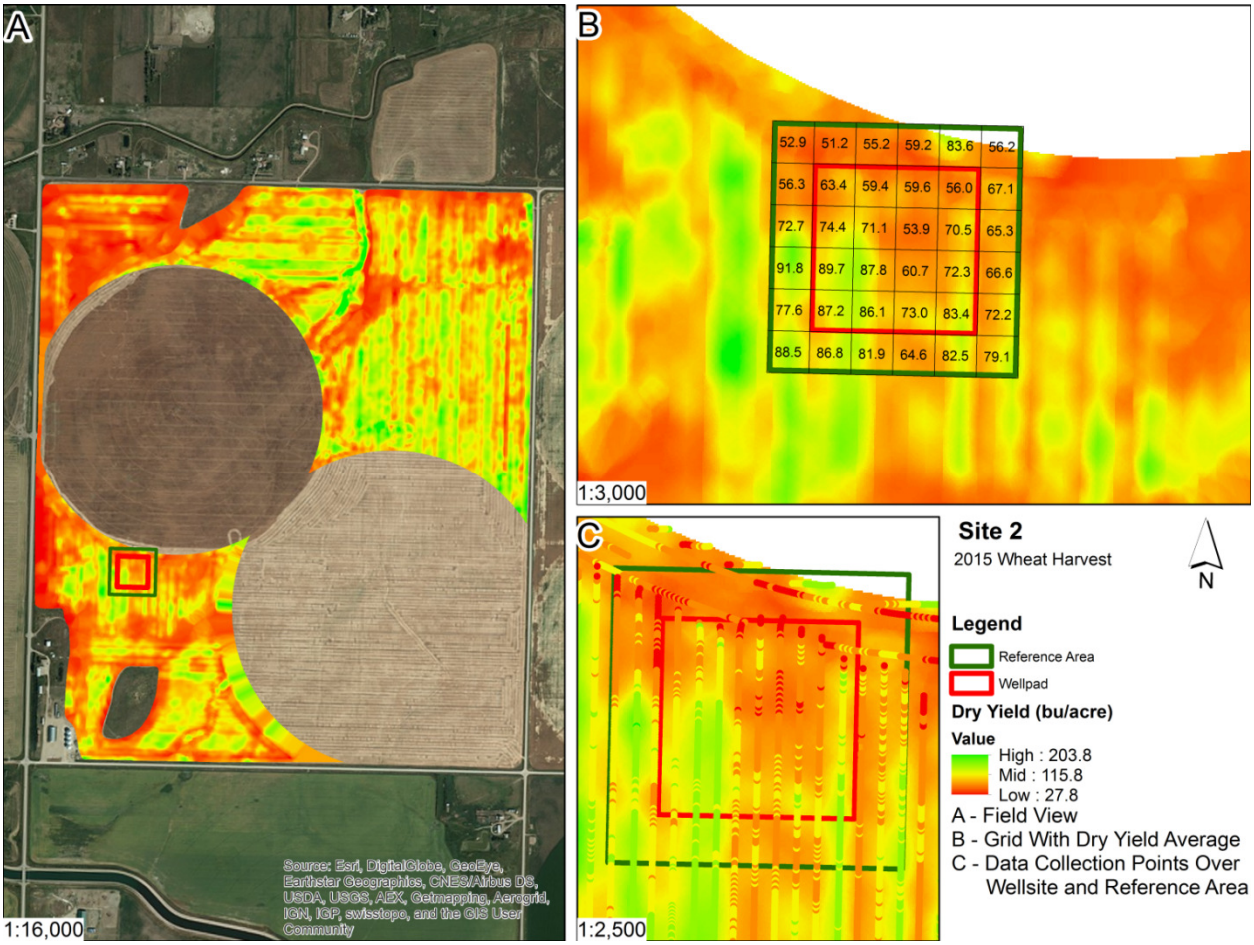

Figure 4: Site 2 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 4: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 2 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	71.5	16.8	695	8.4×10^{-1}
		Reference Area	1.3	71.7	18.6	959	
		Entire Field	136.6	75.6	23.6	91,516	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.4 SITE 4 - 2015

A summary of the crop yield data, collected in 2015, for Site 4 including the wellsite and reference area is provided in Figure 5. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 5.

4.4.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 3.2 \times 10^{-13}$). Comparisons were not made between the wellsite and the entire field.

The area showing the lowest yield on the wellsite was roughly the southwest portion of the wellsite; however, these values were still within the range of those observed across the entire field (Figure 5a). The lowest average crop yield on the wellsite and reference area was 17.5 and 24.3 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 31.4 and 34.0 bu/acre, respectively (Figure 5b).

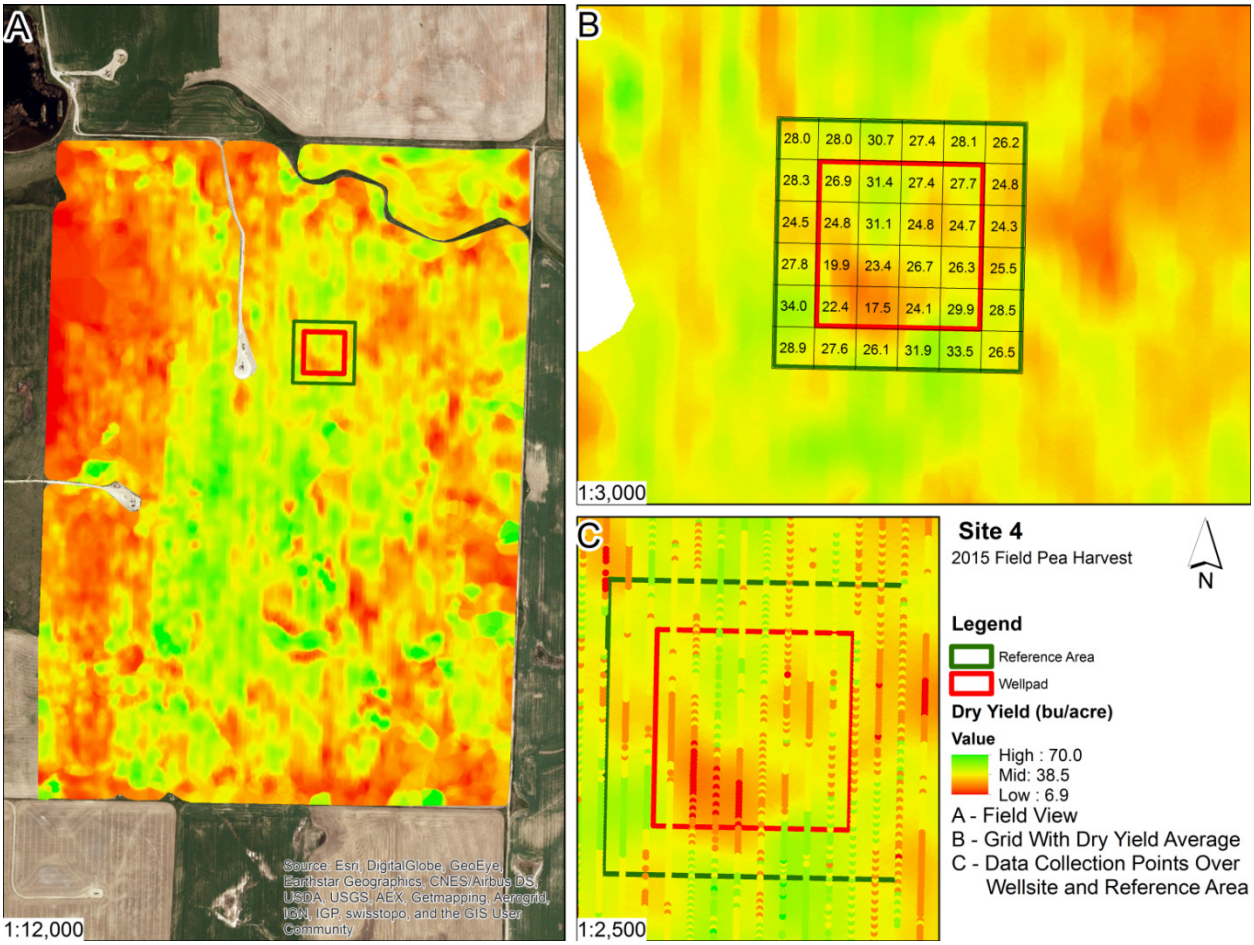

Figure 5: Site 4 dry yield field pea harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 5: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 4 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Field Pea	Wellsite	1.0	25.4	5.1	380	3.2×10^{-13}
		Reference Area	1.3	28.1	4.4	459	
		Entire Field	201.1	25.1	8.6	67,159	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.5 SITE 5 – 2015

A summary of the crop yield data, collected in 2015, for Site 5 including the wellsite and reference area is provided in Figure 6. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 6.

4.5.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was not found to be statistically different between the wellsite and reference area (p = 2.7×10^{-1}). Comparisons were not made between the wellsite and the entire field.

There were no discernible pattern in the crop yield data; the values observed on the wellsite were within the range of those observed across the entire field (Figure 6a). It is important to note that the path of the combine was not continuous over the wellsite and reference area; data were also missing from the centre of the wellsite and sections of the reference area. This resulted in less confidence in the data collected from this site. The highest average crop yield on the wellsite and reference area was 31.9 and 31.7 bu/acre, respectively (Figure 6b).

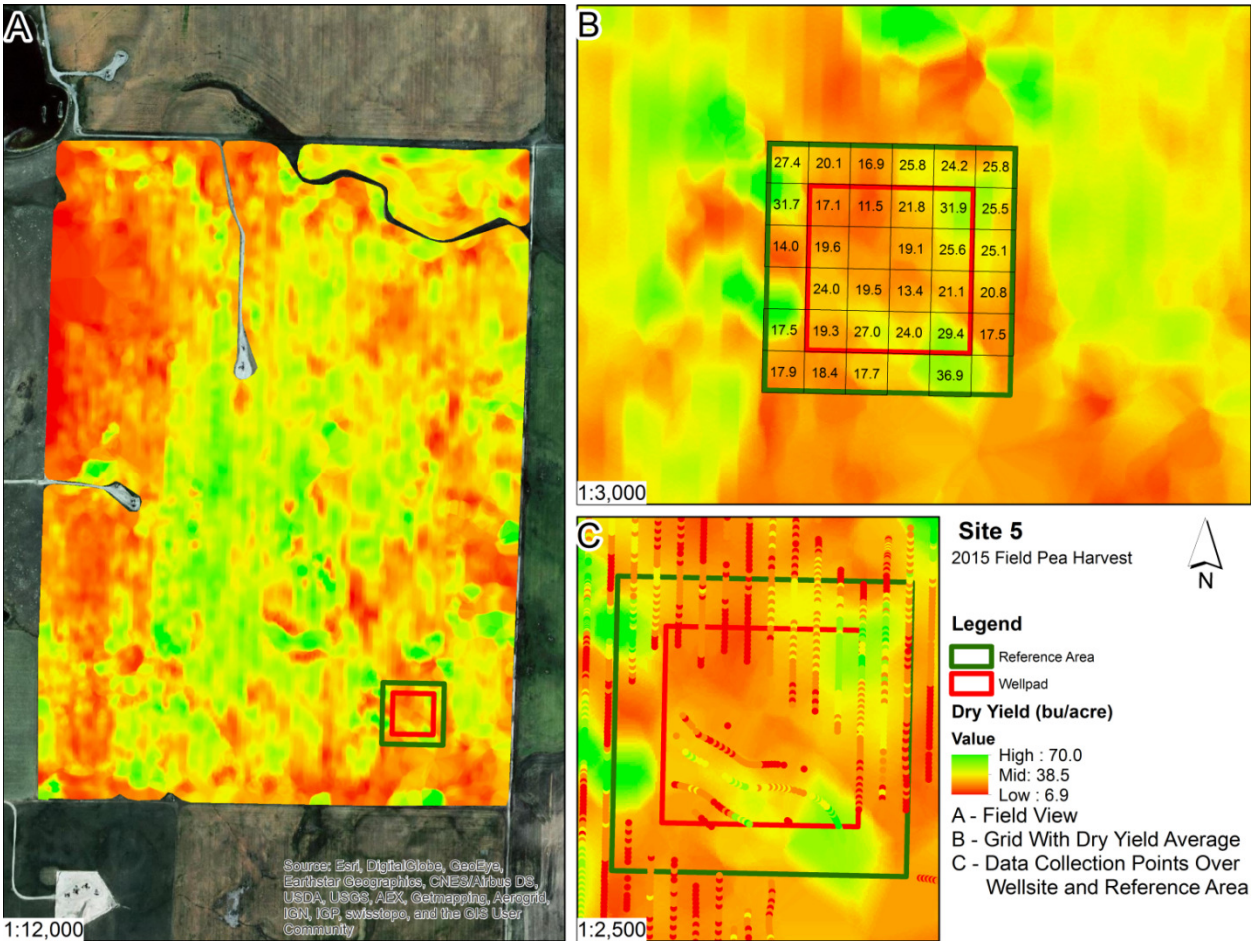

Figure 6: Site 5 dry yield field pea harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 6: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 5 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Field Pea	Wellsite	1.0	23.2	7.9	236	2.7×10^{-1}
		Reference Area	1.3	24.2	8.2	369	
		Entire Field	201.1	25.1	8.6	67159	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.6 SITE 6 – 2015

A summary of the crop yield data, collected in 2015, for Site 6 including the wellsite and reference area is provided in Figure 7. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 7.

4.6.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was not found to be statistically different between the wellsite and reference area (p = 5.5×10^{-1}). Comparisons were not made between the wellsite and the entire field.

The northwest portion of the wellsite contained the lowest yield of barley; however, these values were still within the range of those observed across the entire field (Figure 7a). The lowest average crop yield on the wellsite and reference area was 117.8 and 130.9 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 159.8 and 158.1 bu/acre, respectively (Figure 7b).

