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Minimizing Lentil Harvest Loss through Improved Agronomic Practices in Sustainable Agro-Systems

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Abstract: Lentils are one of the most common legume crops used to diversify the cereal-oilseed cropping system in semi-arid environments. Lentils are a major source of protein and fiber for human consumption worldwide. However, the morphological characteristics of lentil plants—such as a short stem and low pod positioning—and complicated combine harvesting methods often result in yield loss. This also increases the susceptibility of a lentil crop to disease and render it less competitive against weeds. As a result, producers have resorted to using pesticides in order to mitigate the effects of weeds and disease. As a consequence, there have been undesirable negative environmental impacts on sustainable agroecosystems. Although land rolling, stubble management, and pesticide usage are common agronomic practices used to increase lentil yield and mitigate the issues associated with its morphology, their comprehensive effects on lentil growth and harvest loss are still not fully understood. In this study, we examined the impact of stubble management, the timing of land rolling, and the application of common fungicides and herbicides on lentil growth and yield. We found that stubble management and the timing of rolling modified lentil morphological structures, and thus impacted lentil yield and seed loss. These results were influenced by environmental factors, such as precipitation during the growing season. Although the results did not show significant interaction between fungicide application and lentil growth and yield, herbicide applications, stubble management, and the timing of rolling, along with common pesticide application strategies tested in our study, showed effects that were dependent on environmental conditions. Based on our results, we concluded that stubble management and the timing of rolling, combined with pesticide applications, can affect lentil seed loss and yield by modifying plant morphology. This was largely influenced by environmental conditions such as precipitation.

Keywords: lentil; land rolling; stubble management; pesticide strategy; yield lost

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1. Introduction

Lentils (*Lens culinaris*) are ranked fifth in global pulse production and play an important role as a source of protein and fiber in human diet, especially in developing countries [1,2]. Due to symbiotic N benefits and low water requirement during growth, lentils have been commonly used to diversify the cereal-oilseed cropping system in semi-arid environments worldwide [3]. According to the Food and Agriculture Organization (FAO), the total annual global lentil production in 2018 was over 6 million tons and has almost doubled in the last 20 years. Among global lentil producing regions Canada is ranked as the number one producer. Canada contributed over 2 million tons of lentils to the global lentil market in 2018, of which 90% was from Saskatchewan (www.fao.org. Accessed at 10 November 2020).

Lentils are a bushy annual legume plant approximately 20~45 cm tall that bear small purse-shaped pods containing one to two seeds. Since lentils are such short plants, with many small pods on the stem near the soil surface, harvesting with modern mechanical combine harvesters is often difficult and a large number of seeds are lost in the process [4,5].

Land rolling has been commonly used by lentil producers to flatten and smoothen the soil surface in order to increase seed contact with root-soil and optimize soil water content, thus reducing seed loss and enhance harvest efficiency [2,6]. However, improper rolling practices have had adverse agronomic, economic, and environmental impacts, i.e., when rolling does not provide adequate ground pressure or is applied with improper timing. It has caused excessive soil compaction, reduced root growth, increased soil erosion, higher potential of plant injury, seed loss, and added costs for lentil producers and the food industry as a result [6].

Due to limited research focusing on the impact of rolling practices on lentil morphological growth, it is unknown whether improper timing of land rolling would shorten the lentil stem height, making combining more difficult, and thus contributing to the loss of some seed-bearing pods positioned on the lower part of plant stems. Lentils are also normally seeded into standing cereal stubble as part of a cropping sequence to increase lentil yield, especially in Canada [7,8]. Stubble height from previous cereal crops has affected soil micro-climatic conditions—such as reduction in soil surface evaporation, soil surface temperature, solar radiation, and wind speed—which can increase the snow trapping capacity and topsoil water content. These factors in turn can influence lentil root development and growth, especially in the early stages of lentil plant development [9–11]. However, it is unknown whether previous stubble management can affect pod positioning on the plant and thus influence lentil harvest loss. It is therefore important to have an in depth understanding of the effect of stubble management on lentil productivity in modern agriculture.

