Final Report

Impact of land rolling on grain and silage production in cereal crops under irrigated conditions in southern Alberta

Project Overview

The study, based on a robust 9-site-year dataset, revealed clear and consistent effects of rolling timing on crop health, particularly at the Zadock's growth stage Z23-25 (3-5 tiller) and Z32 (2 node) stages. Rolling did not influence tillering in barley or wheat, disproving the hypothesis that later rolling increases tillering. Plant counts showed no significant differences in wheat, however barley exhibited slightly reduced stands when rolled at the 2-3 leaf stage. Rolling at the 3-5 tiller and 2 node stages significantly reduced plant height and increased lodging, particularly in barley, which also experienced greater silage and grain yield losses compared to wheat. Silage yield decreased by 0.8-2.2 MT/acre for barley and 0.4-1.4 MT/acre for wheat when rolled at 3-5 tiller and 2 node stages, with grain yield reductions of 17 bu/acre for barley and 13.4 bu/acre for wheat at the 2 node stage. While grain weight remained unaffected, silage protein and Net Energy for Gain (NEG) improved numerically at later rolling stages, likely due to stress responses. However, these benefits were overshadowed by significant increases in ergot seed disease and yield losses. Visual observations noted stem bending, tiller damage, and lodging, particularly at the 2 node stage, which could hinder harvest efficiency. In general, we did not find any positive agronomic reasons to roll at the 2 node stage. Soil compaction data were inconclusive, with factors like soil moisture and time since soil disturbance appears more influential than rolling timing. There was no interaction between tillage and rolling stage that impacted crop yield or quality, although tillage impacted early development.

Overall, rolling during the early tillering stages, before node formation, is recommended to minimize crop damage and yield losses while maintaining soil health. Knowing this, farmers can confidently prioritize rolling their fields among other operations, regardless of their tillage system.

Project Details

Project Team

Dr. Gurbir Dhillon – Former Research Scientist

Gurbir provided scientific oversight for trial design development, overseeing initiation of the trial in 2022. He oversaw all trial activity management throughout 2022 and 2023, including interim progress and financial reporting. Data management and analysis, utilizing statistical methods and report writing, were key activities he conducted. Gurbir's contributions laid a solid foundation for the subsequent phases of the project. He departed Farming Smarter in winter 2024.

Dr. Thierry Fonville – Research Scientist

Thierry joined Farming Smarter in early spring 2024, assuming scientific oversight from Gurbir. He continued the established protocols and oversaw trial management activities in 2024, working closely with all team members. He ensured rigorous scientific methods were applied to data management, analysis, and report writing, maintaining the project's high standards.

Ken Coles – Executive Director

Ken provided executive management for all trial activities, ensuring adherence to strict scientific methods and standard practices. He secured necessary resources, including staff, equipment, supplies, and land, enabling successful research execution. He also managed project logistics, including scheduling, financial tracking, and reporting, ensuring the project remained on budget and on schedule.

Jamie Puchinger – Assistant Manager

Jamie Puchinger disseminated key findings to farmers and agronomists through various channels. Her Knowledge and Network team created news posts, managed social media, planned presentations, and maintained a dedicated project website. She also assisted Ken with general oversight of trial activities and standard practices, ensuring effective project communication.

Trevor Deering – Research Associate

Trevor contributed to the two-year study funded by George Lubberts (2020 and 2021), which served as the foundation for this larger study. He played a key role in assisting the implementation of the project, from trial design and preparation to seeding, trial maintenance, data collection, analysis, report writing, and presenting results at field events and conferences.

Mike Gretzinger – Research Coordinator

Mike worked closely with the team, assisting with trial management activities similar to Trevor and Carlo, ensuring timely execution and high-quality results. His efforts helped maintain the project's momentum and adherence to established protocols.

Carlo Van Herk – Field Operations Lead

Carlo was integral to the research team, ensuring all trial management activities were executed effectively. He managed supply readiness, seeding, pesticide applications, mowing, data collection, simple data analysis, harvest, and seed testing/grading, contributing to the project's overall success. Carlo also presented results at the Soils and Crops conference in Saskatoon in Winter of 2025.

Toby Mandel – Shop Manager

Toby ensured all equipment, including seeders, irrigation systems, tractors, rollers, and sprayers, was in optimal working order, minimizing downtime and maximizing trial efficiency. His contribution was crucial to the project's smooth operation.

Abbreviations

ac – Acre

AFSC – Agriculture Financial Services Corporation

Bu – Bushel

MT – Metric Ton (Tonne)

NEG – Net Energy for Growth

RCBD – Randomized Complete Block Design

SWS – Soft White Wheat

UTC – Untreated Check

Z – Zadock's growth stage

Background

Land rolling is vital for southern Alberta's wheat and barley silage industry. While pulse rolling data exists (Olson et al. 2004), wheat and barley data was lacking. This study determined best practices to maximize harvest ease while minimizing crop damage, considering irrigation and soil properties. This project, initiated by agronomy consultant requests, built upon a preliminary study that led to increased site years resulting in a robust dataset, tested two tillage systems, tested soft white wheat & barley, and adjusted rolling timing treatments, based on observed trends and expert input. No major modifications were made to the trial; however, a few minor methodology changes were adapted.

- Plots were seeded 14m long in 2022 and 12m long in 2023 and 2024 to better suit maintenance sprayer width, for optimal pesticide applications.

- Rolling was usually conducted in the morning; however, it was sometimes performed later in the afternoon if logistically necessary.
- Tillers per plant, of 5 plants per plot, were counted at the soft dough stage, when conducting the silage biomass sampling, not earlier.
- Soil moisture was measured in 1 untreated plot in wheat and barley at each rolling timing to assess soil moisture, in case rolling was conducted when the soil was too wet and caused excess damage to the crops. Soil moisture was not an issue and doesn't seem to have been a major factor that was influenced by rolling.
- Relative humidity was not recorded, as it was deemed to be a non-important measurement from day one of implementing the study.

Project Objectives:

- Determine the effect of rolling timing (seeding, Z07, Z12-13, Z23-25, Z32) on crop growth, silage & grain yield & quality, and soil quality.
- Compare rolling effects on crop growth and soil properties in zero-tilled and conventionally tilled systems.

Long-term Objective:

- Reduce crop injury and soil erosion, enhancing productivity and soil health through optimized rolling practices.

Deliverables:

Information on optimal rolling timing for irrigated wheat and barley under zero and conventional tillage.

- Nine research trials (3 locations x 3 years) with data collection.
- Annual interim and final reports with data, analysis, and recommendations.
- Peer-reviewed publication (Canadian Journal of Plant Science/Agronomy) and four conference/producer presentations.
- Knowledge transfer through field events, media, and social media.

Performance Measures:

- Industry partners: 1 (Complete Agronomic Services Inc.)
- Public partners: 2 (Alberta wheat/barley commissions)
- Trained personnel: 5-15 summer staff
- Publications/presentations: 1+ publication, 4+ presentations, 4+ plot walks
- Knowledge transfer products: 20+ updates
- Event participants: ~1000 attendees.

Research design and methodology

Land rolling is a common management practice in forage crop production. This project focuses on the southern Alberta region, where the majority of irrigated forage production occurs. Small-plot research trials (~2.5m x 12m) were conducted under irrigated conditions at three sites in southern Alberta over three growing seasons (2022–2024). Sites included locations at Lethbridge, Bow Island, Stirling, and Barons, selected to represent different soil textures on other soil properties, because the effects of rolling on soil moisture, compaction, and plant growth may vary with soil properties according to Tong et al. (2015).

The trials utilized a randomized complete block design (RCBD) for both wheat and barley. The cultivars Sadash (SWS) for wheat and CDC Austenson for barley were used, because they are widely grown for silage production in Alberta. Both crops were seeded at a target rate of 350 seeds/m^2. Land rolling was performed parallel to the seed rows at a speed of approximately 13 km/h, with a ground pressure of approximately 819 kg/m (~550 lb/ft), achieved by adding water to the roller. These practices reflected common regional practices.

The study included two main treatments:
Timing of Rolling: Five crop stages

a) Immediately after seeding (0–1 day after seeding),
b) Coleoptile emergence (Z07),
c) 2–3 leaf stage (Z12–13),
d) 3–5 tiller stage (Z23–25), and
e) Second node detectable stage (Z32).

Tillage System: Two systems were evaluated—zero tillage and conventional tillage.
This resulted in 12 treatments per crop (24 treatments total), as outlined below:

1. Untreated control – Zero tillage
2. Untreated control – Conventional tillage
3. Rolling following seeding – Zero tillage
4. Rolling following seeding – Conventional tillage
5. Rolling at coleoptile emergence (Z07) – Zero tillage
6. Rolling at coleoptile emergence (Z07) – Conventional tillage
7. Rolling at 2–3 leaf stage (Z12–13) – Zero tillage
8. Rolling at 2–3 leaf stage (Z12–13) – Conventional tillage
9. Rolling at 3–5 tiller stage (Z23–25) – Zero tillage
10. Rolling at 3–5 tiller stage (Z23–25) – Conventional tillage
11. Rolling at second node detectable stage (Z32) – Zero tillage
12. Rolling at second node detectable stage (Z32) – Conventional tillage

Measurements

Crop establishment, growth, and yield metrics were measured for both wheat and barley:

a) Emergence (%): Determined by plant counts in two 1-m rows per plot at the 3–5 leaf stage (Z13–15).
b) Plant Injury, Disease Incidence, and Lodging (if present): Notes were taken of visual plant injury post-rolling when injury was present, disease incidence (heading), and lodging before harvest.
c) Tillers per Plant: Five random plants per plot were sampled at soft dough stage (Z85).
d) Plant count @ maturity: to assess plant mortality due to rolling at 3-5 tiller and 2 node stages.
e) Plant Height at Maturity: Measured from the front, middle, and back of each plot before harvest.
f) Biomass: Harvested at the soft-dough stage (Z85) from two 1-m rows in the front and back of each plot for a full 1m2 sample. Subsamples were sent to Down to Earth Labs for feed value testing.
g) Grain Yield and Quality: Yield was measured using a combine harvest master system. Quality parameters (1000-kernel weight, protein content, and seed grade) were assessed post-harvest.
h) Soil moisture measured by using the gravimetric method up to 15 cm depth. Soil moisture measurement done at the time of rolling in one untreated plot to corroborate the visual assessment of appropriate rolling timing, to ensure the soil was not too wet.
i) Soil Penetration Resistance: Recorded using a penetrometer at 0–7.5 cm and 7.5–15 cm depths immediately after rolling and 7 days post-rolling.

Statistical Analysis

Data was analyzed using linear models in R. The significance of rolling timing, tillage system, and their interactions were tested as fixed factors. Significant interactions between factors, specifically site years were assessed and tested separately as needed. Tukey's mean separation was used to identify significant differences between treatments when the ANOVA test indicated significant effects. In addition to the linear models, mixed models were run with site-years and replicates as random factors and the same fixed factors as the linear models. However, the mixed models revealed the same pattern as the linear models, and the simpler linear models will be discussed in the results sections.