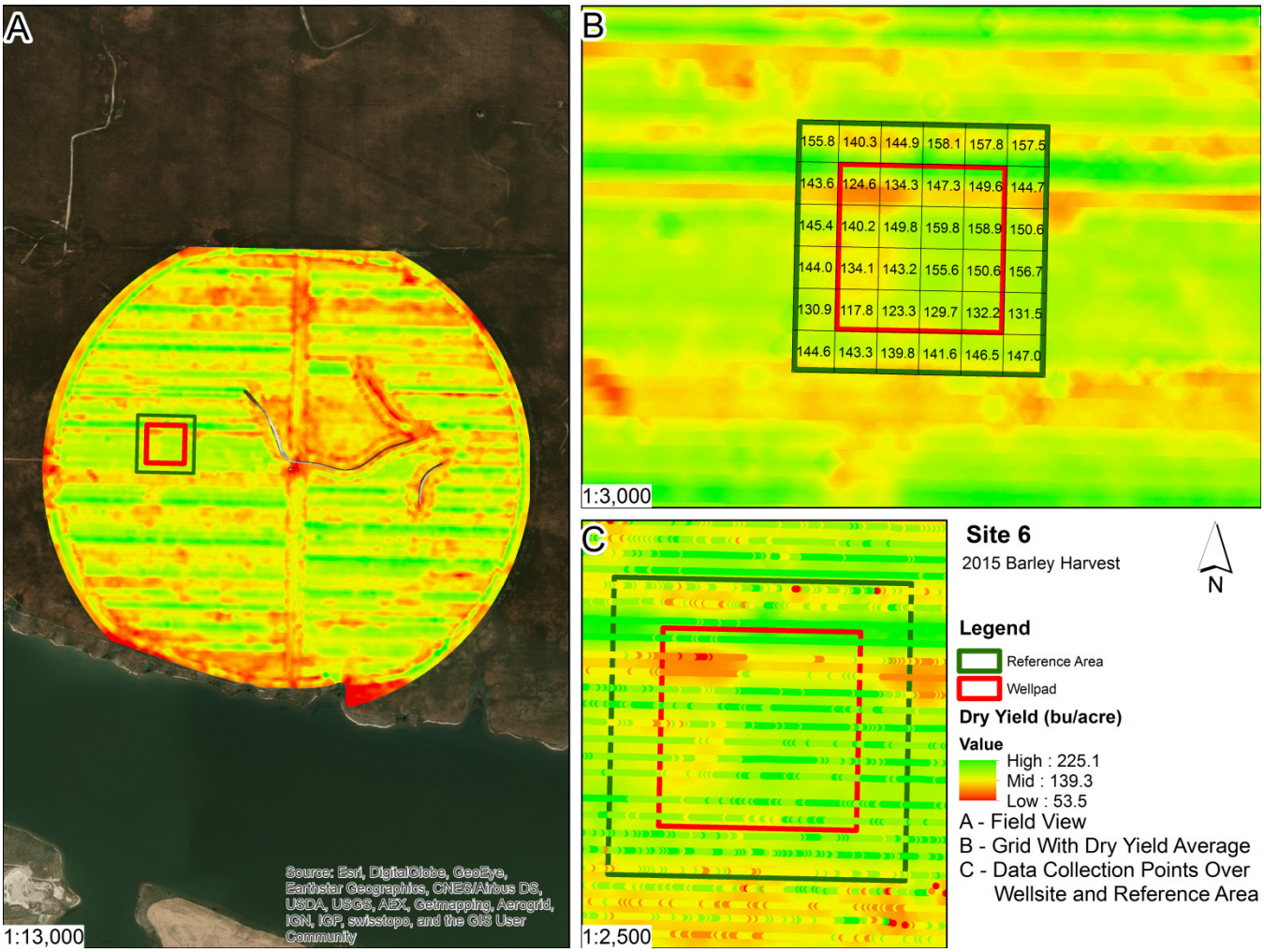

Figure 7: Site 6 dry yield barley harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 7: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 6 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Barley	Wellsite	1.0	146.0	19.6	954	5.5×10^{-1}
		Reference Area	1.3	147.9	22.1	1391	
		Entire Field	122.9	138.3	28.2	116873	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.7 SITE 7 - 2014

A summary of the crop yield data, collected in 2014, for Site 7 including the wellsite and reference area is provided in Figure 8. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 8.

4.7.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was not found to be statistically different between the wellsite and reference area (p = 5.1×10^{-1}). Comparisons were not made between the wellsite and the entire field.

The highest average yields were located in the northern portion of the wellsite. It is important to note that this site was located directly adjacent to a road (Figure 8a – southern edge), resulting in possible edge effects where a smaller swath width could have been collected. Here, impacts from road such as excessive dust and weeds could have lowered the yield (Figure 8a). For the areas with data collected, the lowest average crop yield on the wellsite and reference area was 41.1 and 42.2 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 71.3 and 73.1 bu/acre, respectively (Figure 8b).

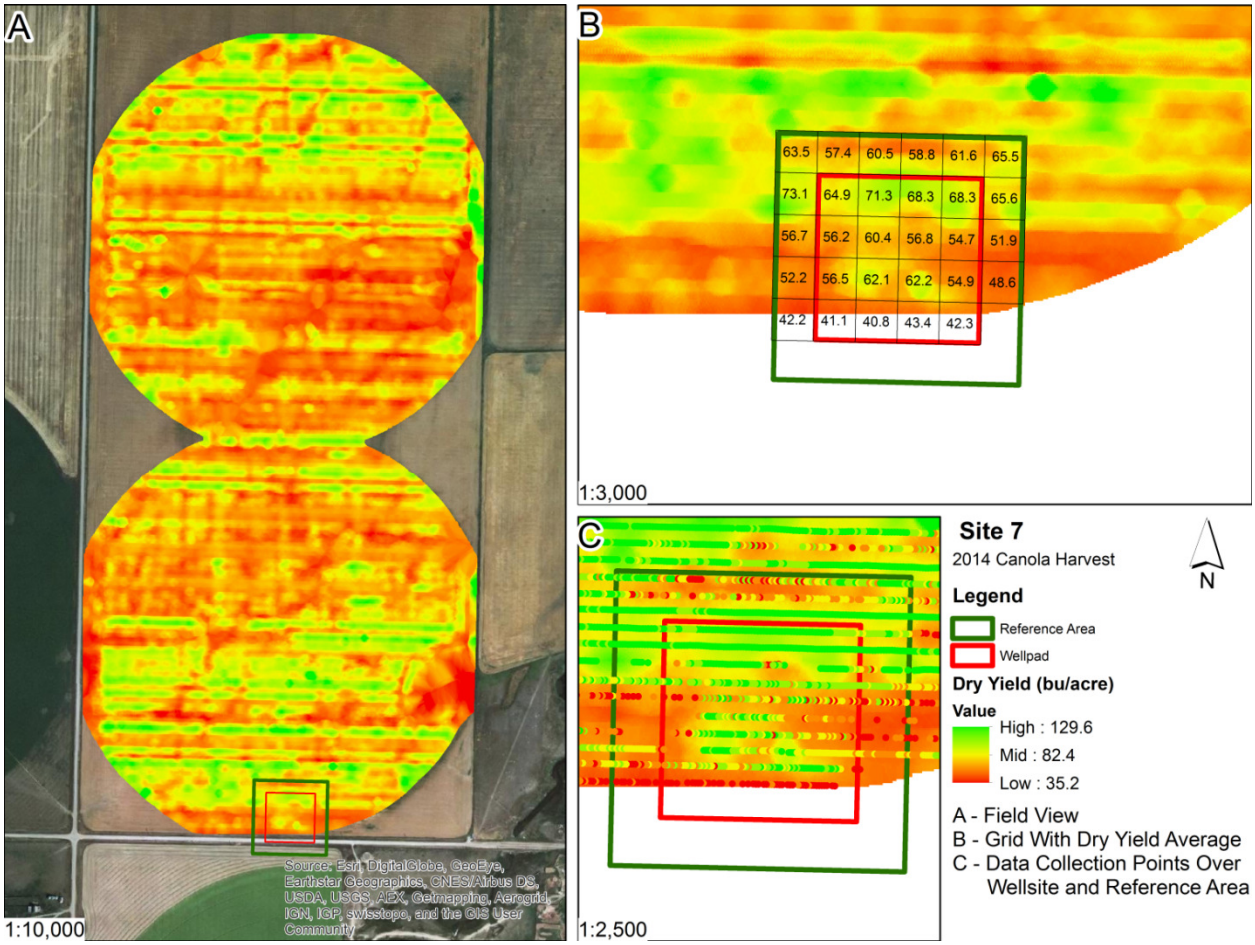

Figure 8: Site 7 dry yield canola harvest data from 2014. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 8: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 7 in 2014. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2014	Canola	Wellsite	1.0	60.2	10.5	644	5.1×10^{-1}
		Reference Area	1.3	60.0	11.4	518	
		Entire Field	110.9	60.8	13.0	76527	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.8 SITE 7 – 2015

A summary of the crop yield data, collected in 2015, for Site 7 including the wellsite and reference area is provided in Figure 9. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 9.

4.8.1 Wellsite and Reference Area Comparison

Unlike 2014, average crop yield was statistically different between the wellsite and reference area ($p = 2.4 \times 10^{-14}$).

The highest average yields were located in the northern portion of the wellsite. It is important to note that this site was located directly adjacent to a road, resulting in possible edge effects at the wellsite centre (Figure 9a). For the area with data collected, the lowest average crop yield on the wellsite and reference area was 80.9 and 82.2 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 123.3 and 126.1 bu/acre, respectively (Figure 9b).

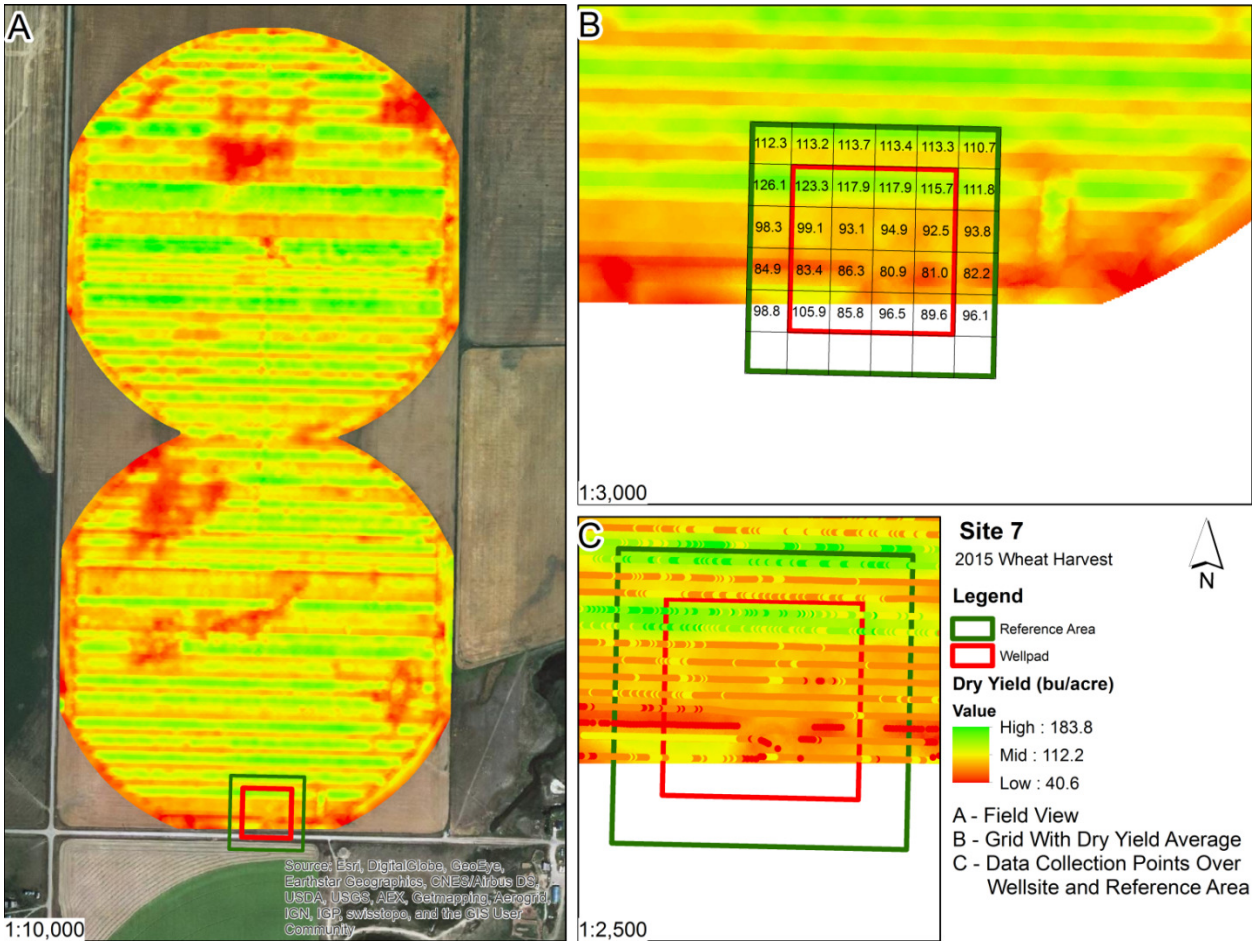

Figure 9: Site 7 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 9: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 7 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	99.4	21.5	772	2.4×10^{-14}
		Reference Area	1.3	106.5	21.6	792	
		Entire Field	111.7	106.8	24.1	105048	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.9 SITE 8 – 2014

A summary of the crop yield data, collected in 2014, for Site 8 including the wellsite and reference area is provided in Figure 10. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 10.

4.9.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was statistically different between the wellsite and reference area ($p = 6.9 \times 10^{-11}$). Comparisons were not made between the wellsite and the entire field.

On average, the yield values were lower on the wellsite in comparison to the reference area in no specific pattern; however, values were observed to be within the range of those observed across the entire field (Figure 10a). The lowest average crop yield on the wellsite and reference area was 23.0 and 19.0 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 41.7 and 44.3 bu/acre, respectively (Figure 10b).