The unique morphological structure of lentil plants, combined with hot and wet micro-climate created by the rolling practice and stubble management, often make lentil plants vulnerable to fungal disease and weed competition. Lentils are one of the least competitive legume crops and are susceptible to various fungal diseases that can lead to severe defoliation, plant girdling, and yield loss [12,13]. Lentils also often suffer yield loss due to their short stem, small canopy, and slow canopy establishment [14]. To counter the effects of disease and weed pressure, producers have relied on fungicide and herbicide applications in order to increase lentil yield. A number of studies have looked at pesticide types, application timing, and their interactions with different lentil cultivars [12,14,15]. However, there is little understanding of how essential pesticide applications in lentils influence plant morphological structure and yield, and whether they can interfere with physical agronomic practices, such as land rolling and stubble management.

To address the uncertainties associated with trying to increase lentil yield through optimizing field management strategies, we formulated and tested the following hypotheses: (1) late timing of land rolling practices in lentil fields can limit lentil plant morphological development, reducing lentil yield as a consequence; (2) growing lentils in cereal stubble from the previous year can promote lentil growth; (3) artificial chemical applications—such as fungicide and herbicide usage—can increase lentil yield by eliminating the negative impact of pests. To examine the above hypotheses, we setup a series of field trials with a split-plot experimental design to examine the following objectives: (1) rolling before seeding or after seeding can change lentil morphological development compared to no rolling practice, influencing lentil yield; (2) stubble practice can modify micro-climate conditions, influencing lentil yield; and (3) fungicide and herbicide application in lentil fields can remove disease and weed effects, influencing lentil yield. In particular, we set out to determine the impacts of stubble management and timing of land rolling on plant height, pod positioning, seed loss during maturation, seed loss during harvest, general plant health (as measured by various levels of plant health scores), and overall harvestability. The results from these trials can provide valuable information for optimizing agronomic strategies in lentil fields to improve lentil health, lentil yield, and reduce seed lost.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted at Swift Current (Brown soil zone) and Scott (Dark Brown soil zone) in Saskatchewan, Canada in 2017, and repeated in 2018 and 2019. The soil texture at Swift Current was 31.4% sand, 50.4% silt, and 18.2% clay. At Scott it was 32% sand, 51% silt, and 17% clay. Average monthly temperature and precipitation at the two experimental stations during the three experimental years are based on data from environment and natural resources Canada on-site weather stations (www.canada.ca/en/services/environment/weather. Accessed on 23 October 2020).

2.2. Experimental Design

A split-plot experimental design with four factorial treatments was applied at both sites to test the impact of common agronomic practices on lentil growth. Each treatment was replicated four times. Each treatment was applied to plots measuring 2 × 8 m in size. The four factors in our experiments and their variants are as follows: (1) land rolling timing: (a) rolling one week before emergence but after planting, (b) rolling one week after completion of seedling emergence, and (c) no rolling; (2) stubble management: (a) rotatory tillage to prepare the seedbed and (b) direct-seeding into 15 cm tall standing wheat stubble from the previous cropping year; (3) fungicide application: (a) no fungicide spray (control) and (b) in-crop application of the fungicides Lance WDG® at 432 g per ha and Headline EC® at 408 mL per ha for all plots; (4) essential weed management practices: (a) no herbicide (control) and (b) in-crop application of the herbicides Solo ADV® at 325 mL per acre, Assure II® at 250 mL per acre, and Reglone® at 830 mL per acre for all plots during the growing season. Pre-seed burn off with glyphosate at 670 mL per acre was applied at all plots (including control) before seeding to bring all plots onto same potential weed pressure level. The experimental field at Swift Current also received Pardner® at 450 mL per acre in 2017 and Aim® at 74 mL per acre in 2019 as pre-seed burn off applications for necessary weed control based on field evaluation. Details of the experimental design are shown in Table S1. For all plots, lentil c.v. CDC Maxim CL was seeded with a rate of 150 seeds per m^2 at both sites.

2.3. Agronomic Parameter Measurements

Plant density was established two weeks after emergence by counting the plants from each plot in four 1-meter rows. At maturity for each plant in the four 1-meter rows, the plant height and lowest pod height were measured. To determine seed loss, we placed two trays—80 cm long, 1 to 2 cm high, a 15 cm width at the top, and 12 cm width at the bottom—between the center rows in each plot. We collected, cleaned, and weighed the seed from the trays every three to six days for a total of six to eight times during the podding stage until the seed was harvested. The seeds from each plot were combined, cleaned, and weighed to obtain yield. We collected the standing lentil stubble after harvest, from four 0.5 m rows. The stubble was thrashed, the seed was collected, and then added to the previously collected seed from the trays to determine total seed loss.