Results, discussion and conclusions

The robust 9 site year dataset allowed for clear and consistent effects of rolling timing on crop health to be observed, most notably at the Z23-25 (3-5 tiller) and Z32 (2 node) stages. There were 5 main questions that the research team kept in mind throughout the trial period and when analyzing the data, regarding crop responses:

1. Do cereals stool more when rolled at later growth stages?
2. Is plant population improved or reduced due to specific rolling timings?
3. Is plant height at maturity affected?
4. How do silage and grain yield respond to different rolling timings?
5. Were silage and grain quality impacted?

1. Do cereals stool more when rolled at later growth stages?

Evidence clearly shows no increase or decrease in the number of tillers per plant due to rolling barley or wheat at any plant stage (Appendix A, Fig. A.1). We reject the hypothesis that rolling later increases tillering in barley and/or wheat, therefore farmers should not roll later hoping to increase silage yield/biomass. We are aware of a recent unpublished project by the University of Saskatchewan that found an increase in tillering, however in our region of Southern Alberta, we did not find any improved tillering at any rolling timing. There were no significant effects of tillage in both crops, nor was there a significant effect of the interaction between tillage and rolling stage on barley tillering. In wheat, there was a trend ($p=0.09$) towards the interaction between tillage and rolling stage. The highest amount of tillering numerically was under zero tillage and rolling at the coleoptile stage, although we observed a small increase in tillering, the effect is likely inconsequential at the field scale. The combination of zero tillage and rolling at the coleoptile stage was not significantly different from the other treatments.

2. Is plant population improved or reduced due to specific rolling timings?

Plant counts were conducted at the 3-4 leaf stage to assess plant stand and conducted again at soft dough stage to assess plant mortality effects of rolling. For plant stand data analysis, untreated control, 3-5 tiller, and 2 node plant counts were combined into one treatment, the un-rolled treatment. The unrolled treatment was tested against the after seeding, coleoptile, and 2-3 leaf rolling timings for each crop. Wheat showed no statistical difference in plant stand between the treatments, however barley showed statistically lower plants when rolled at the 2-3 leaf stage compared to the coleoptile timing only (Appendix A, Fig. A.2.1). Numerically, rolling after seeding and at the coleoptile stage resulted in slightly more plants per square meter than the un-rolled and 2-3 leaf stage in wheat. Rolling at the 2-3 leaf stage appears to reduce plant stand very slightly in barley and not in wheat. Negative effects to barley plant stand did not carry on to silage or grain yield, with no yield differences. The model indicated no significant effect of tillage but there is an interaction of tillage and rolling stage in barley. In zero tillage, rolling at the coleoptile stage led to higher plant stand than untreated and 2-3 leaf, while in conventional tillage no differences were observed (Appendix A, Fig. A.2.2). In wheat, there was a trend of tillage (p=0.06), with zero till having a lower plant stand on average, but no interaction between rolling stage and tillage (Appendix A, Fig. A.2.3. It is not surprising that the conventional till leads to a higher plant stand, as an improved seedbed preparation is known to increase emergence. Rolling at certain stages might improve seed to soil contact and improve germination when soil is pressed back into the seeding row after rolling.

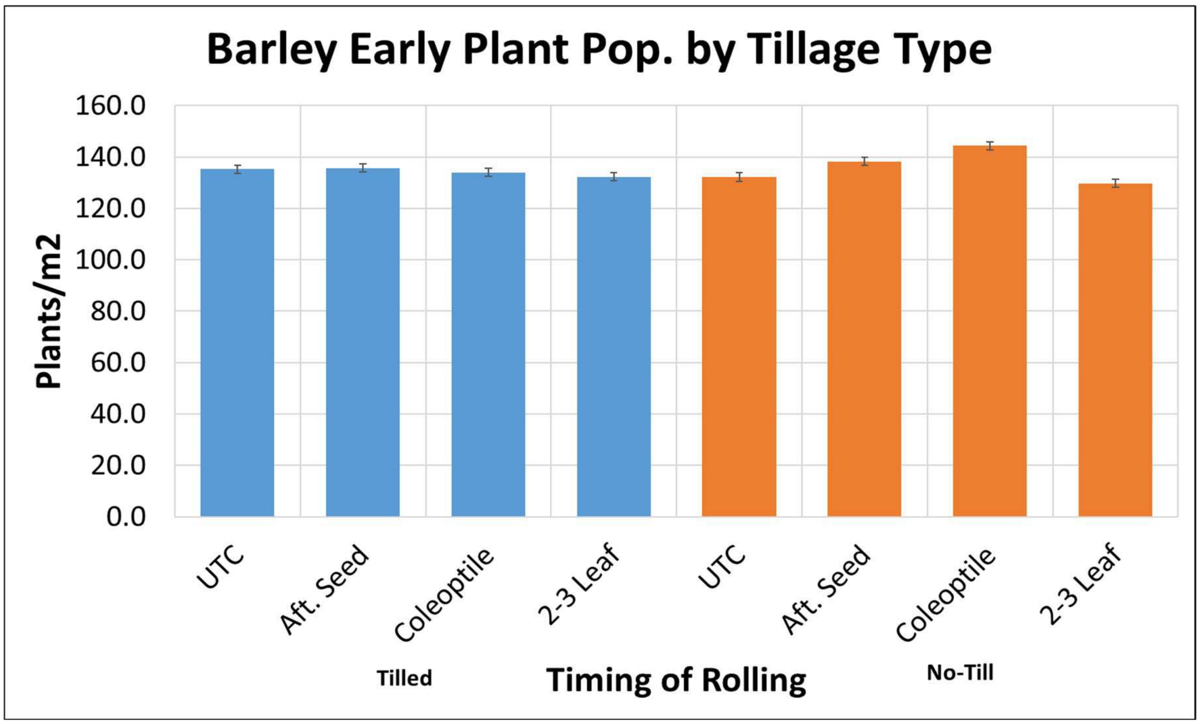

Figure A.2.2: Number of plants per square meter for barley by tillage type, measured around the 3-4 leaf growth stage, and averaged across all site years.

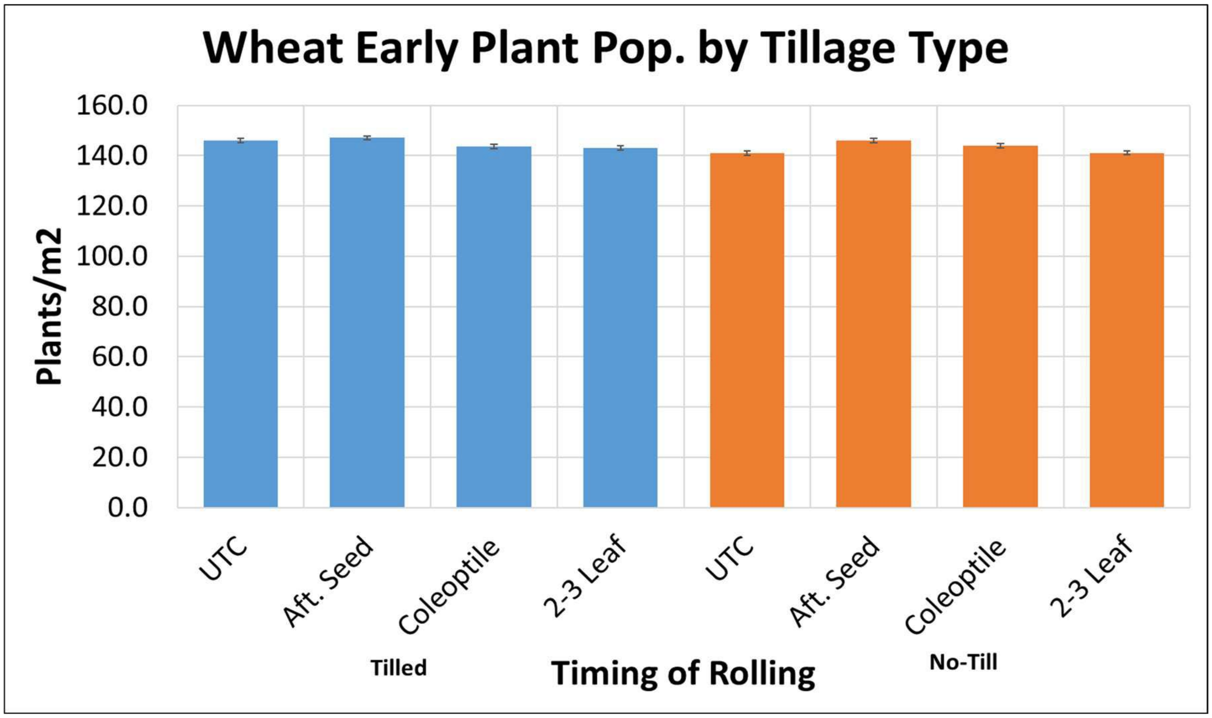

Figure A.2.3: Number of plants per square meter for wheat by tillage type, measure around the 3-4 leaf growth stage, and averaged across all site years.

At the soft dough stage, plants were counted in the untreated, 3-5 tiller, and 2 node rolling timings only, to assess potential mortality that was noted in year one of the study. Plant mortality significantly increased when rolling at the 2 node stage. Barley showed statistically lower plants for the 2 node timing compared to the 3-5 tiller stage. Numerically, rolling at the 2 node stage showed lower plants per square meter compared to the utc and 3-5 tiller stages for both wheat and barley (Appendix A, Fig.A.3). There were no significant tillage effects.

3. Is plant height at maturity affected?

Plant height was clearly reduced when rolling in the 3-5 tiller and 2 node stages for both barley and wheat, with 3-5 tiller being statistically shorter than all treatments except 2 node, and 2 node being statistically shorter than all other treatments (Appendix A, Fig. A.4). The difference in height was around 3-5 cm when rolled at the 3-5 tiller stage and around 5-10 cm when rolled at the 2 node stage. Shortly after rolling, in field visual notes indicated plant stunting (more for the 3-5 tillering rolling timing) and bent over plants that grew at an angle (more for the 2 node stage) as a result of damaged nodes (Appendix A, Image A.1). In barley, there was a significant effect of tillage, with zero tillage crop being about a centimeter shorter (85.6 vs 86.7 cm). In wheat the opposite was observed, with the zero tillage crop one centimeter taller (89.2 vs 88.2 cm). The interaction between tillage and rolling stage was not significant in either crop. In barley the difference could be explained by measurement errors due to soil ridging under conventional tillage, but why wheat had an opposite tillage effect to barley is not entirely clear. Both cereal crops would benefit from increased early soil moisture under zero tillage, though wheat is known to be more drought tolerant. Under zero tillage, crops can have reduced early growth due to lower soil temperatures from residue insulation and reflectance. Our study would suggest that the net effects of increased soil moisture and reduced temperature under zero tillage are not beneficial to wheat height.