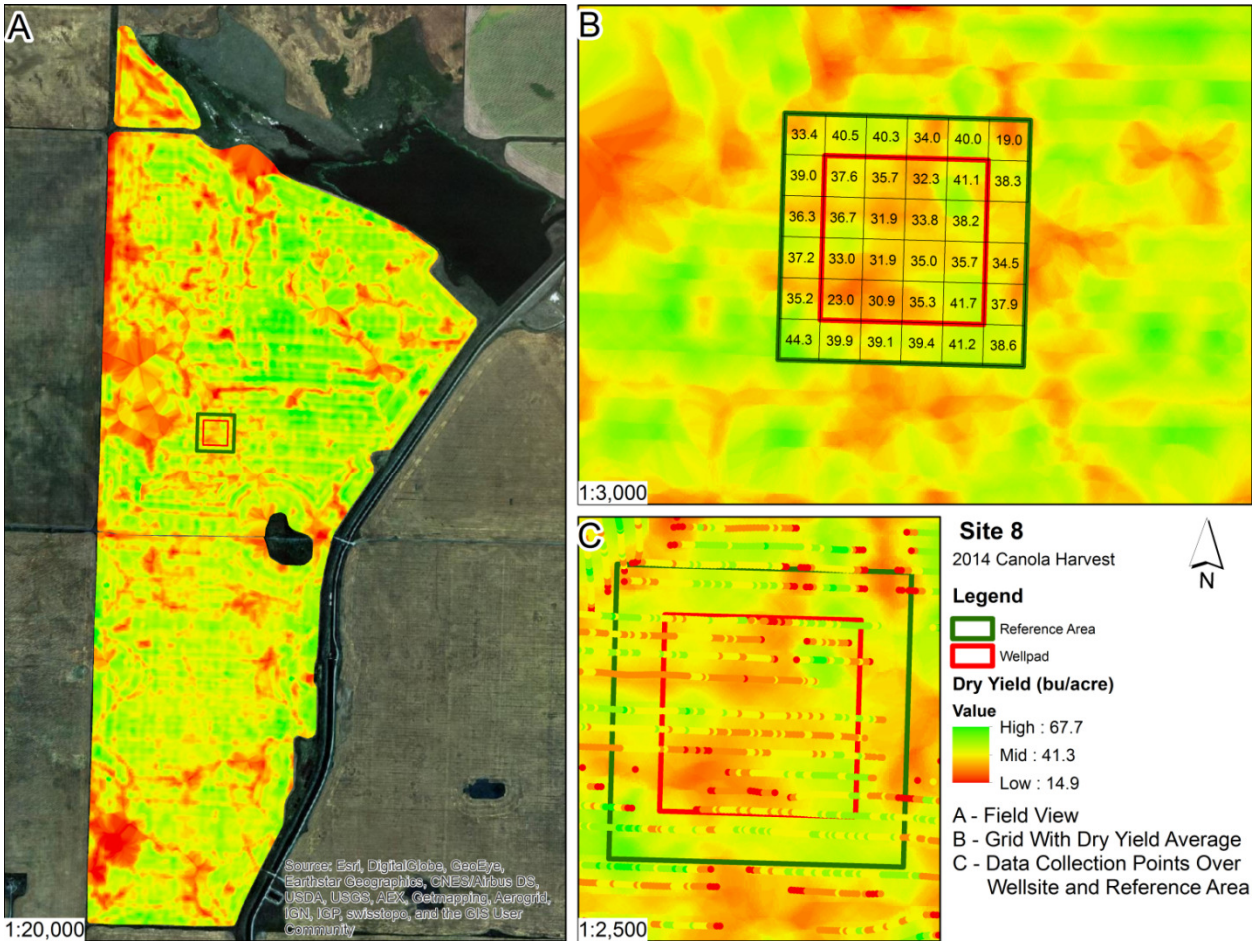

Figure 10: Site 8 dry yield canola harvest data from 2014. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 10: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 8 in 2014. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2014	Canola	Wellsite	1.0	35.6	6.5	491	6.9×10^{-11}
		Reference Area	1.3	38.1	7.0	342	
		Entire Field	328.6	39.5	8.6	131804	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.10 SITE 8 – 2015

A summary of the crop yield data, collected in 2015, for Site 8 including the wellsite and reference area is provided in Figure 11. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 11.

4.10.1 Wellsite and Reference Area Comparison

Similar to 2014, average crop yield was statistically different between the wellsite and reference area ($p = 1.2 \times 10^{-46}$).

On average, the yield values were lower on the wellsite compared to the reference area; however, these values were observed to be within the range of those observed across the entire field (Figure 11a). More specifically, areas of low crop harvest were consistent with non-continuous harvest transects made by the combine (Figure 11c). This has likely impacted the interpolation of the data and the resulting statistical analyses.

The lowest average crop yield on the wellsite and reference area was 51.1 and 53.7 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 72.7 and 78.9 bu/acre, respectively (Figure 11b).

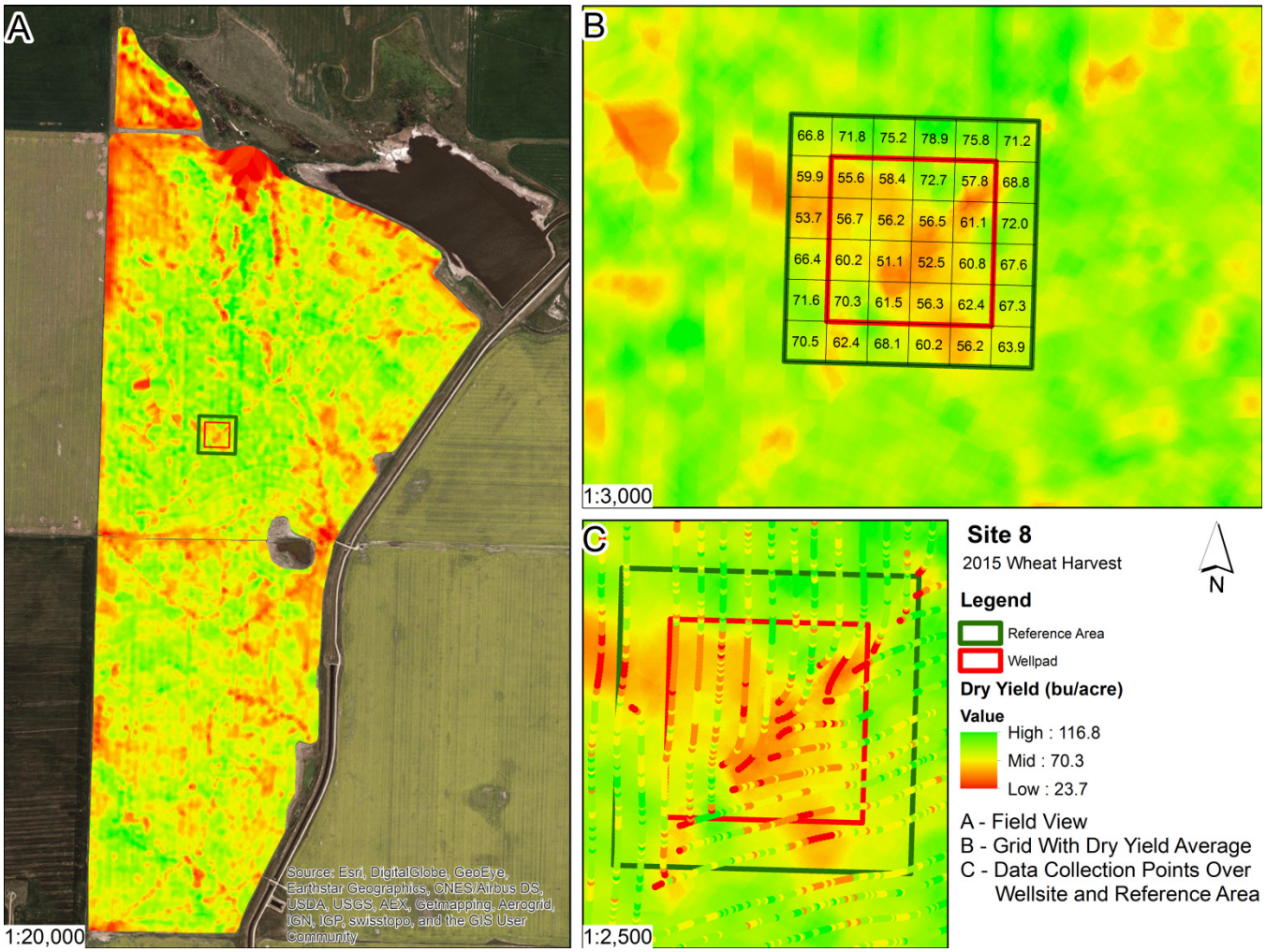

Figure 11: Site 8 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 11: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 8 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	60.0	12.1	562	1.2×10^{-46}
		Reference Area	1.3	69.1	11.0	626	
		Entire Field	328.6	64.0	12.3	156334	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.11 SITE 9 – 2013

A summary of the crop yield data, collected in 2013, for Site 9 including the wellsite and reference area is provided in Figure 12. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 12.

4.11.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was statistically different between the wellsite and reference area ($p = 1.9 \times 10^{-4}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield on the wellsite was found in the northeast corner; however, values were still within the range of those observed across the entire field (Figure 12a). The lowest average crop yield on the wellsite and reference area was 57.2 and 51.4 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 84.6 and 85.5 bu/acre, respectively (Figure 12b).

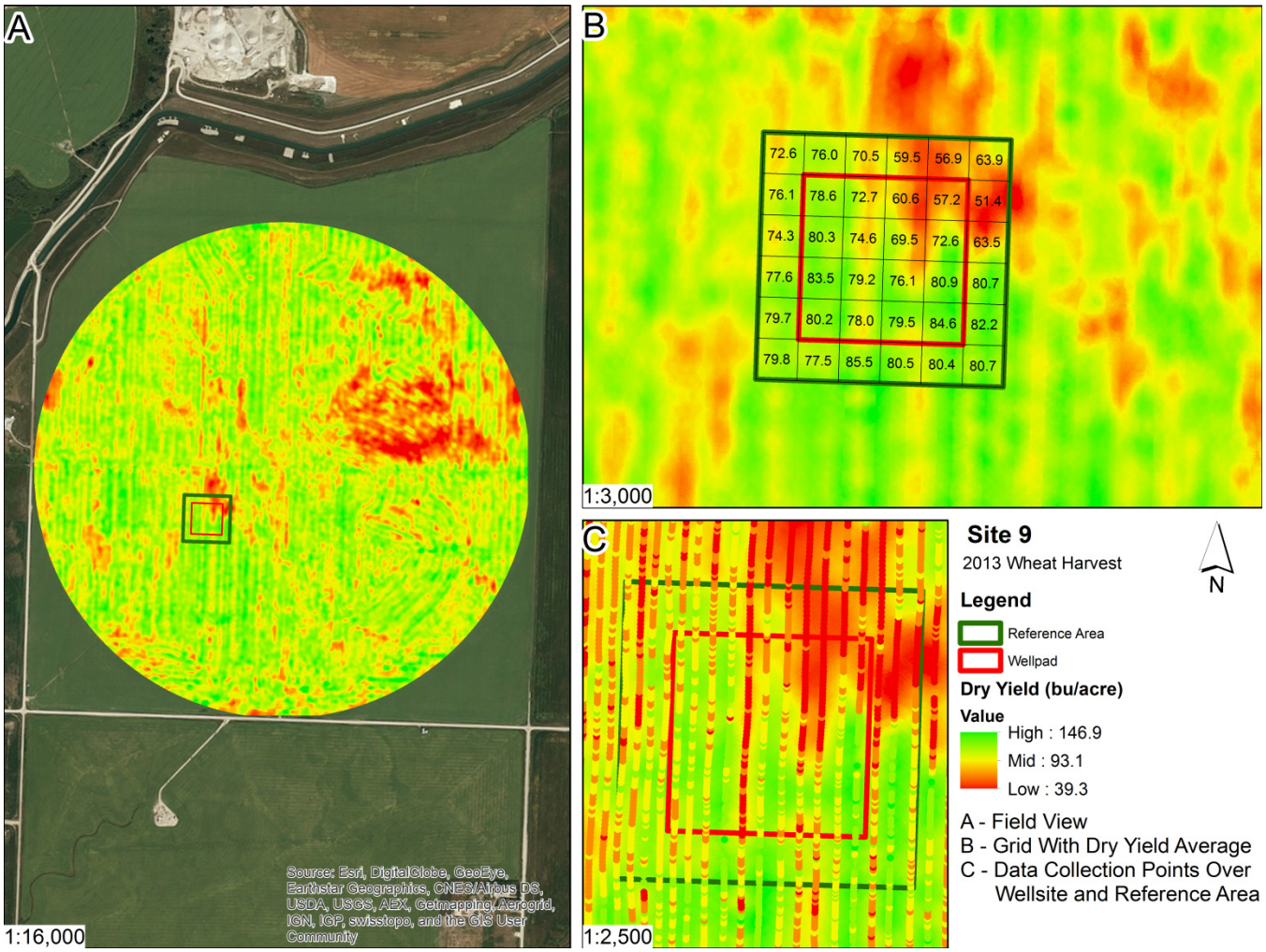

Figure 12: Site 9 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 12: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 9 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	76.2	12.8	692	1.9×10^{-4}
		Reference Area	1.3	74.4	12.7	955	
		Entire Field	201.5	74.5	12.1	157334	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.12 SITE 10 – 2013

A summary of the crop yield data, collected in 2013, for Site 10 including the wellsite and reference area is provided in Figure 13. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 13.

4.12.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 3.9 \times 10^{-29}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was found near the center of the wellsite; however, these values were still within the range of those observed across the entire field (Figure 13a). It is important to note that the combine changed course over the wellsite (Figure 13c), which can lead to error in the crop yield data collection and resulting calculations.

The lowest average crop yield on the wellsite and reference area was 55.2 and 63.9 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 74.1 and 86.8 bu/acre, respectively (Figure 13b).