2.4. Statistical Analysis

The data was analyzed using R programing software (version 3.5.1). We did not detect any significant interactions between the treatments (data not shown). As a result, we used one-way analysis of variance (ANOVA) to determine the main treatment effects on tested lentil yield related parameters under different site-year conditions. The least significant difference (LSD) test was at 95% significance level. Violin graphs were applied to visualize the significant impact of tested factors on lentil growth parameters, using R with package ggplot2. Redundancy analysis (RDA) was conducted using R with package 'vegan' to show how lentil growth parameters responded to agronomic activities.

3. Results

3.1. Impacts of Rolling Timing on Lentil Plant Density and Seed Lost

The timing of rolling significantly influenced lentil growth, especially for lentil seed loss (Figure 1A). In particular, rolling one week before seedling emergence, but after planting, significantly reduced lentil seed loss by up to 48% compared to the no rolling treatment. On the other hand, rolling one week after seedling emergence increased lentil seed loss by up to 11% when compared to no rolling (Figure 2A). However, these effects were only observed at Scott in 2017, indicating a strong environmental interference on these impacts of timing of land rolling. In particular, we found that lentil seed loss was negatively correlated to the amount of precipitation before the seeding stage in April, May, and during the maturity in August (Figure 1B). Precipitation in these months were the highest at Scott 2017 compared with other site-years (Figure S1). These results suggested that environmental moisture conditions influenced the effect of rolling timing on lentil seed loss, which likely is due to pods being prone to less shuttering under good moisture conditions.