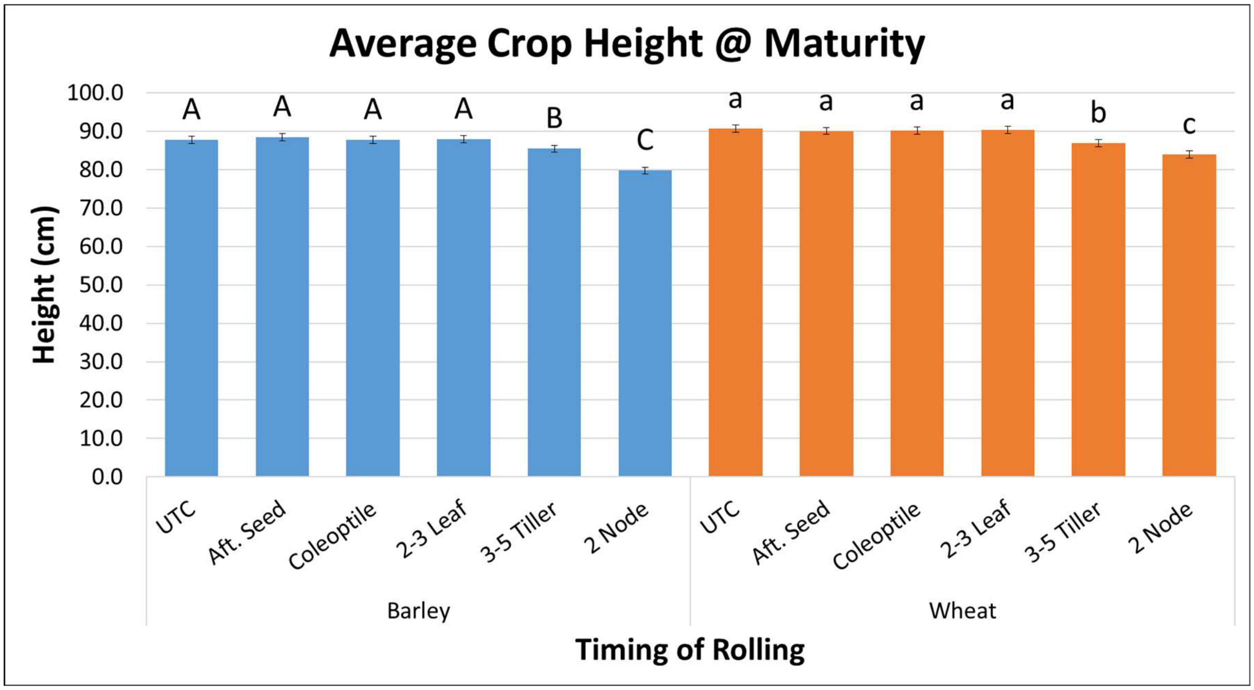

Figure A.4: Crop height at maturity for barley and wheat, averaged across all site years. (Barley $p<0.001$, Wheat $p<0.001$).

Shorter plants or plants that are bent over with biomass nearer the soil surface could be leading factors affecting silage yield. The same or similar impacts that were influencing crop height appear to be impacting the ability of the crop to stand upright. Visual lodging ratings, assessing the percent of a total plot that lodged, were conducted before harvest. Barley and wheat showed increased lodging due to rolling in the 2 node stage, statistically greater than all other timings (Appendix A, Fig. A.5.1). In wheat, rolling at the 3-5 tiller induced slightly more lodging than in the early stages, which was not statistically significant, only numerically (Appendix A, Fig. A.5.2). There was a significant tillage effect in barley, with the conventional tillage having a lower lodging (Appendix A, Fig. A.5.3). The effect of tillage on lodging is well document and associated with poorer root anchoring in zero tillage soils due to reduced root development. In wheat, there was not a significant effect of tillage ($p=0.14$), but there was a trend towards the interaction of tillage and rolling stage ($p=0.08$). For both tillage treatments, only the 2 node had significantly worse lodging than all other treatments. Significant lodging could lead to a decrease in harvest effectiveness leading to less biomass collection and decreased efficiency, leading to decreased revenue and/or increased expenses (wage, equipment, fuel, etc.).

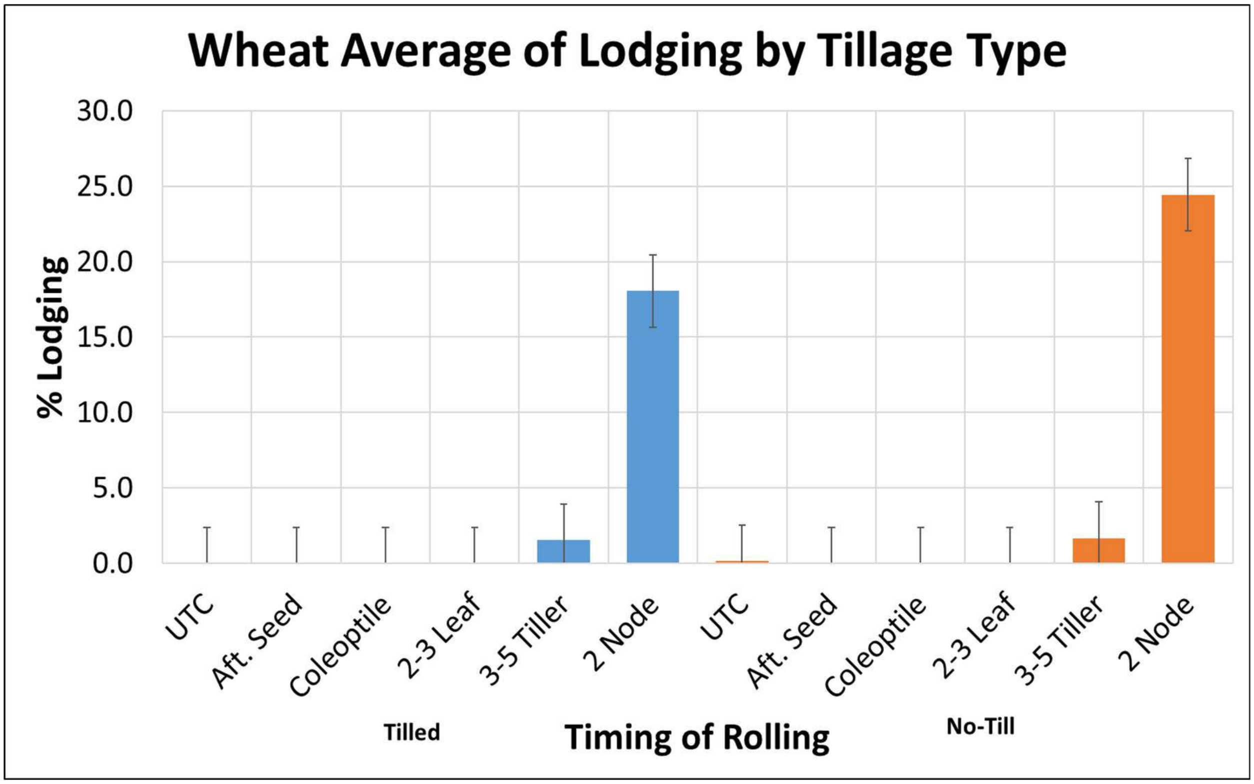

Figure A.5.2: Crop lodging at maturity for wheat by tillage type, averaged across all site years.

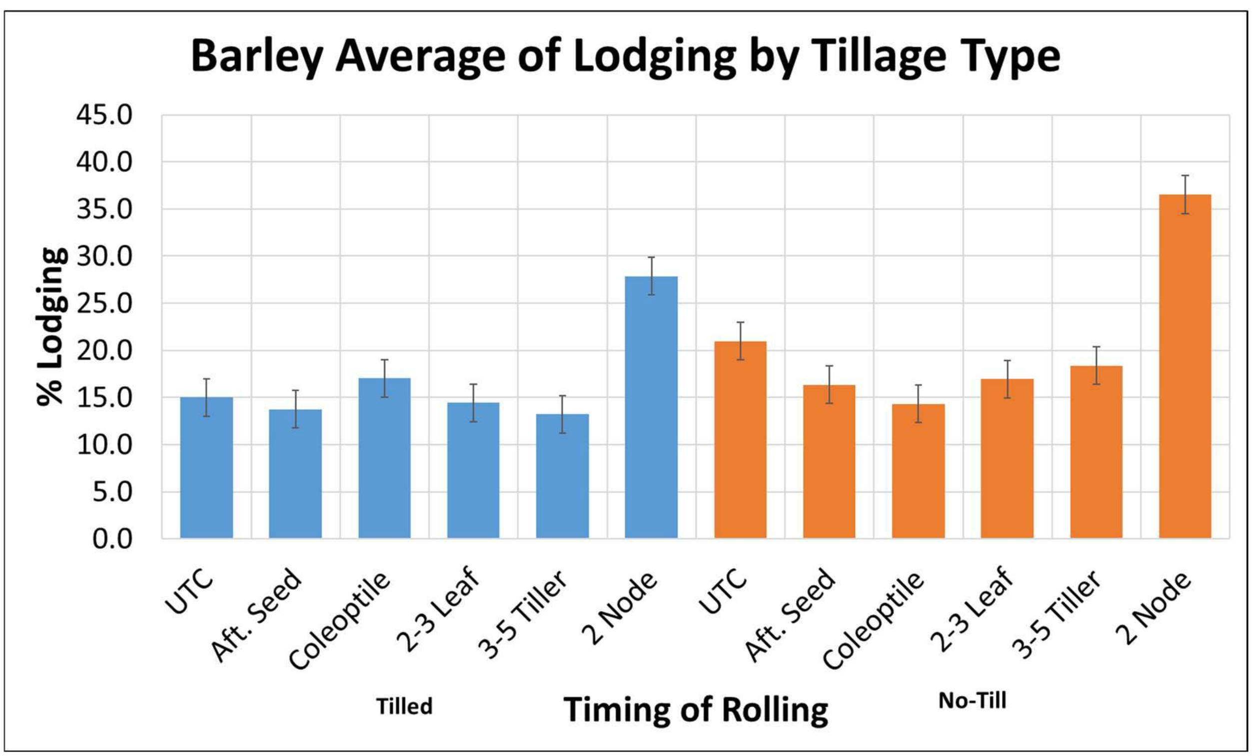

Figure A.5.3: Crop lodging at maturity for barley by tillage type, averaged across all site years.

4. How do silage and grain yield respond to different rolling timings?

The silage yield for wheat and barley was reduced numerically when rolled at the 3-5 tiller stage and reduced statistically significantly when rolled at the 2 node stage for both crops (Appendix A, Fig. A.6). Rolling in the 3-5 tiller stage led to a silage yield decrease of 0.8 to 1.1 MT/acre for barley and 0.4 to 0.6 MT/acre for wheat compared to the earlier crop stages. Rolling in the 2 node stage led to a silage yield decrease of 1.1 to 2.2 MT/acre for barley and 0.6 to 1.4 for wheat. Subsequently, barley silage yield was impacted more than wheat when rolling in the 3-5 tiller and 2 node stages, suggesting wheat was able to buffer or withstand the impact or rolling better than barley. That said, barley yielded 2 MT/acre on average more silage biomass than wheat and, may still be the better choice if rolling must happen in the node stages due to any number of factors (weather, equipment availability, and/or by choice). Rolling at the 2 node stage reduced grain yield significantly in both the wheat and the barley (Appendix A, Fig. A.7). A decrease of 17 bu/acre occurred at the 2 node stage rolling for barley and 13.4 bu/acre for wheat. Again, the wheat was less impacted than the barley and barley yielded 34.8 bu/acre more grain than wheat on average. So, rolling at 3-5 tiller and 2 node stage decreased silage yield, and rolling at the 2 node stage decreased grain yield. There were no tillage or tillage interaction effects in wheat. In barley there was a tillage effect, with the zero tillage yield 3 bu/acre less than the conventional tillage. As mentioned at the plant height discussion, this could be due to lower soil temperature during the early plant development stages. There was no interaction between tillage and rolling stage, in both tillage treatments rolling at the 2 node stage yielded significantly worse than all other treatments.