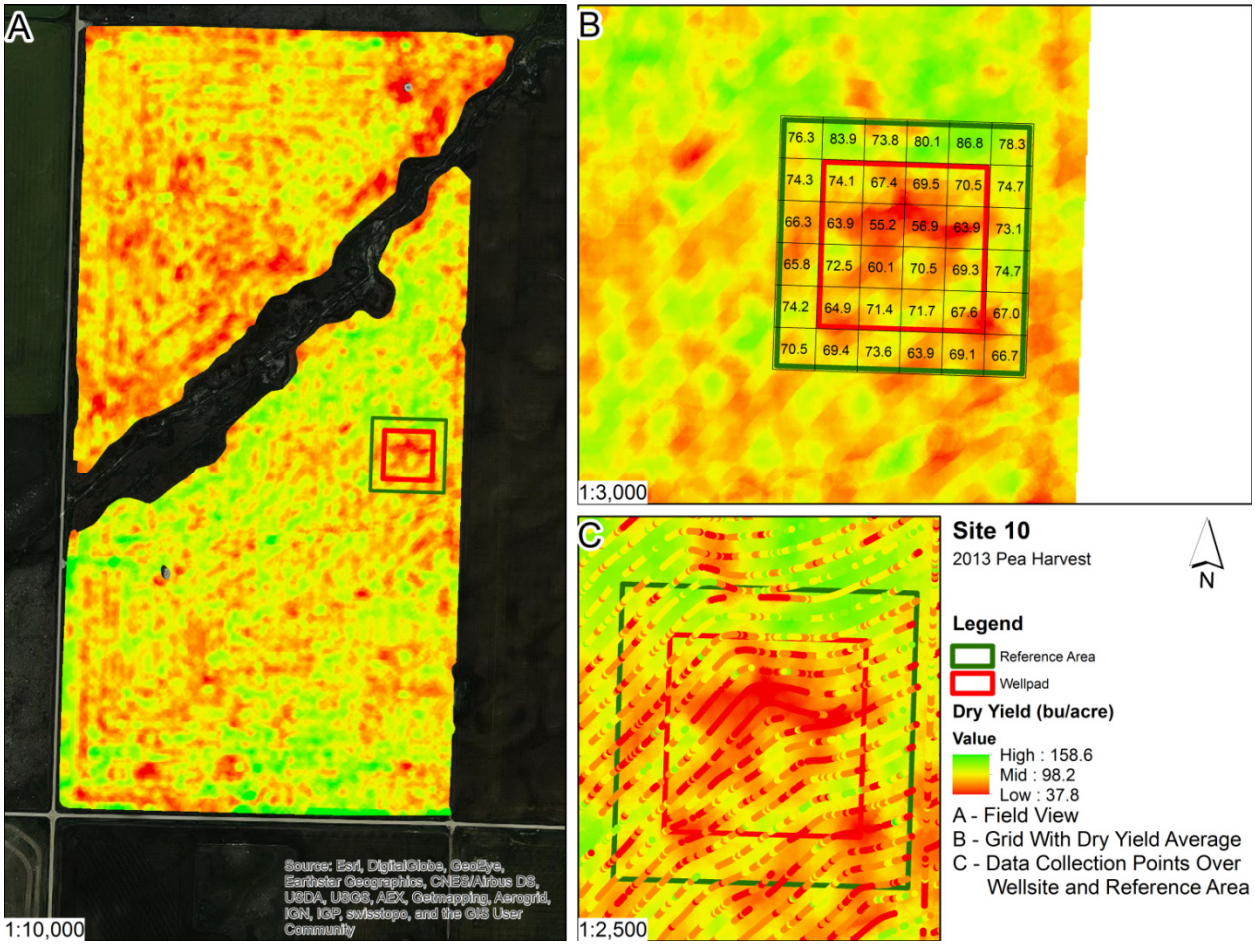

Figure 13: Site 10 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 13: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 10 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Pea	Wellsite	1.0	66.2	12.4	756	3.9×10^{-29}
		Reference Area	1.3	73.1	12.2	897	
		Entire Field	114.7	72.0	12.5	80754	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.13 SITE 10 – 2015

A summary of the crop yield data, collected in 2015, for Site 10 including the wellsite and reference area is provided in Figure 14. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 14.

4.13.1 Wellsite and Reference Area Comparison

Unlike the wheat yield in 2013, average wheat yield in 2015 was not found to be statistically different between the wellsite and reference area ($p = 6.7 \times 10^{-2}$).

Similar average crop yield values were found across the wellsite and reference area (Figure 14a). Similarly to 2013, the crop harvest was not completed in continuous passes by the harvest combine across the wellsite and reference area (Figure 14c); this may cause error in the crop yield data collection and result in artifacts in the data analysis and interpolation.

The lowest average crop yield on the wellsite and reference area was 41.9 and 38.6 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 55.2 and 60.2 bu/acre, respectively (Figure 14b).

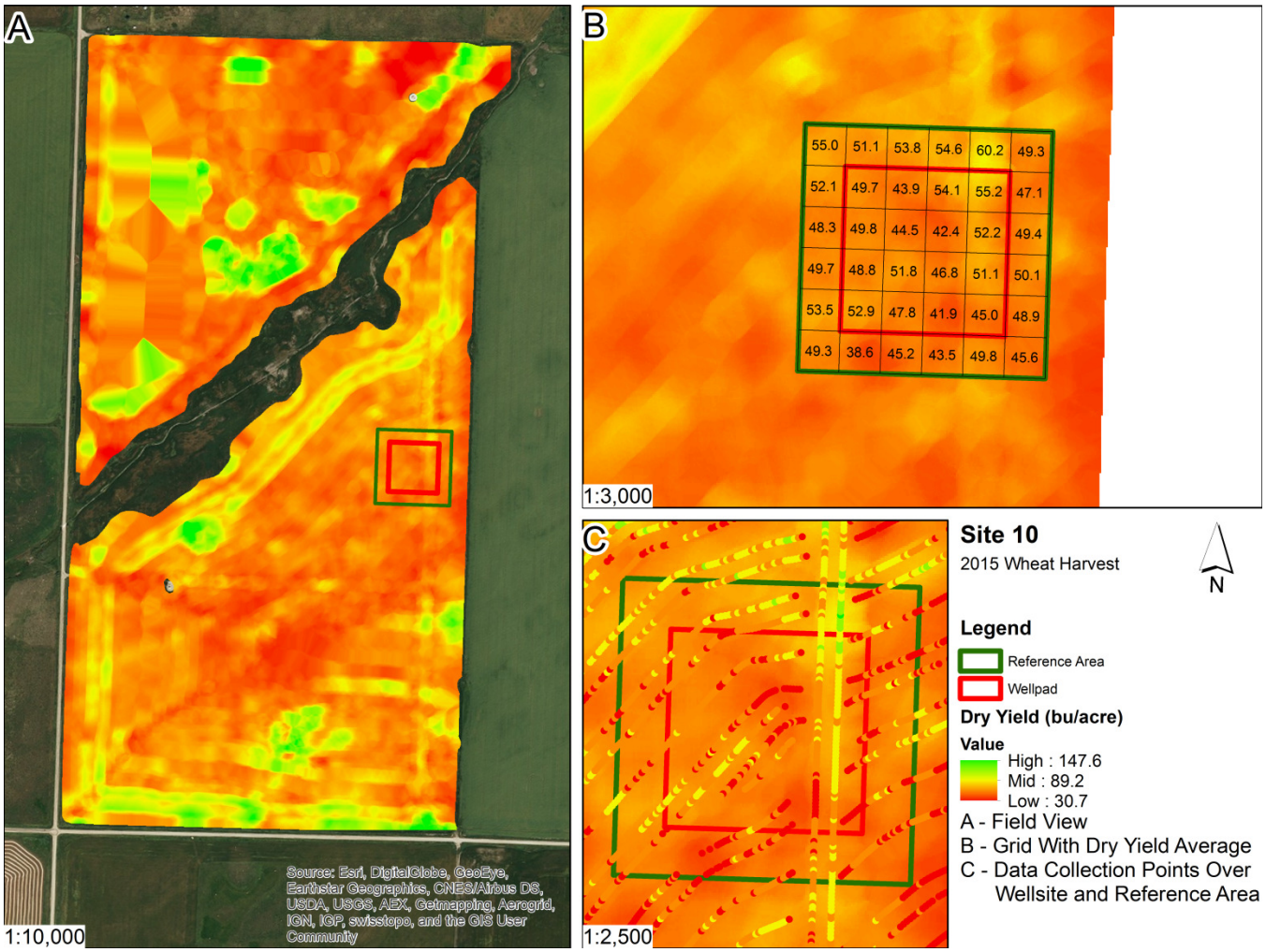

Figure 14: Site 10 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 14: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 10 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	49.2	7.4	410	6.7×10^{-2}
		Reference Area	1.3	50.4	7.6	453	
		Entire Field	114.7	60.0	15.3	81319	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.14 SITE 11 – 2013

A summary of the crop yield data, collected in 2013, for Site 11 including the wellsite and reference area is provided in Figure 15. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 15.

4.14.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 1.8 \times 10^{-5}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was associated with the southwest corner of the wellsite and reference area; a change in the course where the combine harvested the wheat occurred on the wellsite and data may not have been collected consistently (Figure 15c). At this location, it is possible that combine passes were not made across the entire site. Without additional information on the site layout and other factors that may have attributed to irregular combine passes, it is difficult to determine the yield relationship between the wellsite and reference area.

The lowest average crop yield on the wellsite and reference area was 47.5 and 34.4 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 96.6 and 99.5 bu/acre, respectively (Figure 15b). Therefore, more range was observed across the reference area than on the wellsite.

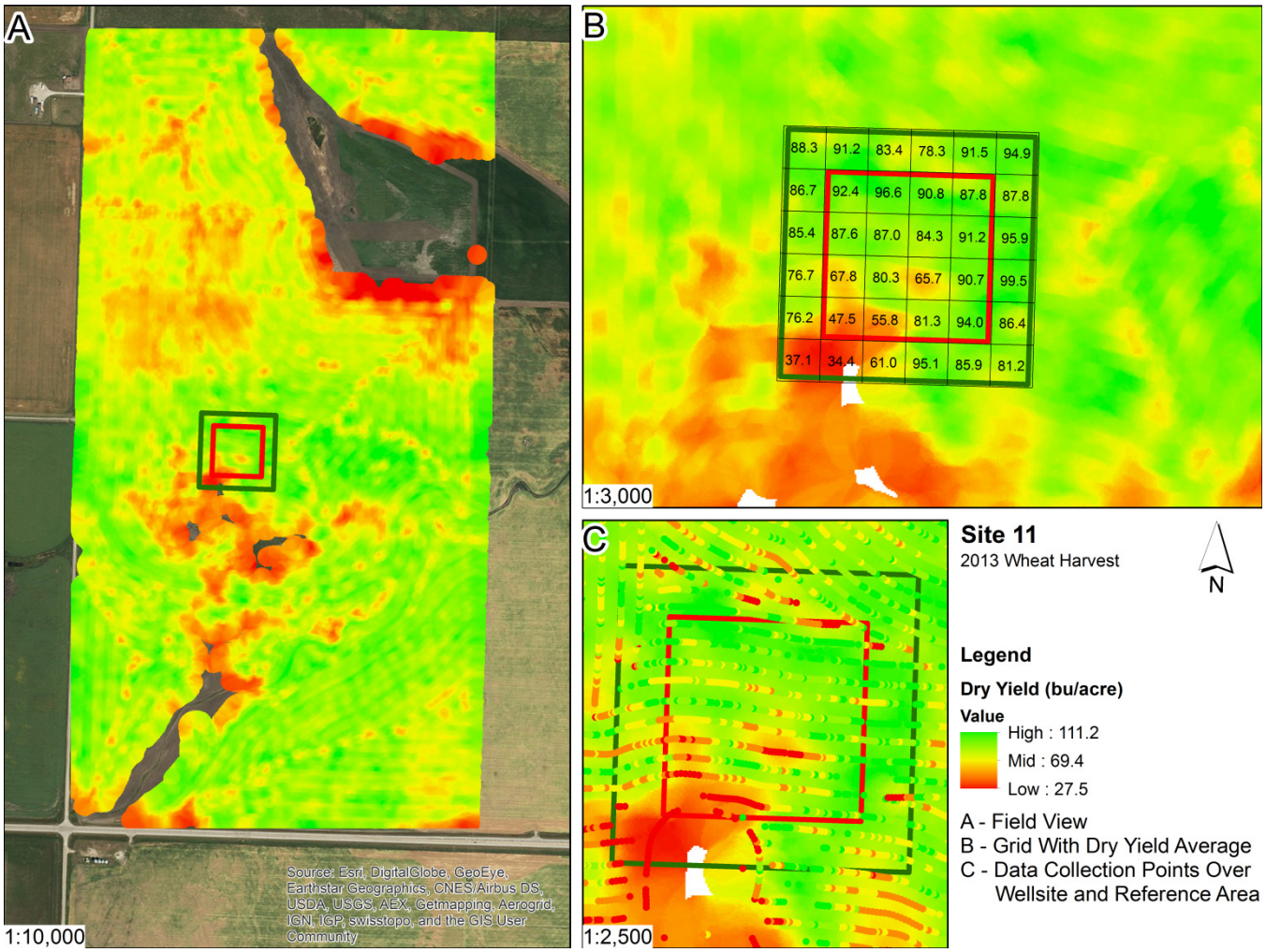

Figure 15: Site 11 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 15: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 11 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	82.4	17.5	606	1.8×10^{-5}
		Reference Area	1.3	86.3	18.5	619	
		Entire Field	123.6	76.4	16.0	62813	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.15 SITE 11 – 2015

A summary of the crop yield data, collected in 2015, for Site 11 including the wellsite and reference area is provided in Figure 16. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 16.

4.15.1 Wellsite and Reference Area Comparison

Unlike the wheat harvest in 2013, average wheat yield in 2015 was not found to be statistically different between the wellsite and reference area (p = 5.0×10^{-1}). However, crop yields on the wellsite were observed to be higher than the majority of the entire field.

In comparison to the northern half the wellsite and reference area, the southern half appears to be part of an area that has higher yield than the rest of the field (see green rectangular pattern in Figure 16a).

The lowest average crop yield on the wellsite and reference area was 64.6 and 62.6 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 98.9 and 97.1 bu/acre, respectively (Figure 16b).