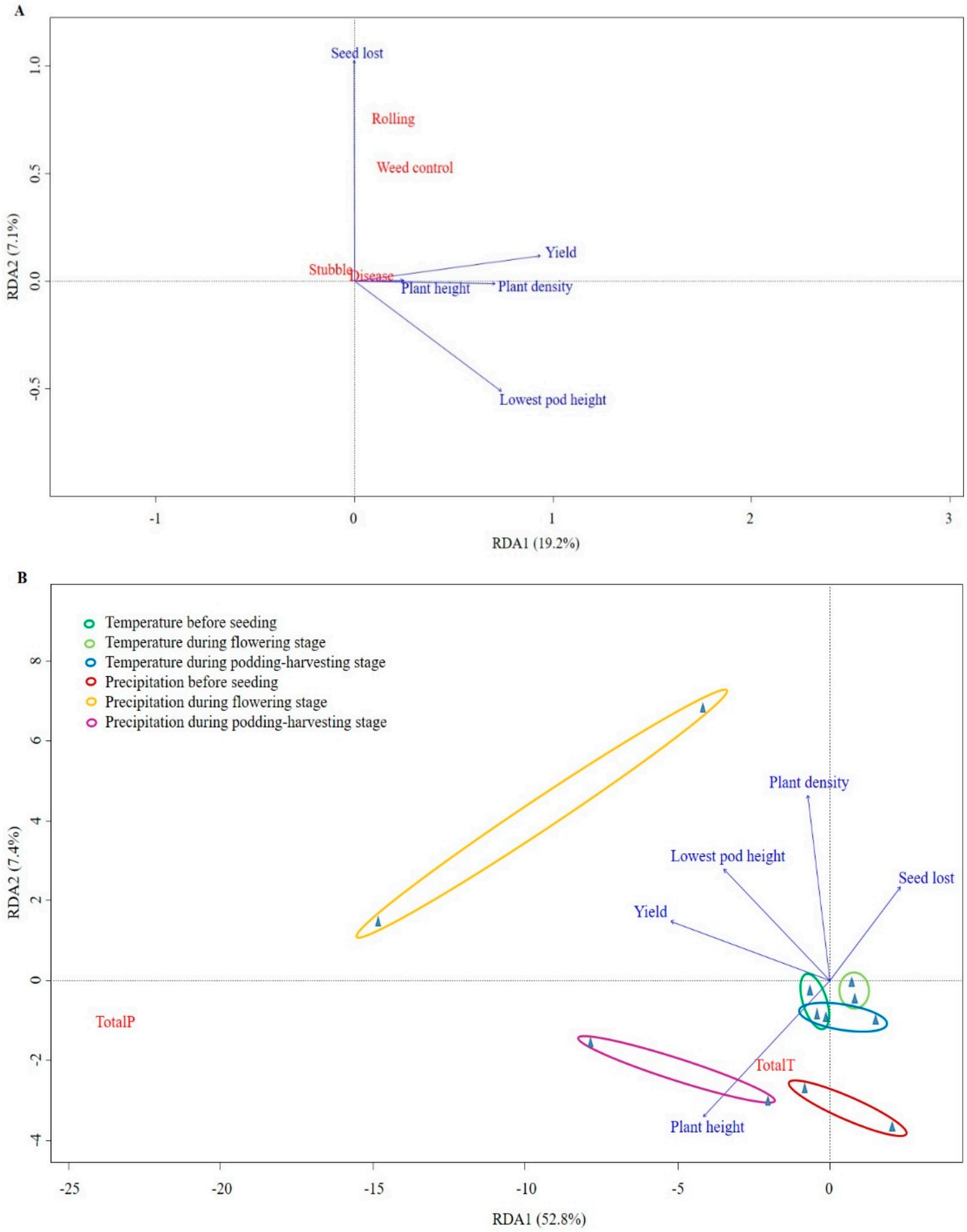

Figure 1. Redundancy analysis (RDA) showed (**A**) the influence of agronomic practice on lentil growth and (**B**) the impact of environmental factors on lentil growth. TotalT: temperature during whole growing season, TotalP: precipitation during whole growing season.