5. Were silage and grain quality impacted?

For grain quality, neither the kernel weight (TKW) or bushel weight was affected at any timing (Appendix A, Fig. A.8 & A.9). Silage protein and Net Energy for Gain (NEG) were numerically improved when rolling at the 3-5 tiller and 2 node stage (Appendix A, Fig. A.10 & A.11) and average grain protein showed a numerical increase in barley when rolled at the 2 node stage and a statistically significant increase in wheat (Appendix A, Fig. A.12). This is likely due to plant stress response mechanisms leading to an increased storage of protein and calories. Grain grading showed that rolling at the 2 node significantly increased the presence of ergot seed disease, more so in barley than wheat (Appendix A, Fig. A.13). So, while protein and energy gain were increased at 2 node, the presence of ergot and other seed disease resulted in a net negative effect at the 2 node stage. There were no significant effects of tillage or tillage interaction with rolling stage in the silage and grain quality.

Parameters dealing with other plant injury symptoms and soil quality were measured and interpreted:

Plant injury symptoms appeared in the field in the form of bending of stems, dying off of tillers/main stems, and disease. Bending of stems occurred occasionally at the 3-5 tiller stage and frequently and noticeably at 2 node stage for both barley and wheat (Appendix A, Image A.1). It was noted that some tillers and occasionally main stems were brown, dying, or very hurt, more so in the 2 node stage than the 3-5 tiller stage. Also, visual leaf disease incidence was assessed per plot using a scale of 0-5 (0 being no disease & 5 being fully infected). Barley and wheat both showed significantly increased leaf disease incidence in the 2 node rolling timing (Appendix A, Fig. A.14). The increased disease pressure doesn't seem to have led to reduced yield or other impacts to crop growth, but it does indicate decreased plant health. There were no significant effects of tillage or tillage interaction with rolling stage for crop injury and soil parameters.

Compaction due to rolling the crops was measured, but no differences were observed. Rolling when there was maximum biomass, showed counterintuitive results, with higher than expected soil strength in the 0-3" depth (Appendix A, Table A.1). As well, after rolling at each stage, there was no compaction levels above 300 psi between 0- 6" depth, which would signify truly compacted soils that would restrict plant or root penetration (Appendix A, Table A.2). This suggests there are other factors other than rolling that determine soil compaction, such as days after soil disturbance (tillage or seeding) and soil moisture level (Shaheb et al., 2021).

It was recognized that rolling should not take place within approximately 7 days before or after a stressful event, such as spraying pesticides or adverse weather such as hail. Pesticide applications in this study were timed to avoid this situation. For the case of adverse weather, like minor hail that creates extra stress on the plants, rolling 7 days before or after could reduce plant stress. We were fortunate to avoid rolling timings with these events. Another observation was that the more leaf matter present and greater root structure at the time of rolling leads to less soil erosion due to wind. There was some evidence that tillage impacted crop performance, with regard to rolling at the coleoptile stage (tillering and plant stand) and 2 node stage (plant height and lodging). We can confidently recommend that rolling should be done before node formation under any tillage system.

In conclusion, this project demonstrated that the optimum time for farmers to roll is once the plants develop sufficient leaf matter and root structure. Ideally rolling should occur sometime from the 2 leaf to the early tillering stages of wheat and barley before nodes start to form and 7 days before or after stressful events such as pesticide spraying or adverse weather. By rolling in this window of crop growth, soil erosion will be limited and plant damage avoided, as well as other field activities will be able to be scheduled well before or after rolling.

Appendix A – Figures

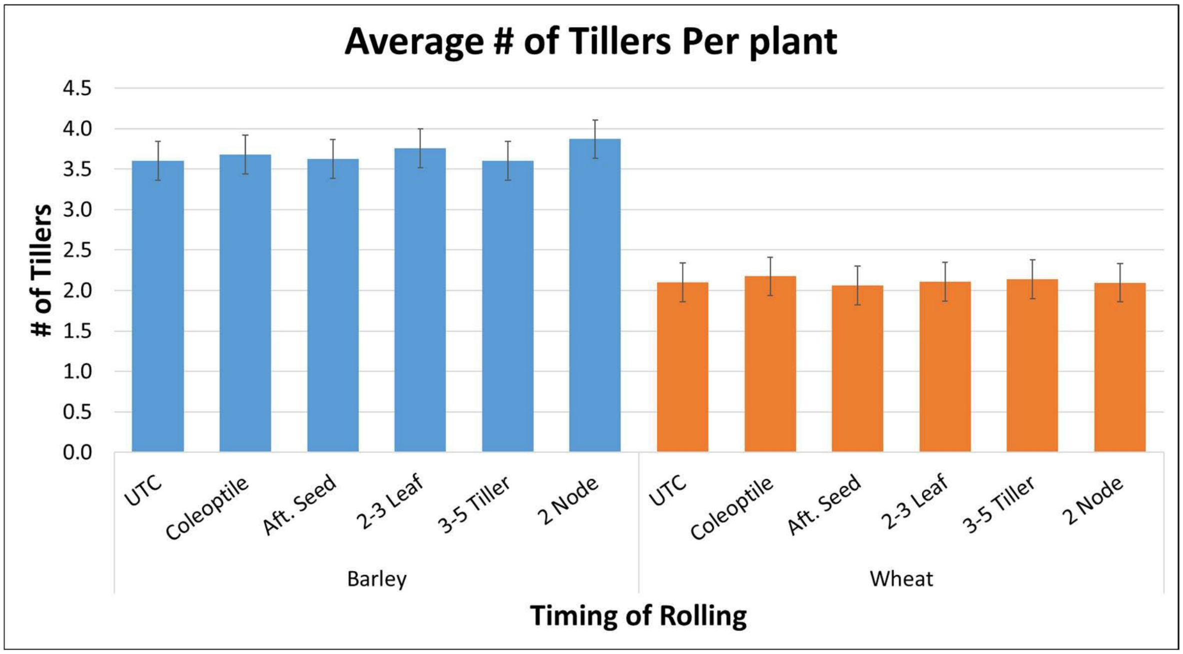

Figure A.1: Number of tillers per plant for barley and wheat, averaged across all site years (Barley p=0.63, Wheat p=0.92).

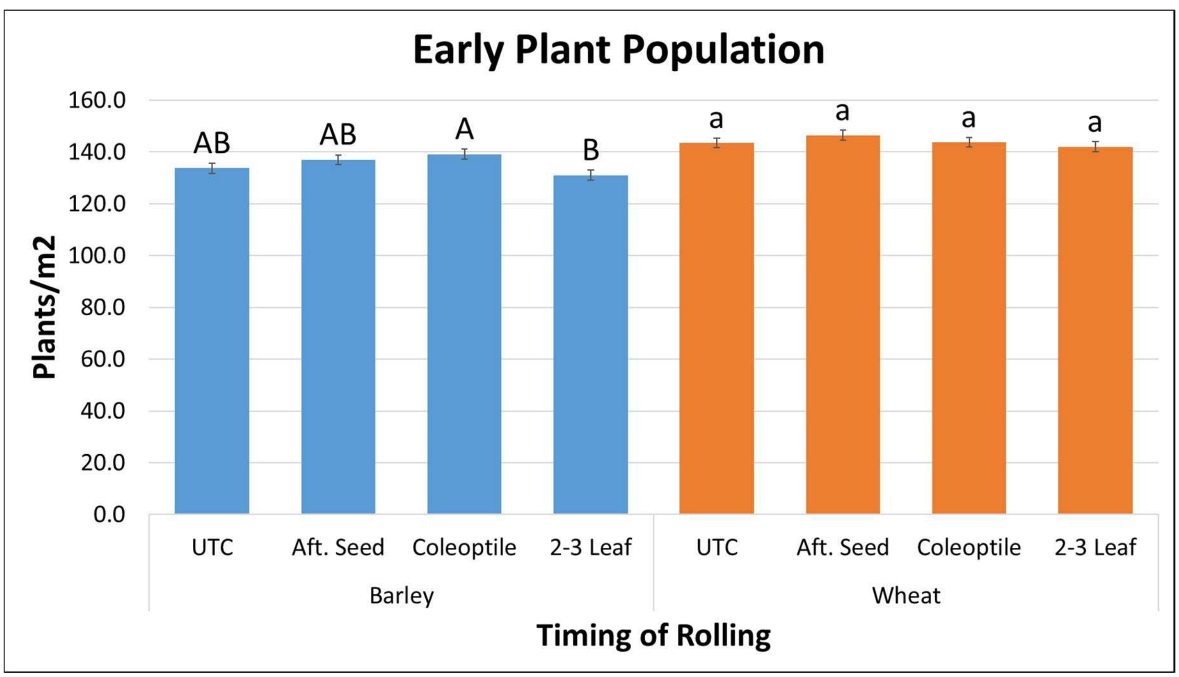

Figure A.2.1: Number of plants per square meter for barley and wheat, measured around the 3-4 leaf growth stage, and averaged across all site years (Barley p=0.0082, Wheat p=0.39).