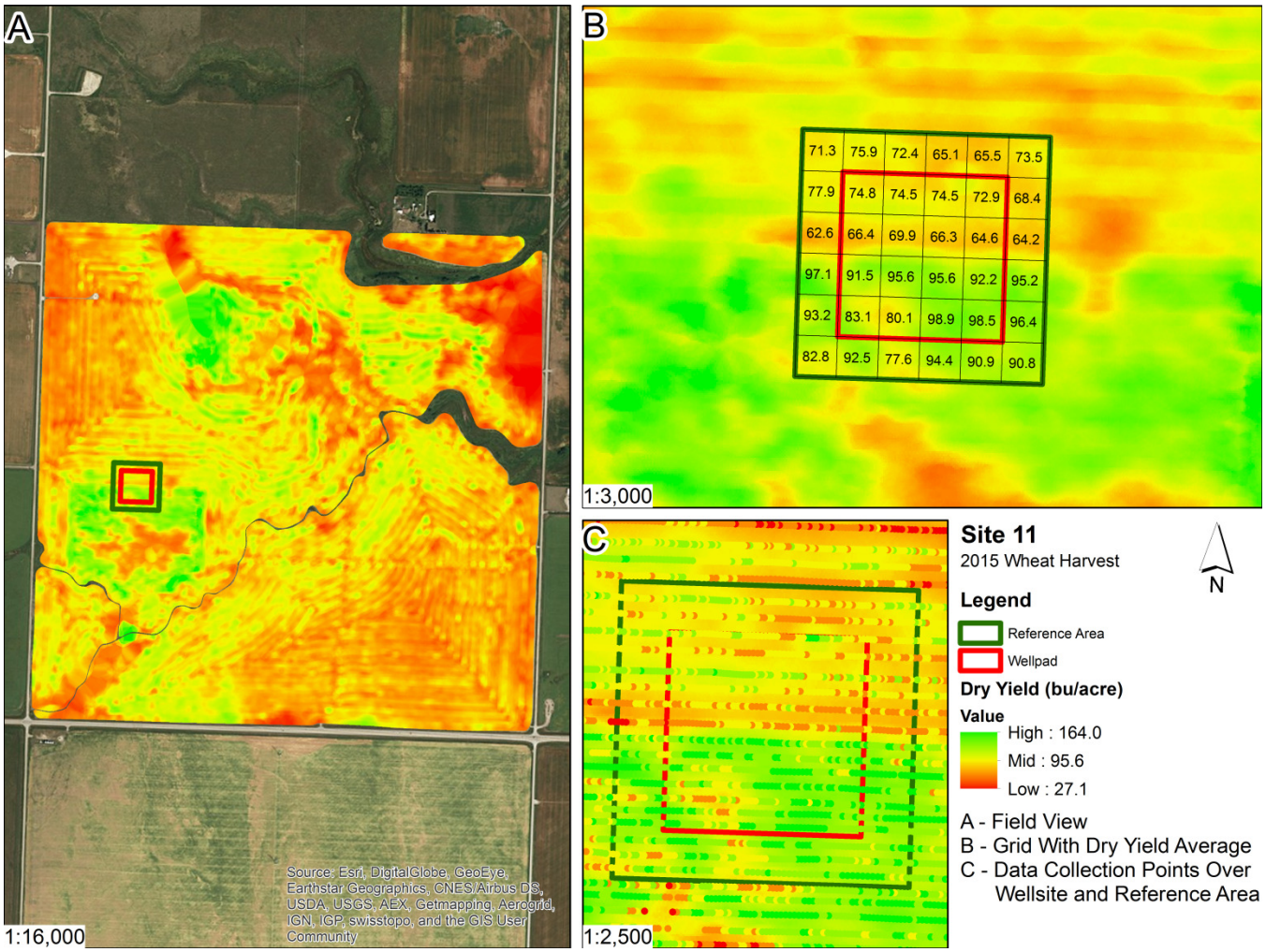

Figure 16: Site 11 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 16: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 11 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	82.1	15.7	645	5.0×10^{-1}
		Reference Area	1.3	81.6	16.0	708	
		Entire Field	248.0	70.3	18.1	180587	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.16 SITE 12 – 2013

A summary of the crop yield data, collected in 2013, for Site 12 including the wellsite and reference area is provided in Figure 17. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 17.

4.16.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 3.1 \times 10^{-12}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was associated with a change in combine direction; this was observed through the center of the wellsite (Figure 17c). The non-continuous harvest transects may have led to misrepresented actual crop yield.

The lowest average crop yield on the wellsite and reference area was 75.2 and 75.5 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 101.6 and 99.5 bu/acre, respectively (Figure 17b).

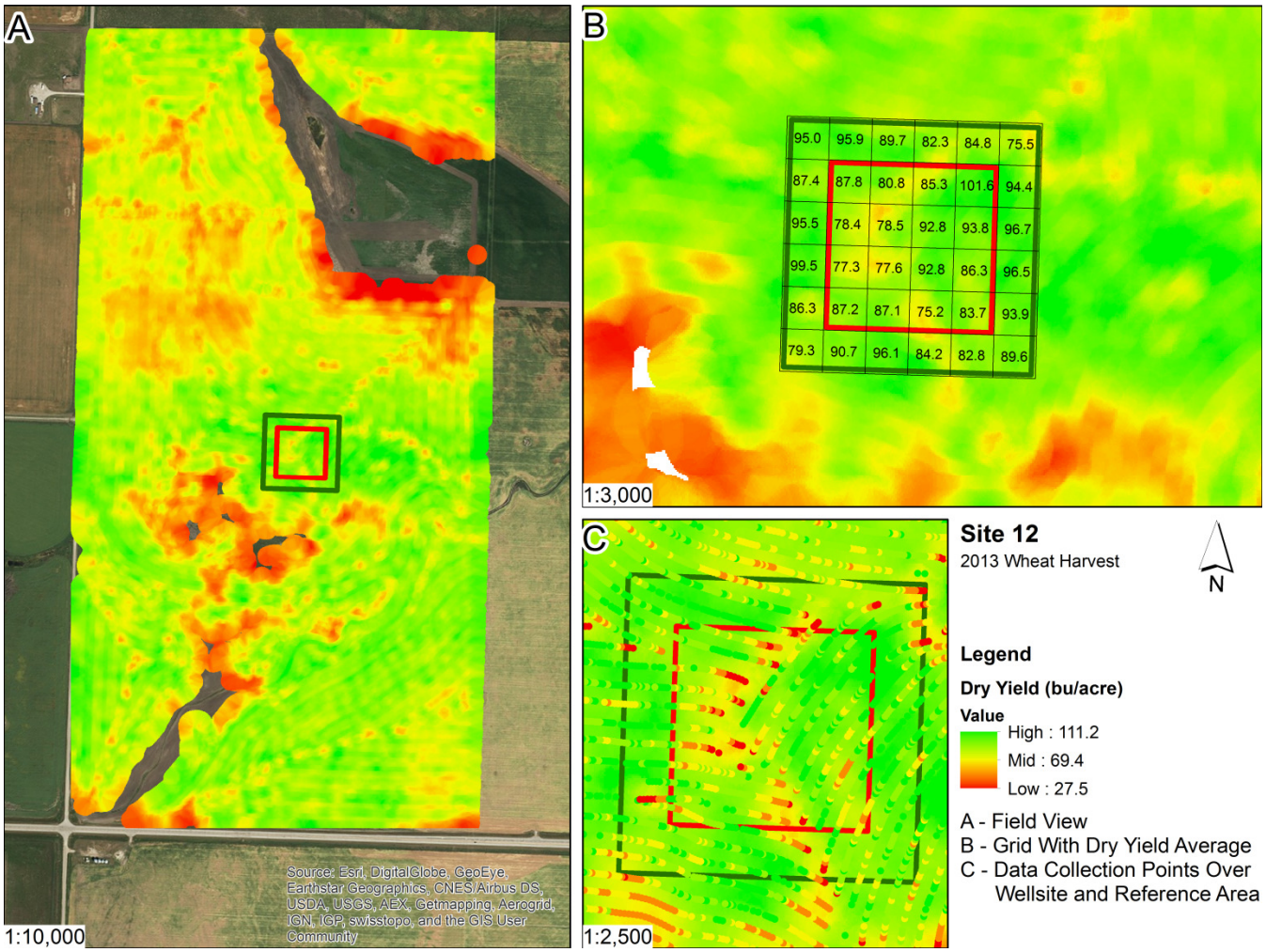

Figure 17: Site 12 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 17: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 12 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	84.9	15.6	616	3.1×10^{-12}
		Reference Area	1.3	90.6	14.6	758	
		Entire Field	123.6	76.4	16.0	62813	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.17 SITE 12 – 2015

A summary of the crop yield data, collected in 2015, for Site 12 including the wellsite and reference area is provided in Figure 18. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 18.

4.17.1 Wellsite and Reference Area Comparison

Similar to the 2013 wheat yield data, the average wheat yield data in 2015 was found to be statistically different between the wellsite and reference area ($p = 9.4 \times 10^{-10}$).

The combine paths were consistent across the wellsite and reference area (Figure 18c). The lowest average crop yield was observed in the northwest portion of the wellsite. The lowest average crop yield on the wellsite and reference area was 51.8 and 63.7 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 101.1 and 117.1 bu/acre, respectively (Figure 18b).

Sites 11 and 12 are on the same field. The same harvest artifact observed in the 2013 data in Site 11 was also observed in Site 12 (Figure 18a).

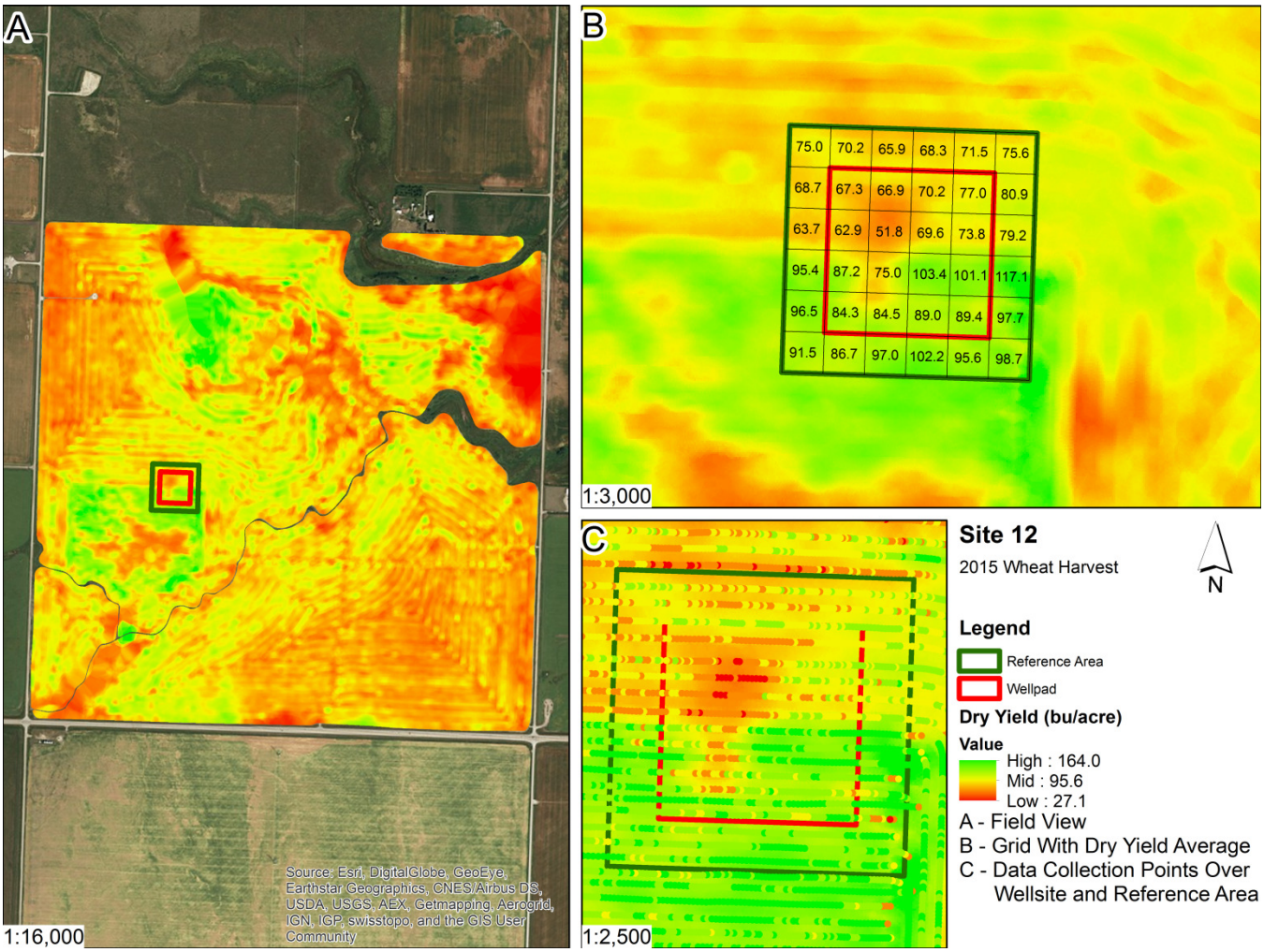

Figure 18: Site 12 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 18: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 12 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	79.1	17.2	650	9.4×10^{-10}
		Reference Area	1.3	86.1	19.2	725	
		Entire Field	248.0	70.3	18.1	180587	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.18 SITE 15 – 2014

A summary of the crop yield data, collected in 2014, for Site 15 including the wellsite and reference area is provided in Figure 19. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 19.

4.18.1 Wellsite and Reference Area Comparison

Average crop yield was found to be statistically different between the wellsite and reference area ($p = 9.0 \times 10^{-3}$).

The lowest average crop yield was associated with the northern portion of the wellsite and reference area; but these values were consistent with those measured in the northern portion of the field (Figure 19a). On the wellsite, a change in the combine harvest paths may have occurred and data were not collected consistently (Figure 19c). These non-continuous harvest transects may misrepresent the actual crop yield.

The lowest average crop yield on the wellsite and reference area was 60.9 and 52.6 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 78.5 and 84.4 bu/acre, respectively (Figure 19b).