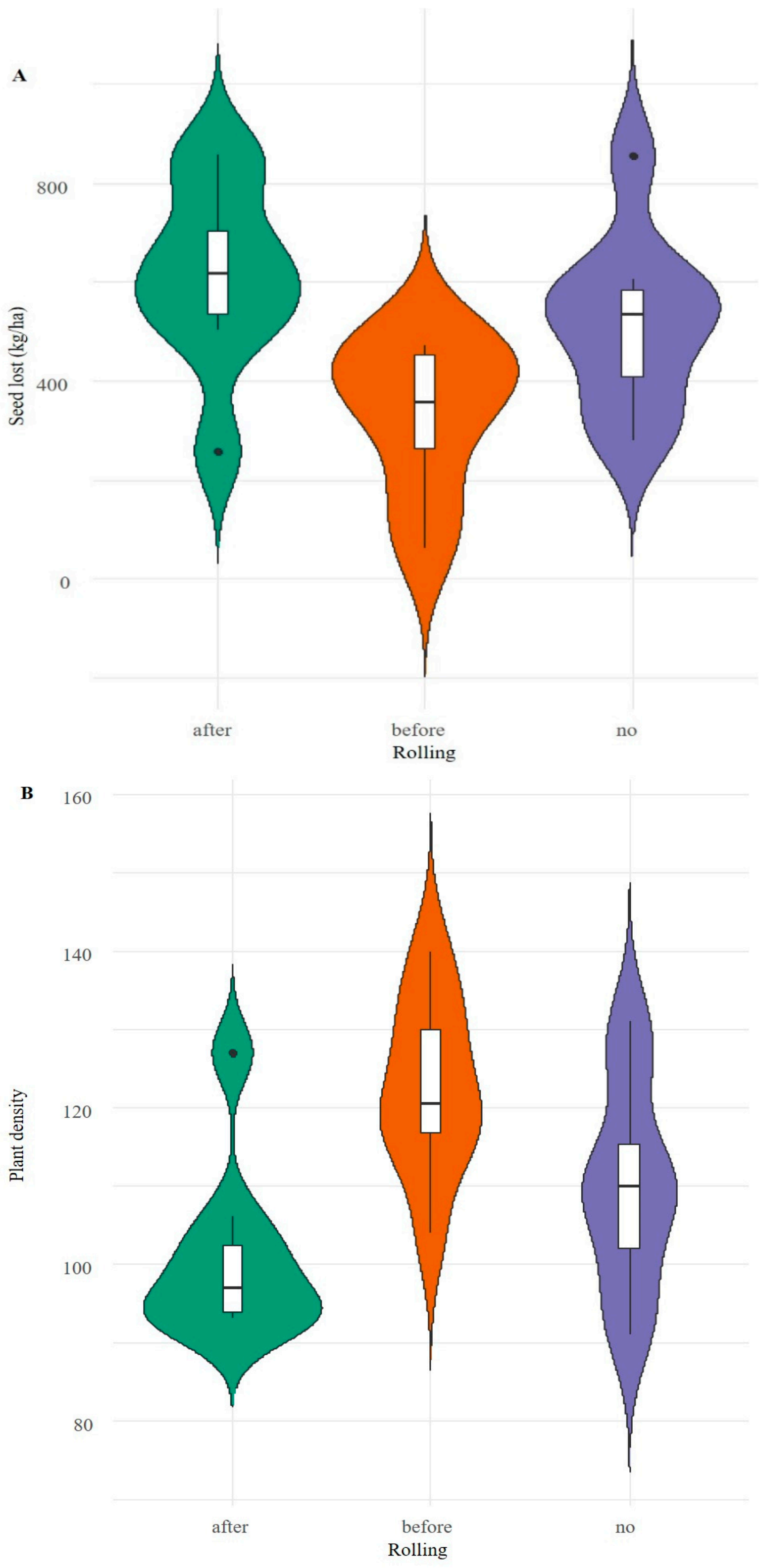

Figure 2. Rolling practice impacts on (**A**) seed lost at Scott 2017, and (**B**) plant density at Swift Current 2019. The different colored violin graphs use width to show data density for each treatment; the white box within each violin graph show the interquartile range of each dataset; the black bar in the middle of each box showed median number for each dataset; and the vertical black bar above and below the box show the 95% confidence interval of each dataset.

We observed that rolling at one week before seedling emergence significantly increased plant density, about 9%, while rolling at one week after seedling emergence reduced lentil plant density, up to 16%, when compared with no rolling (Figure 2B, Table S2). These effects were only observed at Swift Current in 2019, which had the highest amount of rainfall during all test site-years, especially during the early parts of the growing season in June (Figure S1). Based on the RDA results, plant density was positively correlated to precipitation (Figure 1B). It can thus be deduced that the effect of rolling timing on lentil stem height was likely influenced by the high precipitation received at Swift Current in 2019. We did not detect any significant interaction between rolling and fungicide usage, suggesting that, at least in this study, physical agronomic activities such as rolling did not affect the efficacy of the fungicides in controlling disease.

3.2. Stubble Management Impact on Lentil Plant Height, Lowest Pod Position and Seed Loss

Stubble management significantly impacted lentil plant height, lowest pod position on the plant stems, and seed loss. This was strongly influenced by environmental factors. In particular, seeding in a 15 cm cereal stubble significantly reduced seed loss by about 260% when compared with the no stubble treatment at Scott 2017 (Figure 3A, Table S2). This indicates a strong impact of stubble management on lentil growth, which in this case was also influenced by environmental conditions. In particular, we observed that lentil seed loss was negatively correlated with precipitation received before seeding in April, May, and during the maturing stage in August (Figure 1B). Precipitation was the highest at Scott 2017 for these three months among all tested site-years (Figure S1), suggesting that moisture influences the benefits of stubble management on lentil growth.

Seeding in 15 cm wheat stubble significantly increased plant height by 11% at Scott 2018 (Figure 3B, Table S2) and elevated the lowest pod positioning by 18% at Swift Current 2018 (Figure 3C, Table S2), compared with the no stubble treatment. In 2018, both experimental locations received lower precipitation in June than the other tested site-years (Figure S1). The RDA results showed that the lentils' lowest pod height and yield were positively related, while seed loss was negatively correlated with precipitation, especially during the early growing season in June (Figure 1B). This suggests that environmental conditions interfered with the effect of stubble management. However, we did not detect any significant interactions between stubble management, nor fungicide or herbicide applications, suggesting that, at least in this study, stubble management did not interfere with pesticide usage.