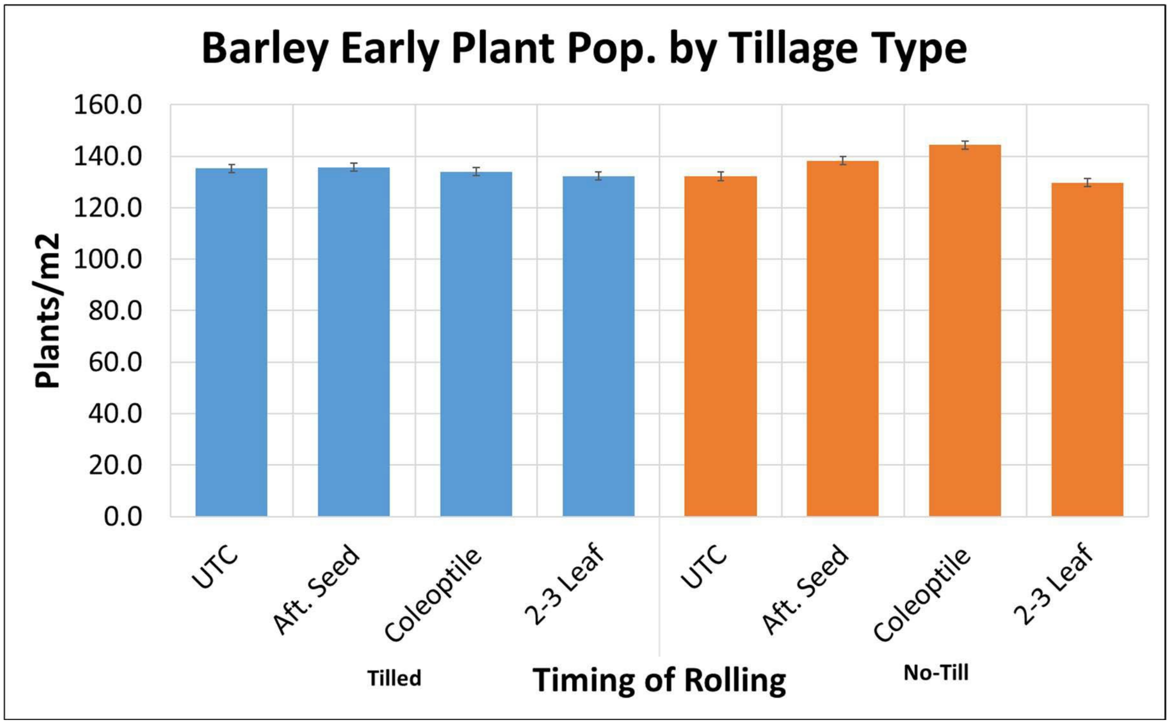

Figure A.2.2: Number of plants per square meter for barley by tillage type, measured around the 3-4 leaf growth stage, and averaged across all site years.

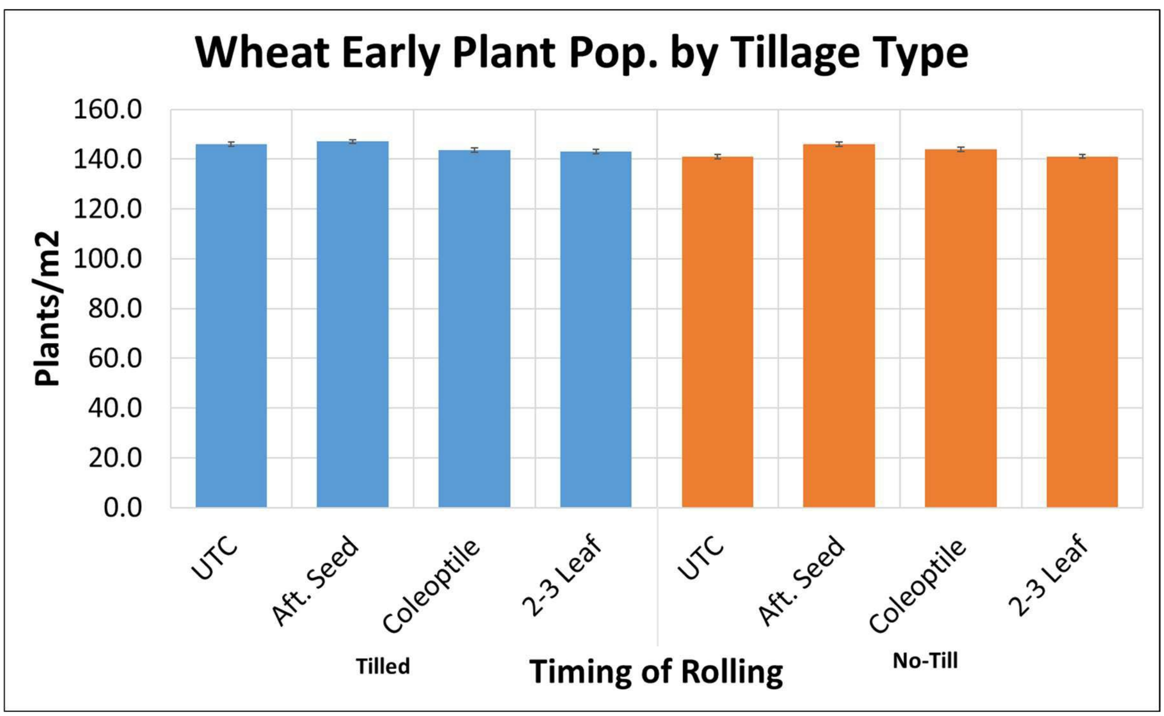

Figure A.2.3: Number of plants per square meter for wheat by tillage type, measured around the 3-4 leaf growth stage, and averaged across all site years.

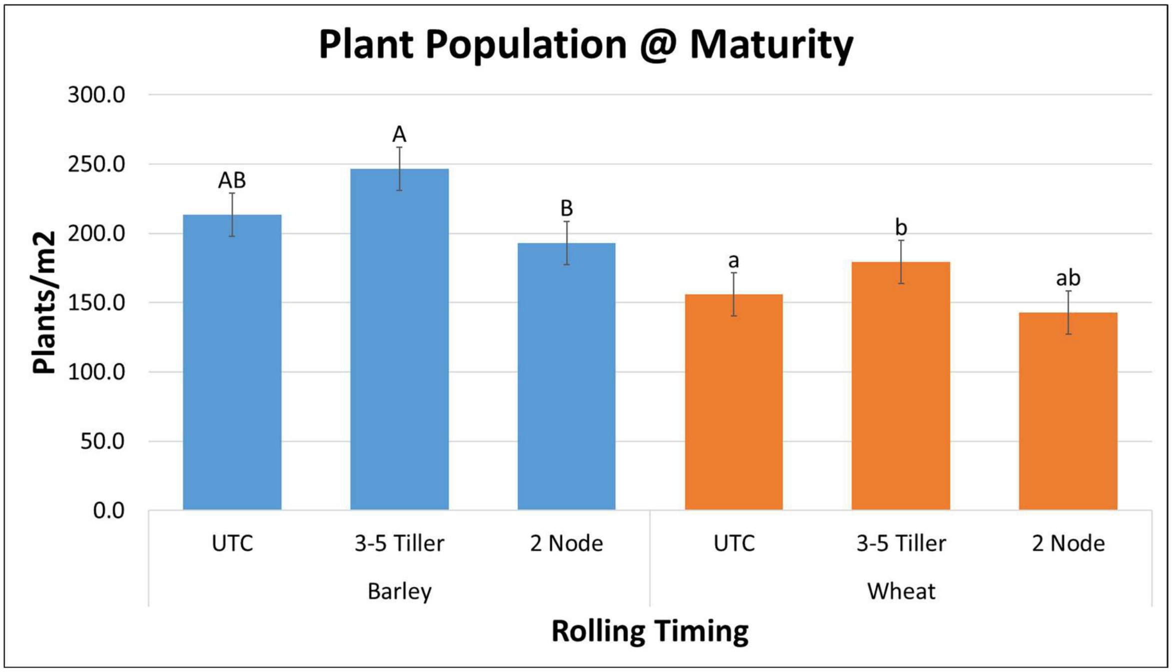

Figure A.3: Number of plants per square meter for barley and wheat, measured at the soft dough stage, and averaged across all site years (Barley p=0.032, Wheat p=0.0077).

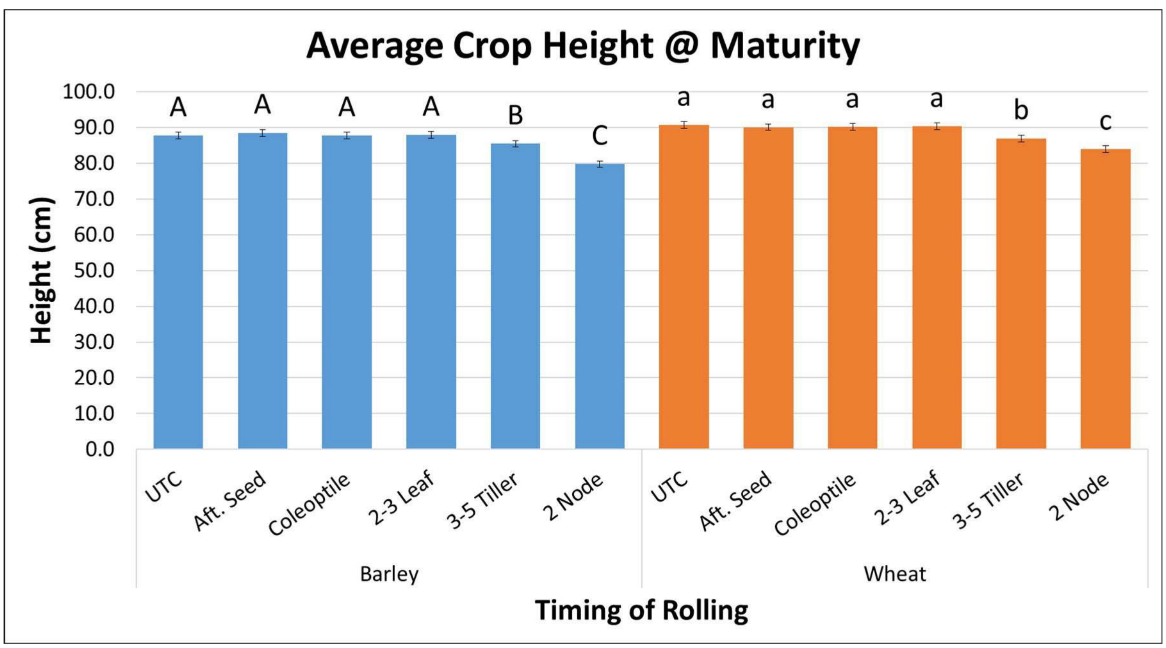

Figure A.4: Crop height at maturity for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p<0.001).

Image A.1: Picture of a bent over plant due to roller damage in the 1 node stage, July 2021.

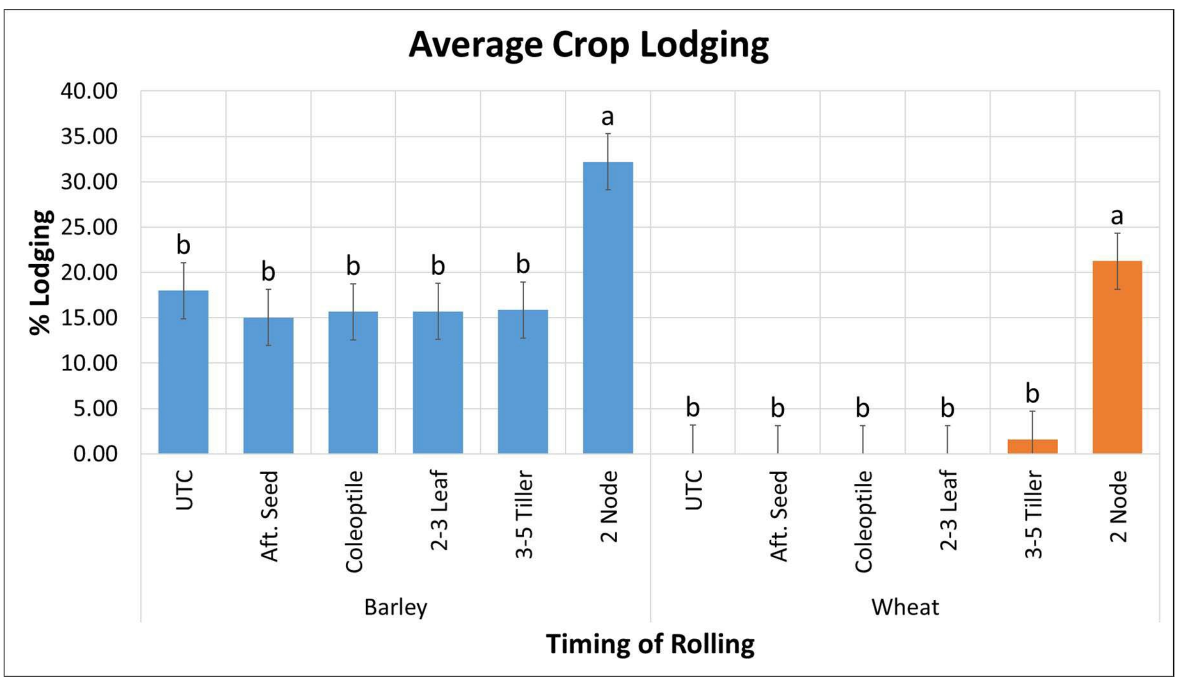

Figure A.5.1: Crop lodging at maturity for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p<0.001).