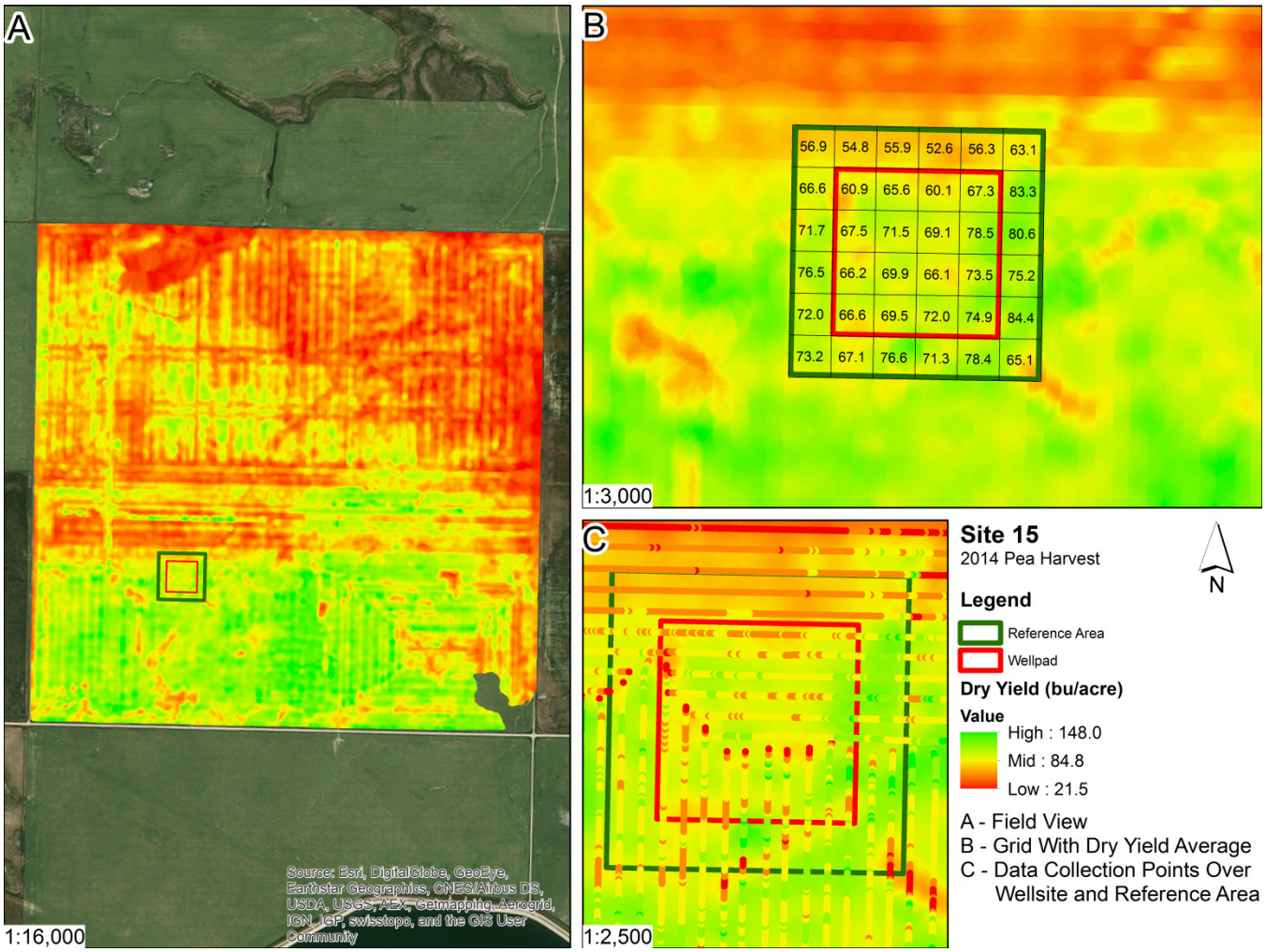

Figure 19: Site 15 dry yield pea harvest data from 2014. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 19: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 15 in 2014. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2014	Pea	Wellsite	1.0	68.9	11.0	698	9.0×10^{-3}
		Reference Area	1.3	70.7	13.3	727	
		Entire Field	261.1	59.7	20.5	150156	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.19 SITE 15 – 2015

A summary of the crop yield data, collected in 2015, for Site 15 including the wellsite and reference area is provided in Figure 20. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 20.

4.19.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average canola yield was found to be statistically different between the wellsite and reference area ($p = 1.3 \times 10^{-39}$). Comparisons were not made between the wellsite and the entire field.

During harvest, the combine paths were consistent across the wellsite and reference area (Figure 20c). The highest average crop yield was observed in the center of the wellsite; however, values were still within the range of those observed across the entire field (Figure 20a). The lowest average crop yield on the wellsite and reference area was 45.4 and 40.1 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 62.0 and 53.4 bu/acre, respectively (Figure 20b). Therefore, the crop harvest was, on average, significantly lower in the reference area than on the wellsite.

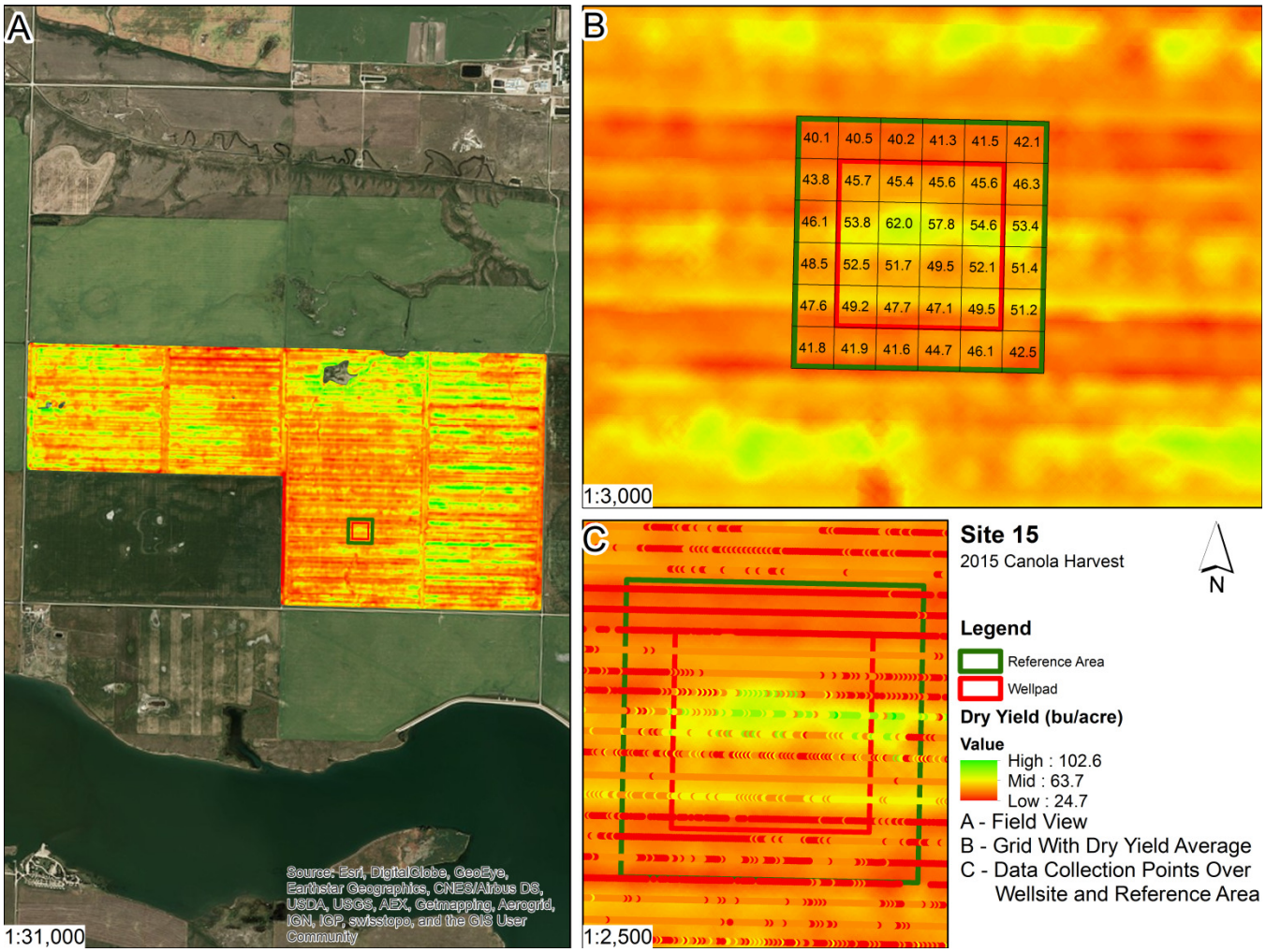

Figure 20: Site 15 dry yield canola harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 20: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 15 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Canola	Wellsite	1.0	50.1	7.9	837	1.3×10^{-39}
		Reference Area	1.3	45.6	6.2	934	
		Entire Field	388.8	52.3	11.1	293481	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.20 SITE 16 – 2013

A summary of the crop yield data, collected in 2013, for Site 16 including the wellsite and reference area is provided in Figure 21. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 21.

4.20.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield data was found to be statistically different between the wellsite and reference area ($p = 3.8 \times 10^{-19}$). Comparisons were not made between the wellsite and the entire field.

Non-continuous harvest transects occurred over the wellsite and reference area (Figure 21c), likely influencing the statistical analysis. The lowest average crop yield on the wellsite and reference area was 51.0 and 57.0 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 79.6 and 83.2 bu/acre, respectively (Figure 21b).

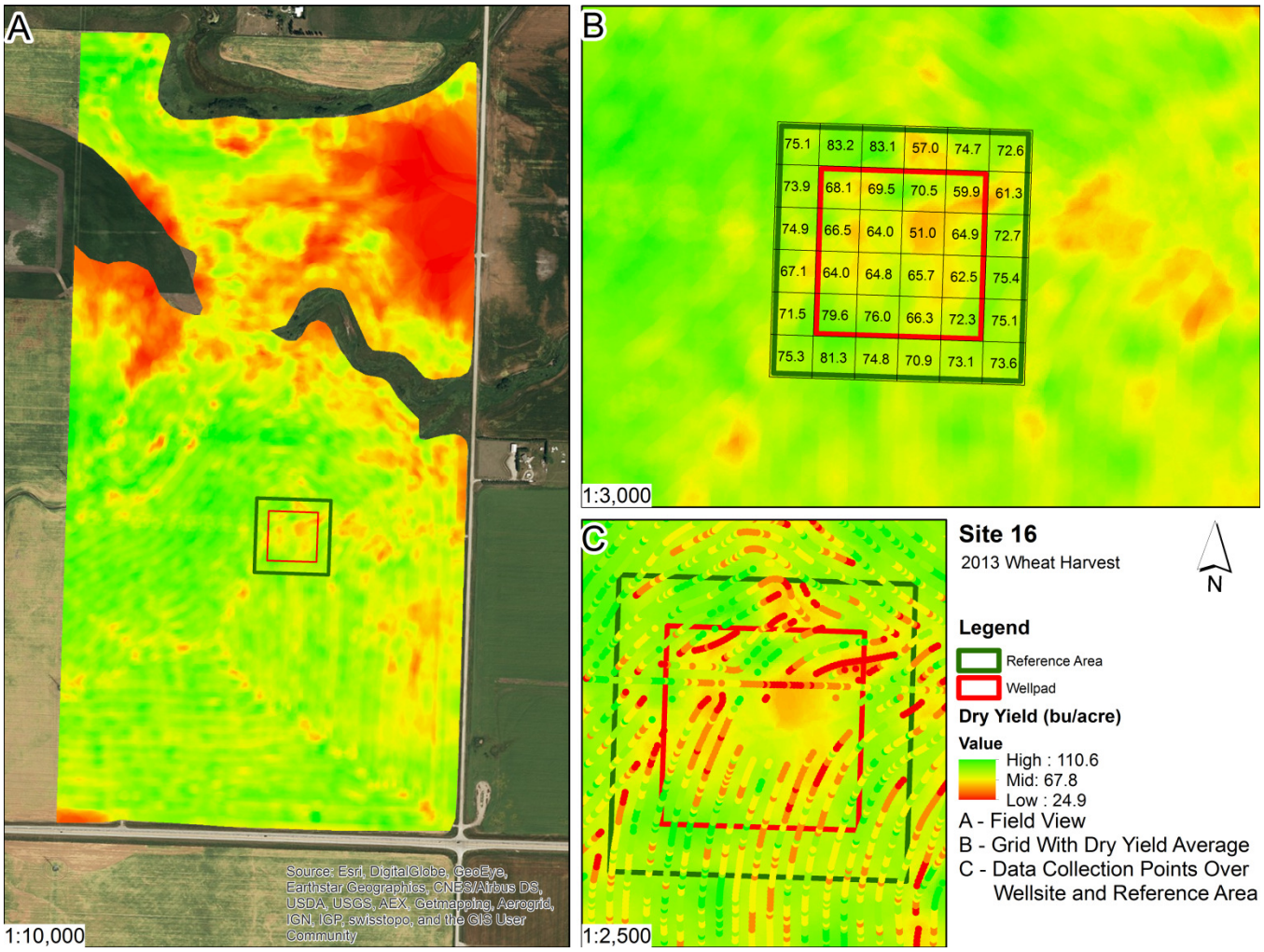

Figure 21: Site 16 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 21: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 16 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	67.3	13.4	511	3.8×10^{-19}
		Reference Area	1.3	73.1	12.2	787	
		Entire Field	112.4	69.9	15.5	55803	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.21 SITE 16 – 2015

A summary of the crop yield data, collected in 2015, for Site 16 including the wellsite and reference area is provided in Figure 22. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 22.

4.21.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 2.3 \times 10^{-2}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was found near the centre of the wellsite (Figure 22c); however, these values were still within the range of those observed across the field. It is important to note that the crop harvest paths were not consistent and/or continuous across the field. The non-continuous harvest transects may have led to erroneous yield data.

The lowest average crop yield on the wellsite and reference area was 46.5 and 56.4 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 81.1 and 79.5 bu/acre, respectively (Figure 22b).