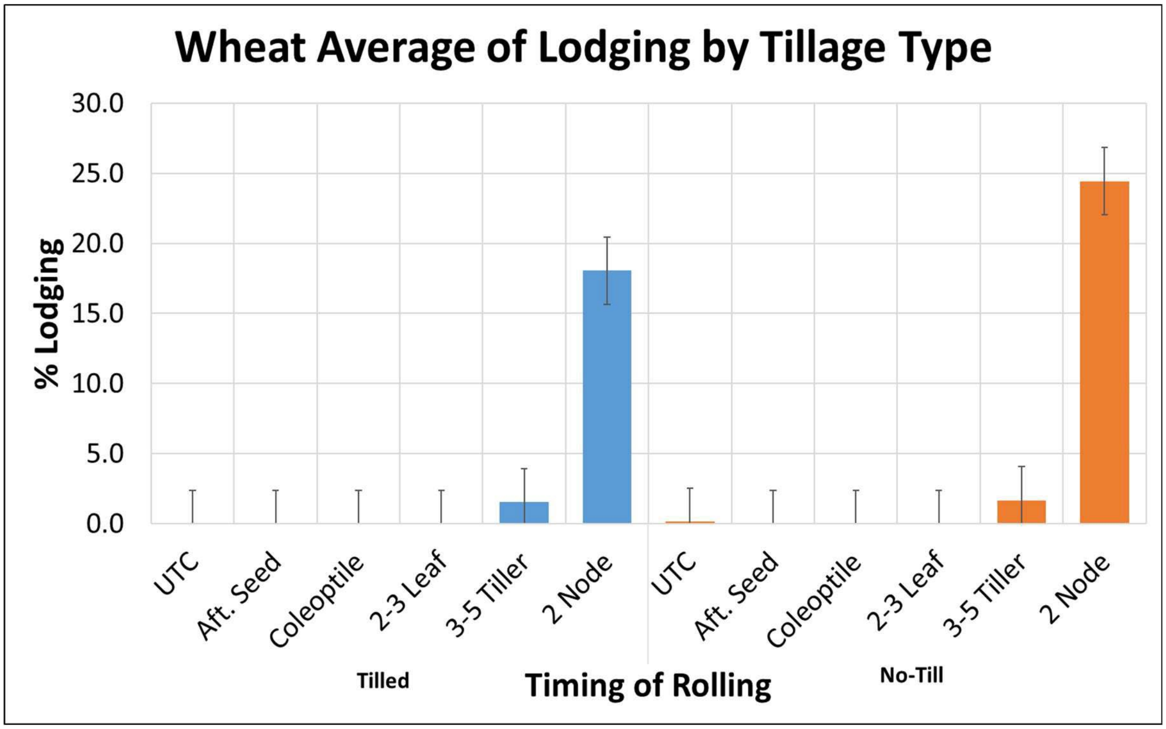

Figure A.5. 2: Crop lodging at maturity for wheat by tillage type, averaged across all site years.

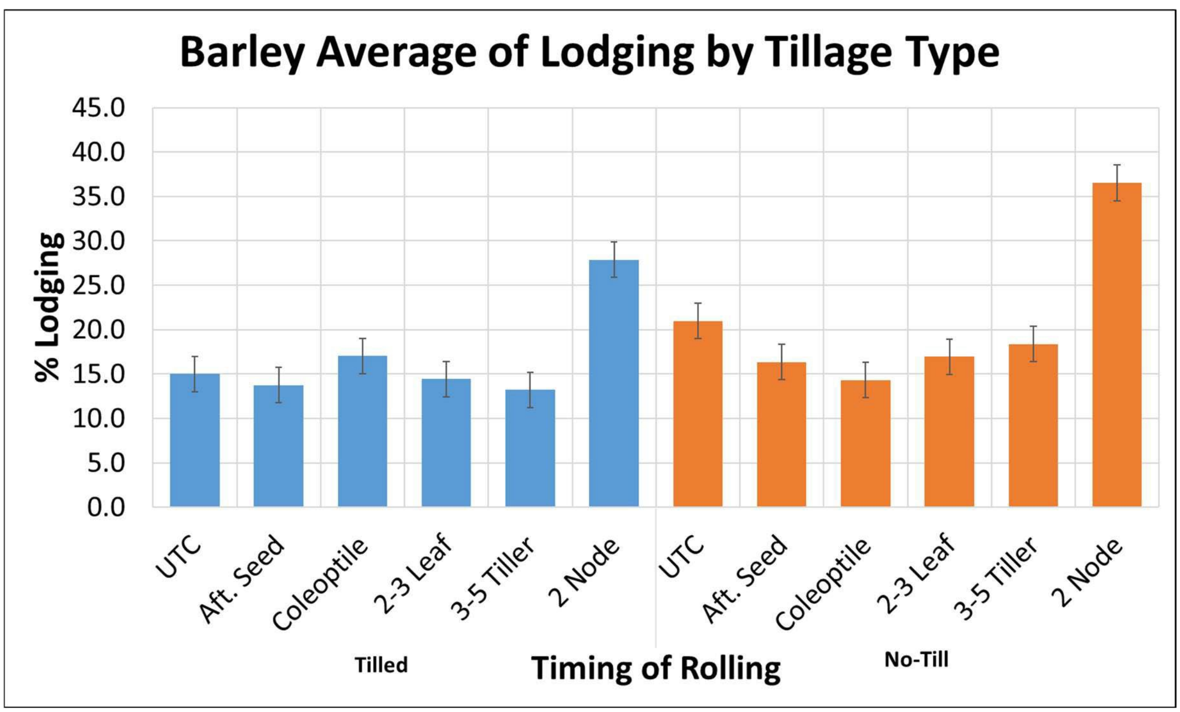

Figure A.5.3: Crop lodging at maturity for barley by tillage type, averaged across all site years.

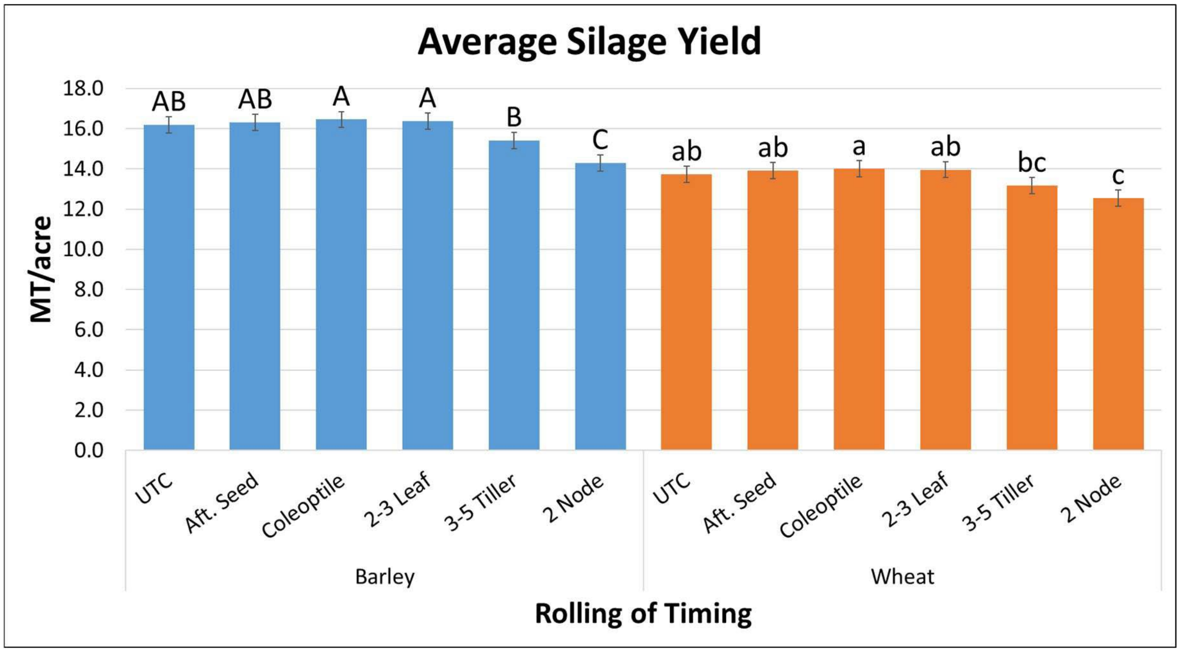

Figure A.6: Average silage yield for barley and wheat, averaged across all site years (Barley $p<0.001$, Wheat $p<0.001$).

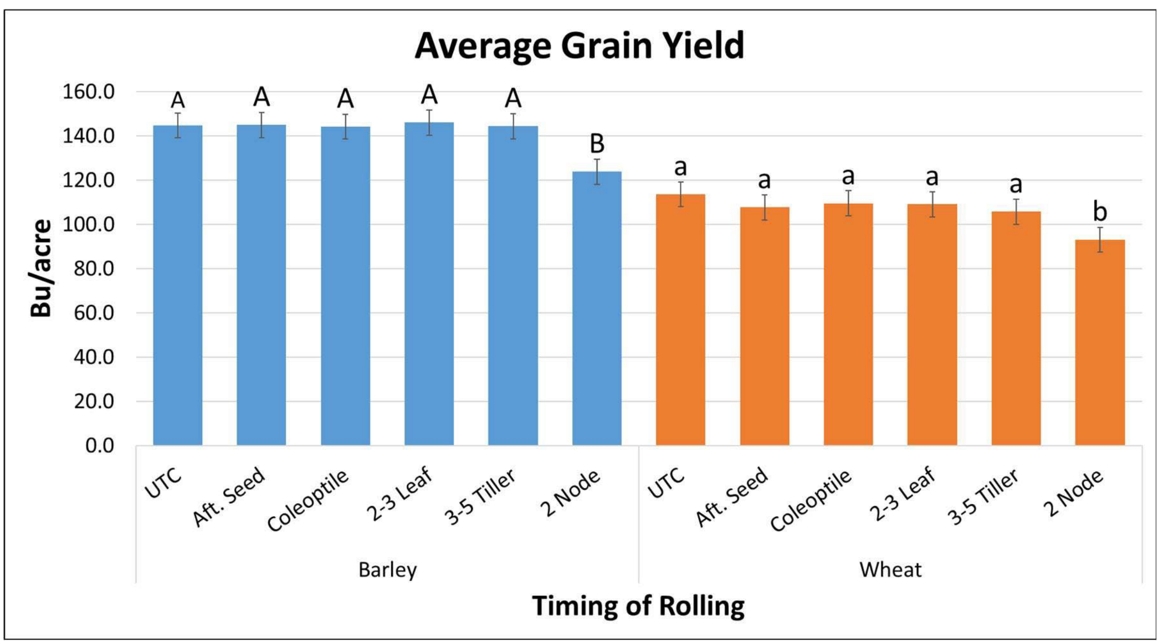

Figure A.7: Average grain yield for barley and wheat, averaged across all site years (Barley $p<0.001$, Wheat $p<0.001$).

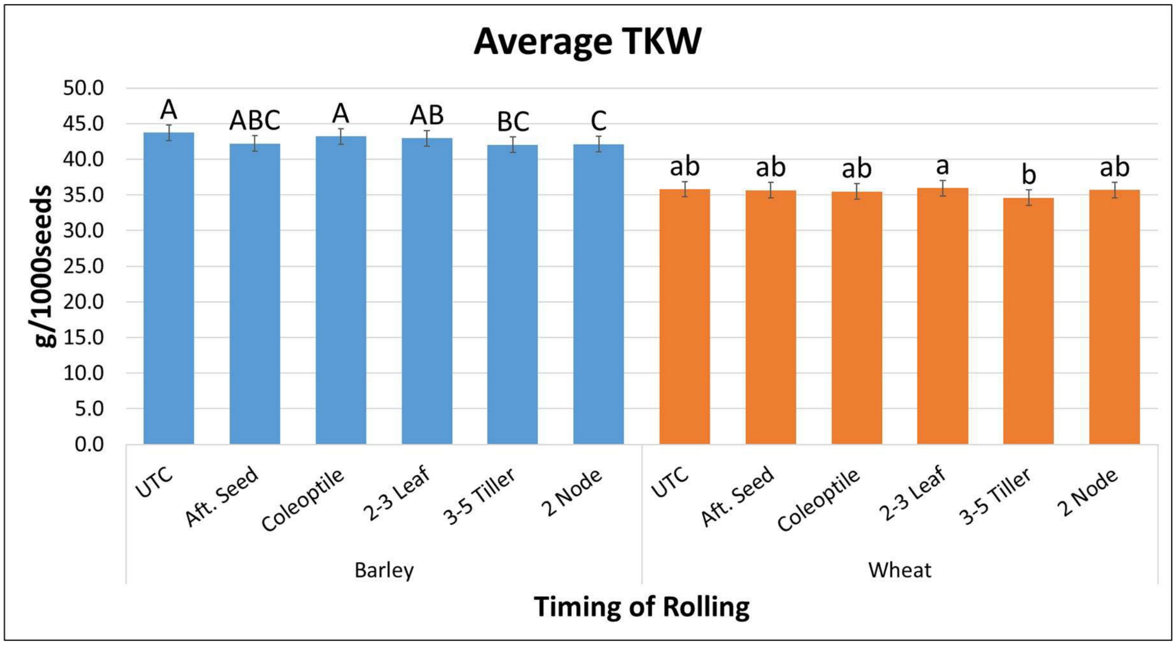

Figure A.8: Average grain Thousand Kernel Weight (TKW) for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p=0.058).

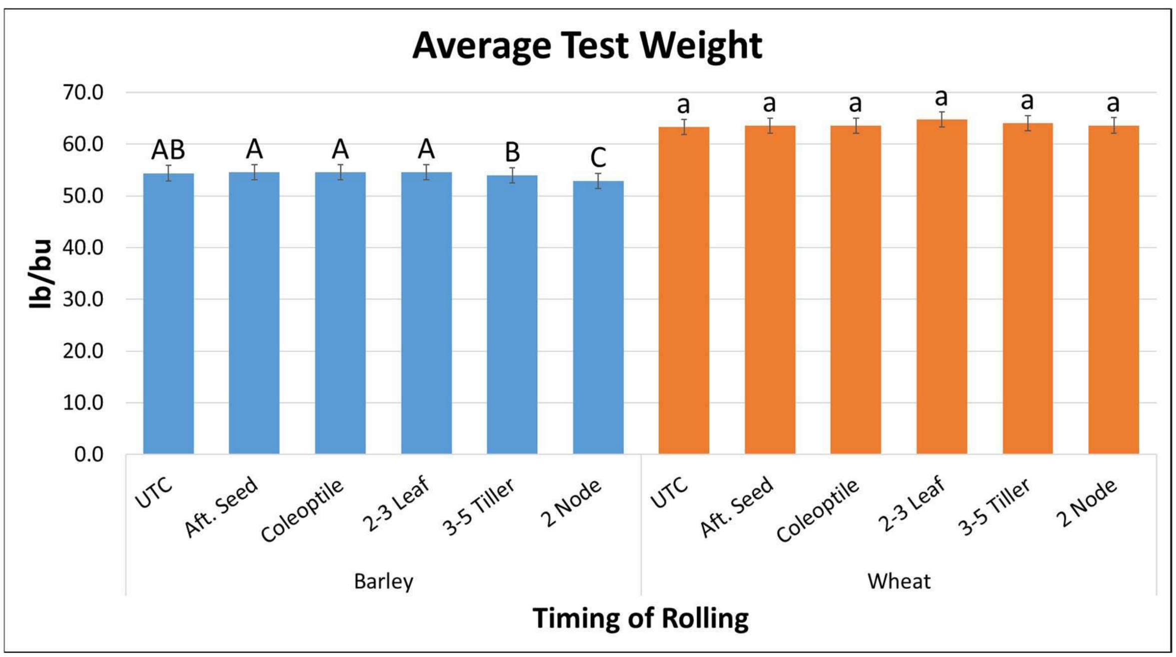

Figure A.9: Average grain Thousand Kernel Weight (TKW) for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p=0.97).

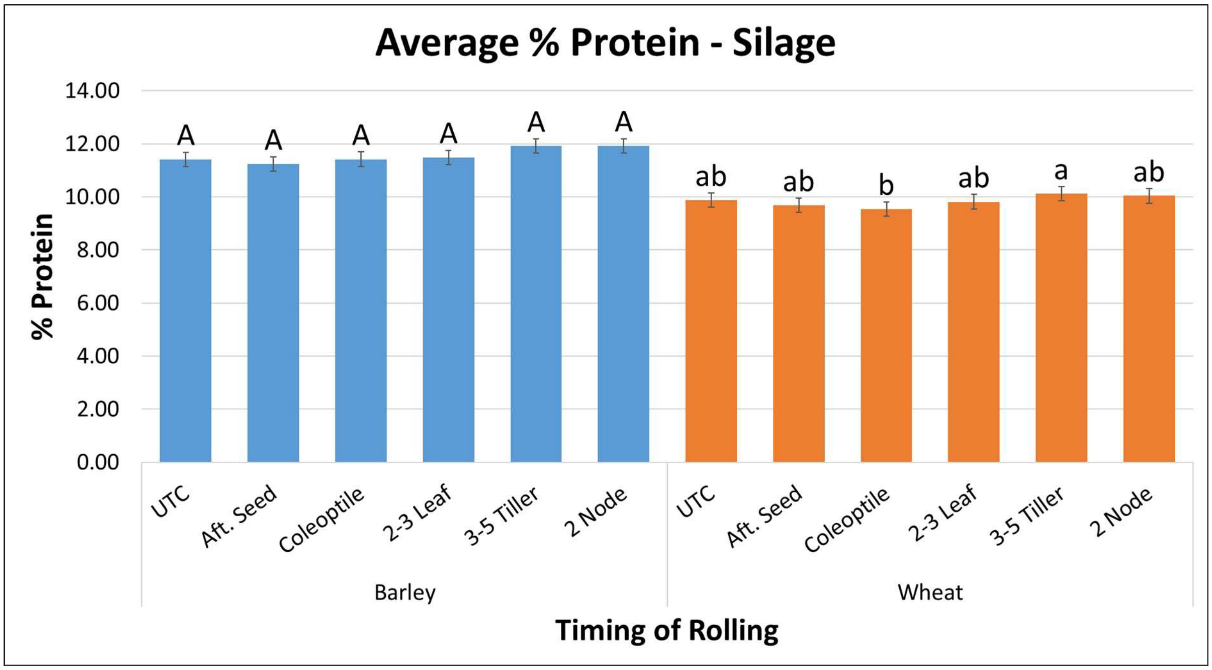

Figure A.10: Average percent silage protein for barley and wheat, averaged across all site years (Barley p=0.019, Wheat p=0.019).

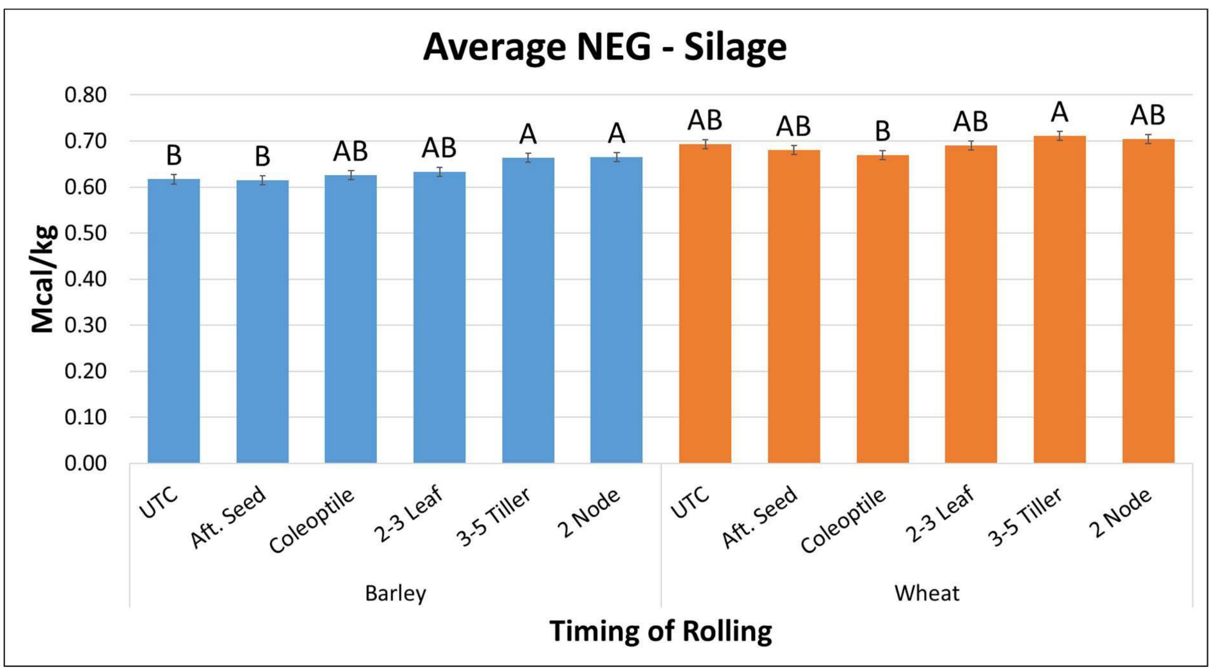

Figure A.11: Average Net Energy for Growth (NEG) for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p=0.018).