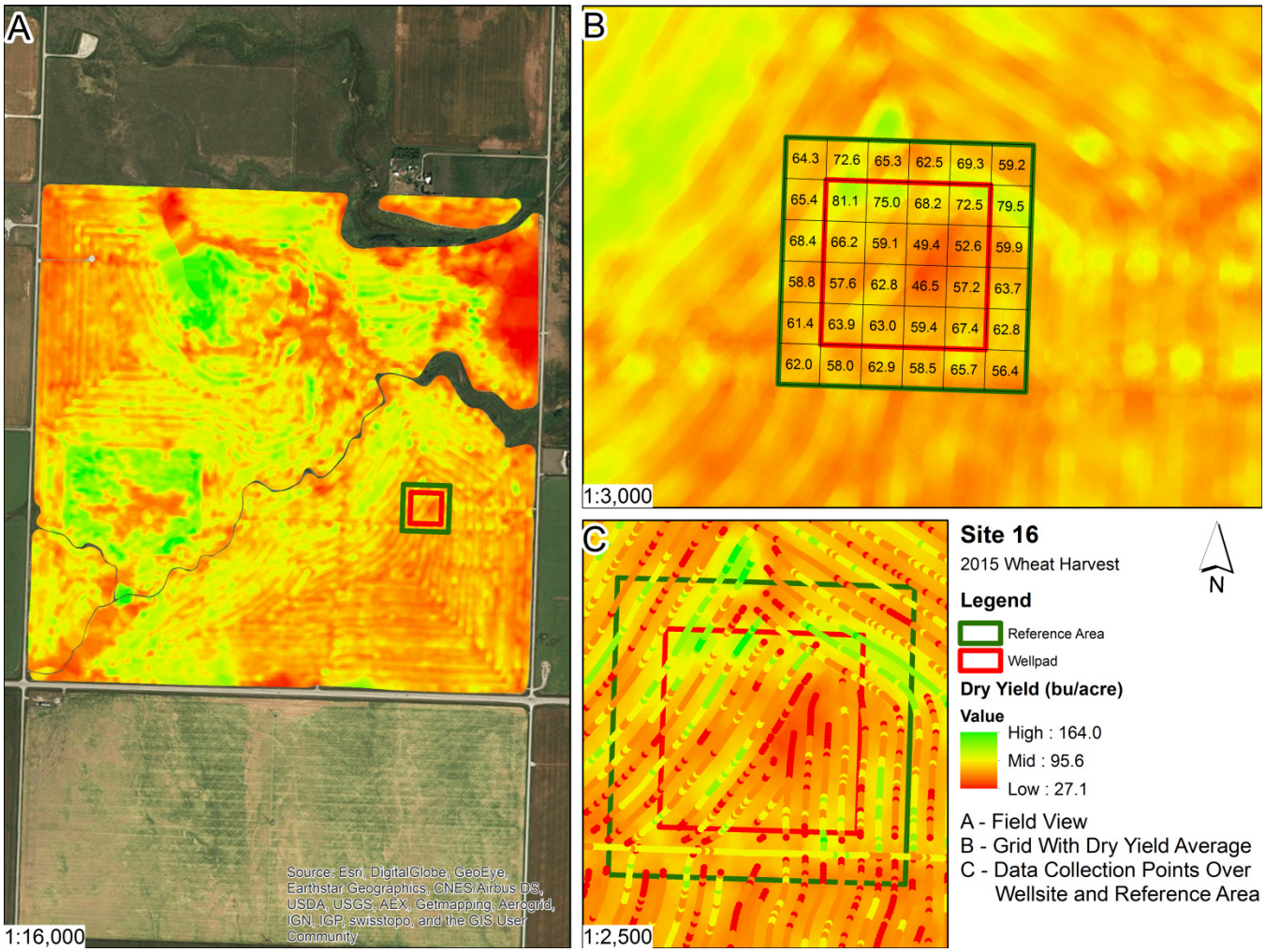

Figure 22: Site 16 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 22: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 16 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	62.8	14.8	582	2.3×10^{-2}
		Reference Area	1.3	63.8	13.5	720	
		Entire Field	248.0	70.3	18.1	180587	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.22 SITE 17 – 2015

A summary of the crop yield data, collected in 2015, for Site 17 including the wellsite and reference area is provided in Figure 23. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 23.

4.22.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 2.4 \times 10^{-2}$). Comparisons were not made between the wellsite and the entire field.

Crop yields were similar between the wellsite and the reference area, consistent with those values found across the entire field (Figure 23a). The lowest average crop yield on the wellsite and reference area was 52.5 and 48.1 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 58.9 and 61.9 bu/acre, respectively (Figure 23b).

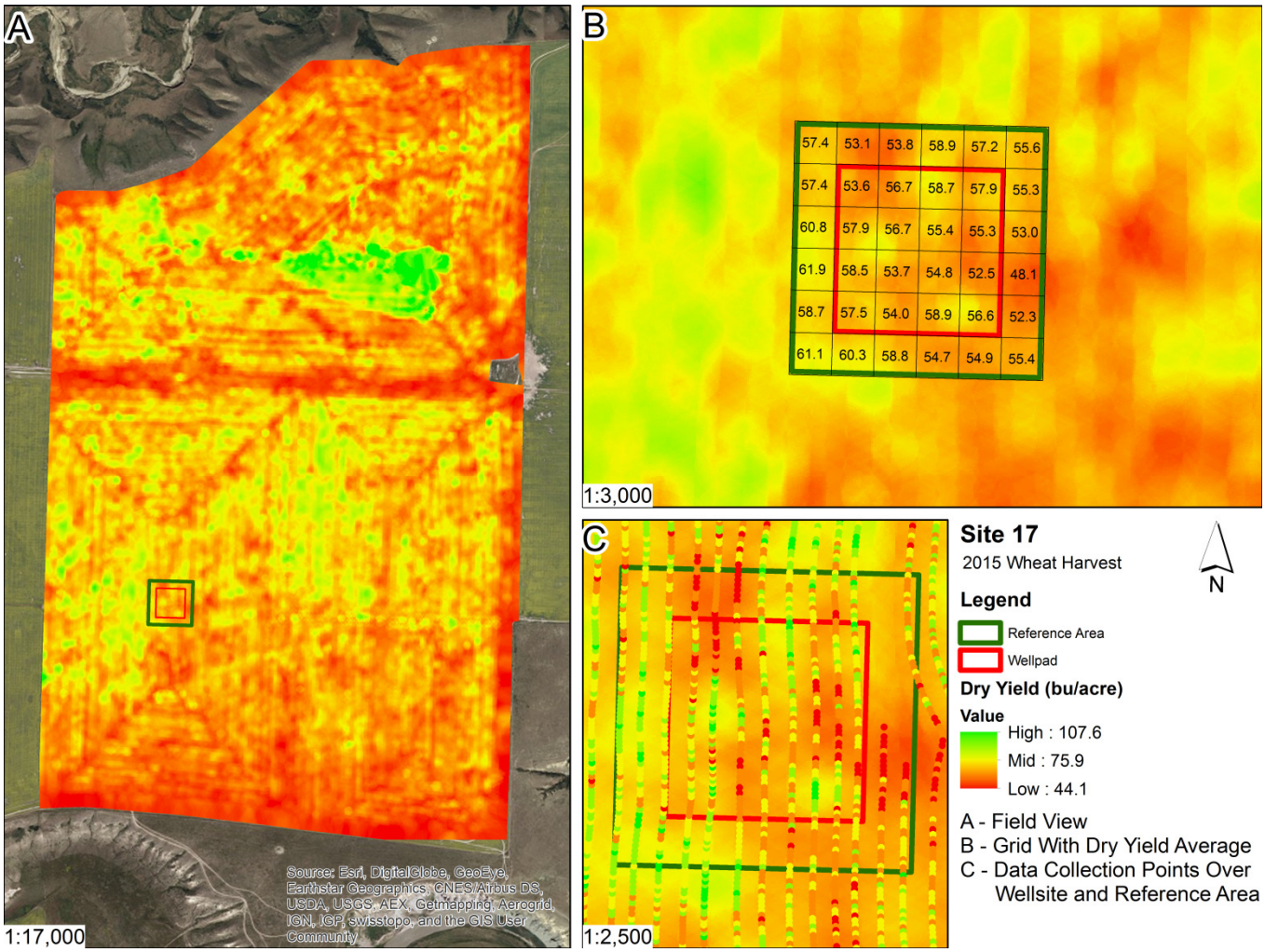

Figure 23: Site 17 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 23: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 17 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	56.3	5.5	369	2.4×10^{-2}
		Reference Area	1.3	56.9	4.8	452	
		Entire Field	400.5	56.5	7.3	133831	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.23 SITE 21 – 2013

A summary of the crop yield data, collected in 2013, for Site 21 including the wellsite and reference area is provided in Figure 24. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 24.

4.23.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), analysis, average crop yield was found to be statistically different between the wellsite and reference area (p = 2.8x10^{-9}). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was associated with the south eastern portion of the wellsite; however, these values were still within the range of those observed across the entire field (Figure 24a).

The wellsite and reference area crossed over to another field; crop harvest data were only available for the western part of the field. As a result, some grid squares on the eastern part of the wellsite and reference area do not have harvest data available resulting in incomplete crop harvest data (Figures 24a, b, c).

In the areas with yield data collected, the lowest average crop yield on the wellsite and reference area was 46.5 and 54.2 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 70.4 and 81.7 bu/acre, respectively (Figure 24b).

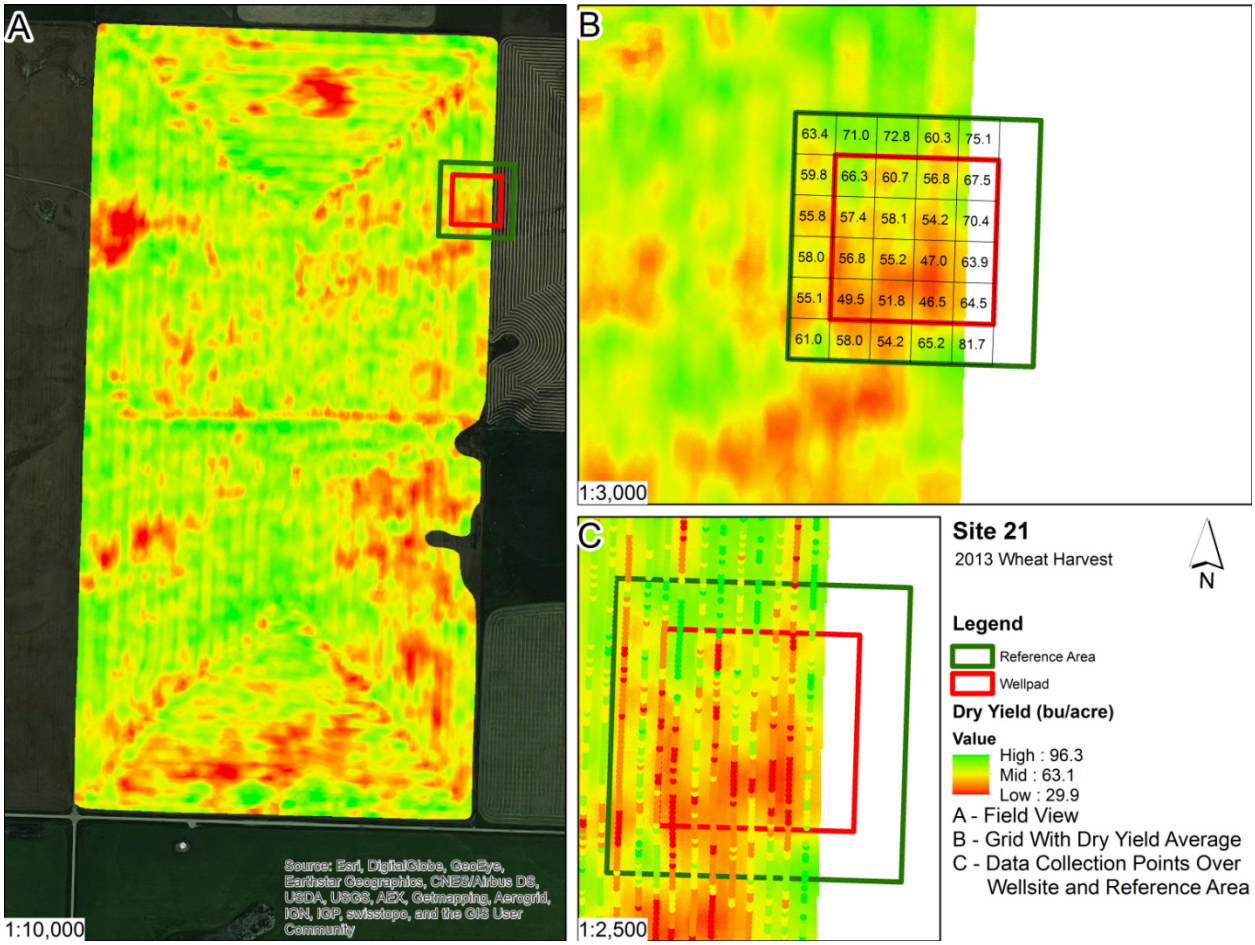

Figure 24: Site 21 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 24: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 21 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	57.0	10.1	360	2.8×10^{-9}
		Reference Area	1.3	62.1	11.2	336	
		Entire Field	128.7	63.4	10.9	57177	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.24 SITE 22 – 2015

A summary of the crop yield data, collected in 2015, for Site 22 including the wellsite and reference area is provided in Figure 25. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 25.

4.24.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), average crop yield was found to be statistically different between the wellsite and reference area ($p = 1.4 \times 10^{-14}$). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was associated with most of the western part of the wellsite; however, these values were still within the range of (and even higher than) those observed across the entire field (Figure 25a).

The lowest average crop yield on the wellsite and reference area was 31.2 and 36.4 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 47.5 and 45.6 bu/acre, respectively (Figure 25b).