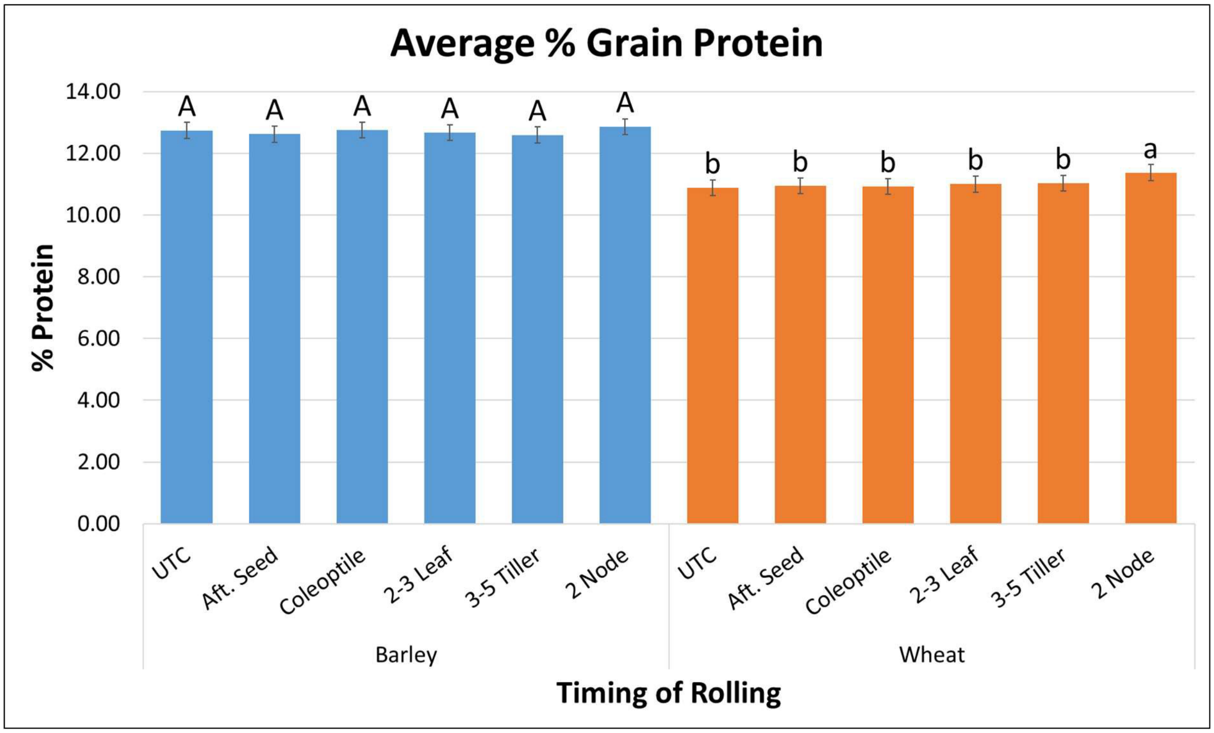

Figure A.12: Average % grain protein for barley and wheat, averaged across all site years (Barley p=0.32, Wheat p<0.001).

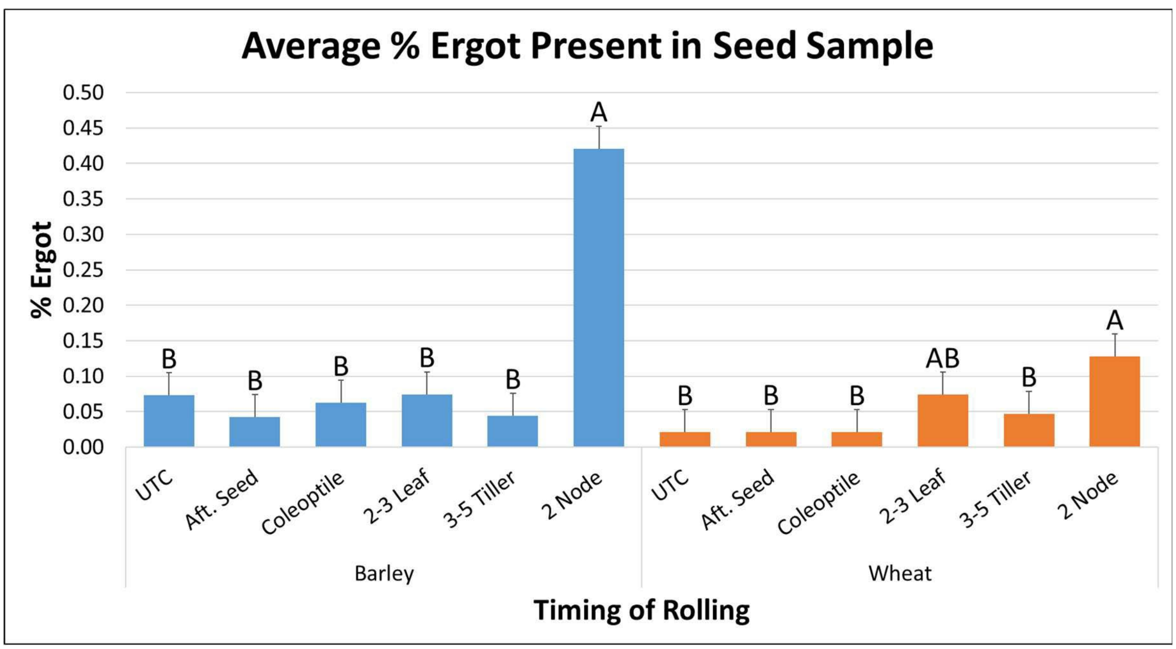

Figure A.13: Average % ergot in grain for barley and wheat, averaged across all site years (Barley p<0.001, Wheat p<0.001).

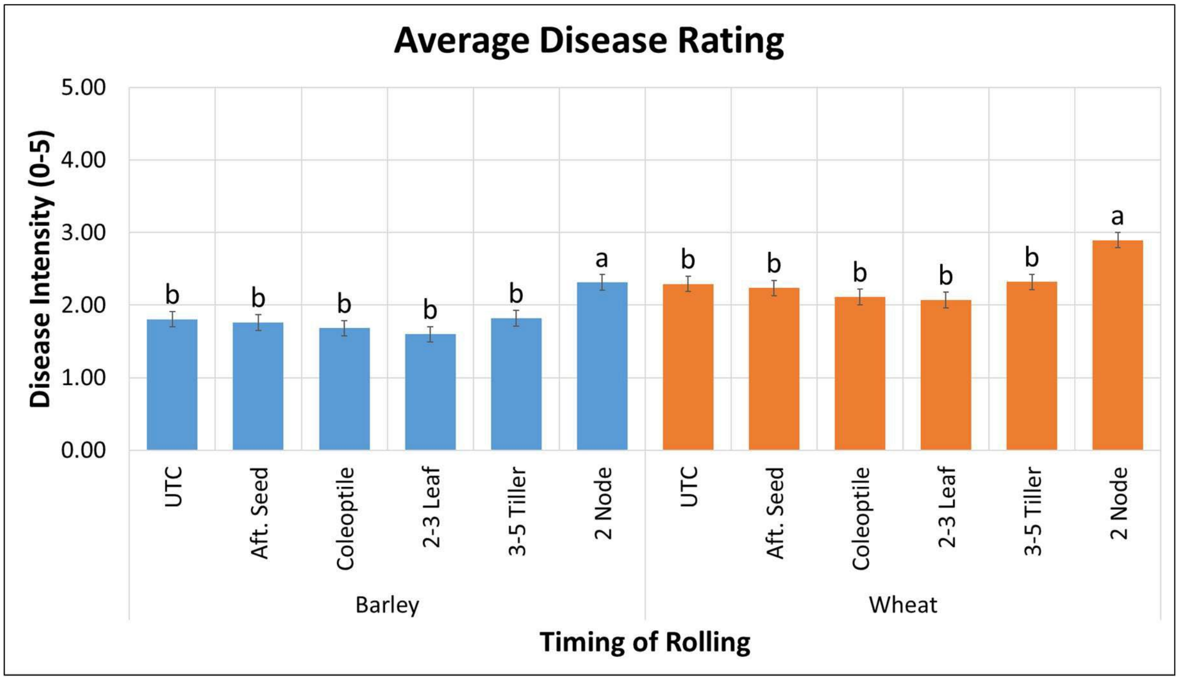

Figure A.14: Average leaf disease incidence for barley and wheat, averaged across all site years (Barley $p<0.001$, Wheat $p<0.001$).

Barley	
Treatment #	**Compaction After Rolling (PSI @ 0-3")**
UTC	136
Aft. Seed	160
Coleoptile	107
2-3 Leaf	135
3-5 Tiller	81
2 Node	135
Wheat	
Treatment #	**Compaction After Rolling (PSI @ 0-3")**
UTC	136
Aft. Seed	151
Coleoptile	80
2-3 Leaf	126
3-5 Tiller	78
2 Node	144

Table A.1: Average compaction right after rolling, at 0-3" depth, for wheat and barley, averaged across all site years.

Barley	
Treatment #	**Compaction After Rolling (PSI @ 3-6")**
UTC	248
Aft. Seed	242
Coleoptile	176
2-3 Leaf	191
3-5 Tiller	144
2 Node	225
Wheat	
Treatment #	**Compaction After Rolling (PSI @ 3-6")**
UTC	236
Aft. Seed	218
Coleoptile	131
2-3 Leaf	184
3-5 Tiller	136
2 Node	230

Table A.2: Average compaction right after rolling, at 3-6" depth, for wheat and barley, averaged across all site years.

Rolling Timing	Silage Yield (MT/ac)	Grain Yield (Bu/ac)	Silage (Price/MT)	Grain Price/ bu	Revenue/ ac	Loss/ acre
Barley Silage						
Average	16.3		76		$ 1,238.80	---
3-5 Tiller	15.4		76		$ 1,170.40	-$ 68.40
2 Node	14.3		76		$ 1,086.80	-$ 152.00
Wheat Silage						
Average	13.9		76		$ 1,056.40	---
3-5 Tiller	13.2		76		$ 1,003.20	-$ 53.20
2 Node	12.6		76		$ 957.60	-$ 98.80
Barley Grain						
Average		144.9		7.9	$ 1,144.71	---
2 Node		123.8		7.9	$ 978.02	-$ 166.69
Wheat Grain						
Average		109.2		7.9	$ 862.68	---
2 Node		93.1		7.9	$ 735.49	-$ 127.19

Table A.3: Estimated revenue and loss for average silage and grain yield at specific rolling timings, for both barley and wheat.