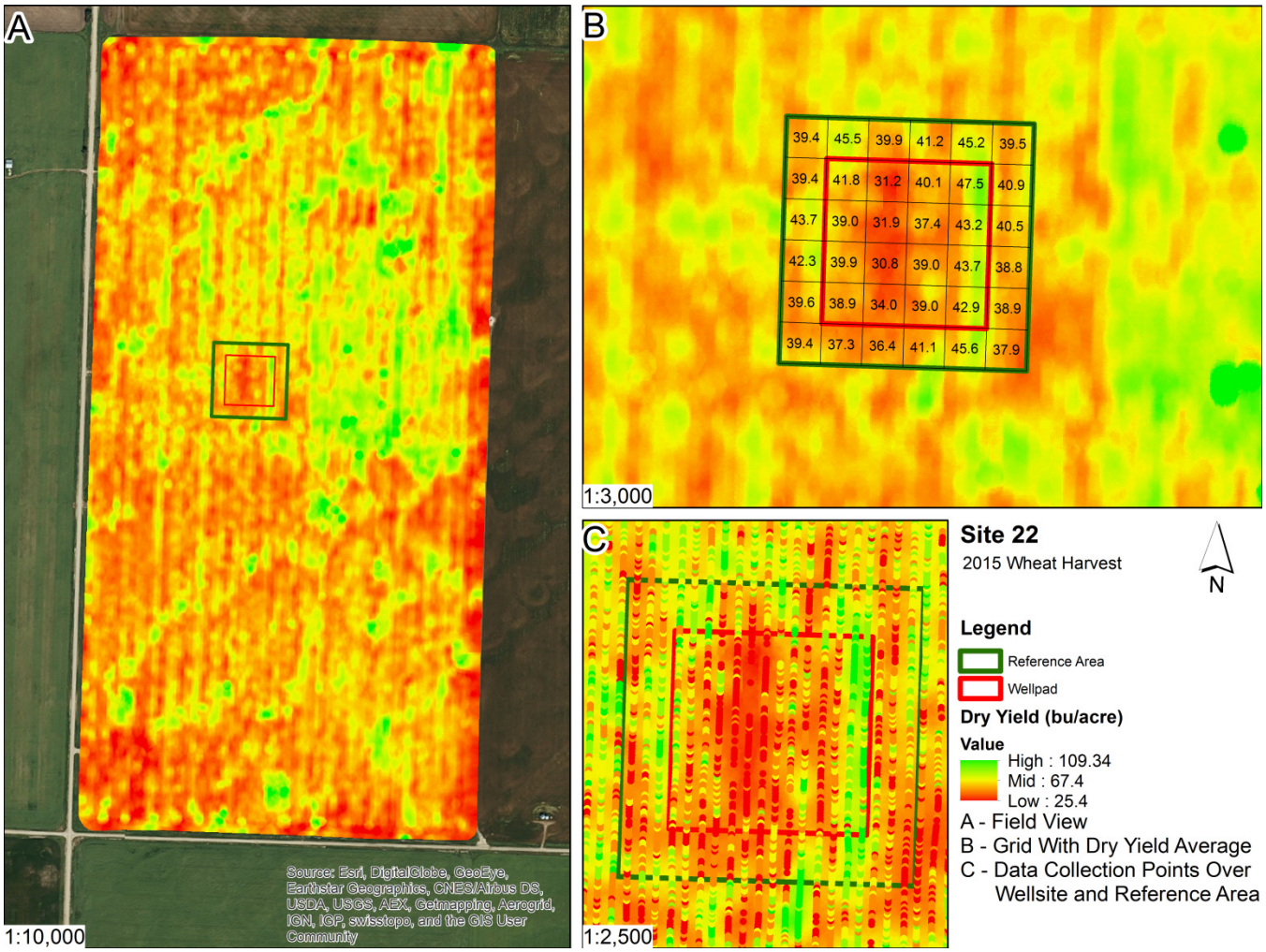

Figure 25: Site 22 dry yield wheat harvest data from 2015. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 25: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 22 in 2015. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2015	Wheat	Wellsite	1.0	84.9	15.6	616	1.4×10^{-14}
		Reference Area	1.3	90.6	14.6	758	
		Entire Field	318.6	51.6	9.7	28412	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

4.25 SITE 24 – 2013

A summary of the crop yield data, collected in 2013, for Site 24 including the wellsite and reference area is provided in Figure 26. A summary of the crop type and average crop yield for the wellsite and reference area is provided in Table 26.

4.25.1 Wellsite and Reference Area Comparison

Based on the comparison between the wellsite and reference area only (as defined in *Section 3.3*), analysis, average crop yield was found to be statistically different between the wellsite and reference area (p = 5.0x10^{-10}). Comparisons were not made between the wellsite and the entire field.

The lowest average crop yield was associated with the southern area of the wellsite; however, these values were still within the range of those observed across the entire field (Figure 26a).

The wellsite and reference area intersects two quarter section fields in a west-to-east direction, resulting in non-continuous harvest transects (Figure 26c). This may have caused errors in the crop yield data collected and resulted in artifacts in the Kriging interpolation and resulting data analysis.

The lowest average crop yield on the wellsite and reference area was 53.6 and 51.6 bu/acre, respectively. Conversely, the highest average crop yield on the wellsite and reference area was 64.7 and 73.0 bu/acre, respectively (Figure 26b).

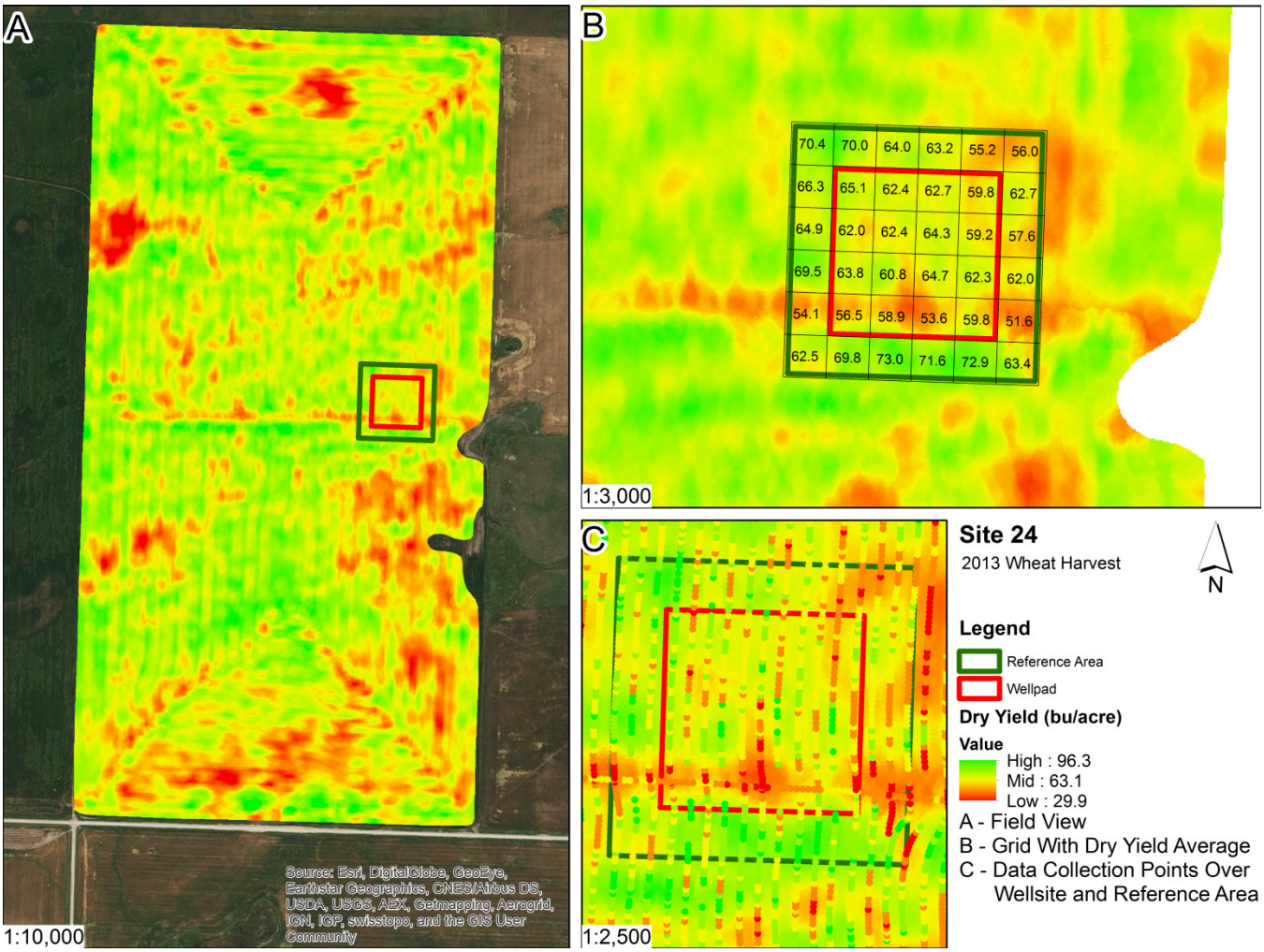

Figure 26: Site 24 dry yield wheat harvest data from 2013. Views A (*Field View*), B (*Grid with Dry Yield View*), and C (*Data Collection Points over Wellsite and Reference Areas View*) indicate the wellsite area (red square) and the reference area (green square) area. Colours represent the range of crop yield in bushels per acre (bu/acre). The numbers within the grids in View B are an average of crop yield (bu/acre) within each grid.

Table 26: Summary of average crop yield harvest data, in bushels per acre (bu/acre), for the wellsite, reference area, and the entire field at Site 24 in 2013. Statistical significance was evaluated between the wellsite and reference area.

Year	Crop	Location	Area (ha)	Average Crop Yield (bu/acre)	Standard Deviation (bu/acre)	# data points (n)	Significance p-value
2013	Wheat	Wellsite	1.0	57.0	10.1	360	5.0×10^{-10}
		Reference Area	1.3	62.1	11.2	336	
		Entire Field	128.7	63.4	10.9	57177	N/A

Note: The wellsite and reference area compared in terms of significance, in this study, are smaller in size than the entire field; the wellsite area is smaller than the reference area.
N/A = not applicable

5.0 CONCLUSIONS

Key learnings from this study included the following:

- Wellsite and reference area comparisons, if analyzed alone, can provide very different results than a comparison between a wellsite and an entire field. Such analyses should be considered in future assessments, including the incorporation into a long-term monitoring project. The definition of a reference area, in terms of size and location, should also be considered.
- The statistical significance of average crop yield on a wellsite, in comparison to the prescribed reference area, may not be meaningful, in terms of the grand scheme of farming. A long-term monitoring plan should consider whether the assessment impacts, limits, changes, or influences the end land use.
- Many of the sites assessed exhibited data problems for a variety of reasons (i.e., the wellsite was too close to a road, the wellsite crossed over fields with different crop types, the combine harvest pattern was incomplete or inconsistent across the wellsite). As a result, the tool may not be reliable if sites are not selected appropriately for the tool, and communication is not conducted with the farmers to ensure that data is collected appropriately for the assessment. A summary of parameters that influence data sets is provided in Table 27.

Table 27: Summary of those parameters that influence crop yield harvest data sets.

Parameter	
Good Data (Ideal)	**Poor Data**
• Site is on level ground, in terms of elevation • Harvest pattern is continuous and in straight lines, at an even swath width and velocity across the assessment area • Farmer did not apply fertilizer during the assessment year • Harvest combine is calibrated prior to use or when required during use (i.e., moisture sensor, swath width, etc.) • Crop is free of disease and/or pest impacts during the assessment year • Crops have not been impacted by major climate and/or weather conditions during the assessment year • No surface stones within the assessment area • No obstacles (i.e., creek, ephemeral wetland, etc.) across the assessment area	• Site is uneven or sloped, in terms of elevation, or there is uneven relief • Harvest pattern is discontinuous (e.g., start and stop, change direction, or interface with other harvest paths) across the assessment area • Farmer applied fertilizer to low productivity areas during the assessment year • Harvest combine is not calibrated prior to use or when required during use (i.e., moisture sensor, swath width, etc.) • Crop is impacted by disease or pests during the assessment year • Crops have been impacted by major climate and/or weather conditions during the assessment year • Surface stones within the assessment area • Obstacles (i.e., creek, ephemeral wetland, etc.) within the assessment area

Overall, this study showed that crop yield maps have the capacity to provide valuable information on annual field performance, allowing users to easily assess the range in crop productivity across a field.

On the data collection side, crop harvest mapping largely depends on quality harvest data, especially over the disturbed location[3] and reference areas. Ideally, harvest data should be collected in continuous straight paths, with an even swath width, and uniform velocity. In an ideal scenario, the mapped area should be uniform in topography, to prevent the harvest machine from altering course, slowing or stopping (Table 27). Changes in elevation can also lead to moisture and solar radiation gradients, which can affect crop yield data. Harvesting in a double-back[4] pattern can help ensure data quality, as it is expected that the harvesting machine (e.g., combine) can produce a level of pass-to-pass harvest data repeatability. Although this may not be feasible or realistic for harvesting an entire field, it may be worthwhile for harvesting over the area where good quality data is required to inform on site assessment and decision-making.

Comparing crop yield data for the same field from different growing years is only valid if the field was planted with the same crop (preferably the same variety), the field experienced similar annual climate conditions, and the field was managed by the farmer similarly. For example, comparing the same crop that experienced drought conditions one year and normal conditions on another year may not be preferable. In addition, if a farmer applied fertilizer to low productivity areas, it may additionally influence data interpretation. Furthermore, crop yield data should be collected in a similar fashion in order to compare data points more accurately against each other. As a result, a one-time assessment of a cultivated site may not be appropriate for a long-term monitoring program where crop type, farm management, and seasonality can influence data interpretation.

On the data analysis and interpretation side, experience in data cleaning and data interpretation was identified to be essential for producing accurate maps and for comparing crop yield data across a site. To do this, site, climate and farm management history is critical to avoid drawing ill-informed conclusions caused by confounding factors (e.g., soil organic matter differences as a result of landform positions, soil moisture deficits, disease, weed infestation etc.). Without detailed crop harvest methodology and site conditions, it is difficult to determine relationships between a disturbed area and reference area. To improve interpretation of the crop yield data, it is recommended that maps are incorporated, layered or placed side-by-side with soil specific maps or data (e.g., tabulated, etc.) to ensure that conclusions are validated by other sources of information. Types of information that would be valuable for this type of assessment are included in Table 28.

Table 28: Summary of information that may be complementary to the crop yield data useful for validating trends in crop productivity on cultivated sites.

Information Type	Availability	Cost Range
Topography	Readily available	Low
Precipitation	Readily available	Free
Soil moisture	Survey required	High
Soil bulk density	Survey required	High
Soil nutrients	Survey required	High

[3]In this study the disturbed area was a certified reclaimed wellsite.

[4]A 'double-back pattern refers to leaving every odd pass to be harvested after every even pass has been harvested. This allows for comparison between adjacent passes over time which helps to ensure pass-to-pass repeatability. This can also assist in the identification of calibration issues with the combine.

Information Type	Availability	Cost Range
Soil series	Readily available	Free
Fertilizer application history	Farmer dependent	Free
Land management history	Farmer dependent	Free
Crop history	Farmer dependent	Free
Disease, weed and pest information	Farmer dependent	Free

Those soil indicators measured in the ERM pilot program (Degenhardt et al., 2016) that may also be suitable for comparison to crop yield include: soil bulk density, electrical conductivity, pH, total nitrogen, and total organic carbon. Without this type of information, conclusions on the ecological recovery, solely based on crop yield, should not be made at smaller scales on a field (i.e., between a disturbed area and reference area). By including this data in the assessment, crop yield maps may have the capacity to be used along with other indicators to inform on the status of ecological recovery of wellsites on cultivated land.

For this project, the cost of producing the crop yield maps for 24 sites, including code development, data cleaning, ArcGIS image preparation, and statistics was roughly $10,000. Costs do not include data interpretation and reporting. Costs can be lowered by following a data cleaning algorithm in Excel (or other). Costs may be further reduced by investing in the creation of a data cleaning script, acquiring the history of the data, and repeating the analysis on the same sites for multiple years.

6.0 REFERENCES

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