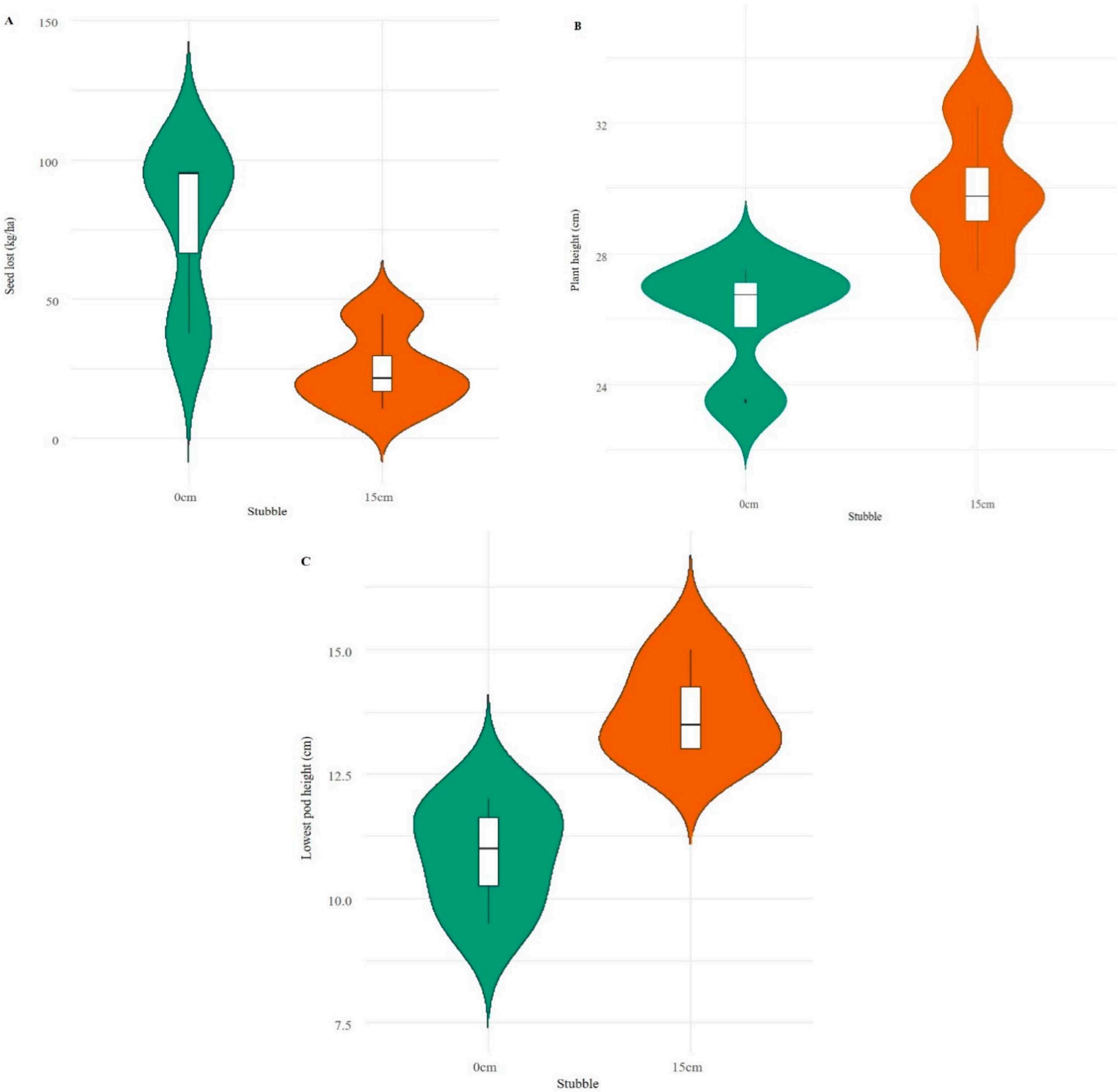

Figure 3. Stubble practice impacts on (**A**) seed lost at Scott 2017, (**B**) plant height at Scott 2018, and (**C**) lowest pod height at Swift Current 2018.

3.3. The Impact of Pesticide Application on Lentil Growth

We found that herbicide applications can significantly effect lentil yield and seed loss (Figure 1A). Herbicide applications promoted lentil yield by about 33% (Figure 4A) when compared with no herbicide treatment. As a result, lentil seed loss after herbicide applications also increased by 200% from the no herbicide treatment (Figure 4B). In this study, no significant site-year effects were found on weed control, indicating that herbicide use was not as sensitive as rolling and stubble managements to environmental effects. In addition, there were no detected interactions nor main factor effects for fungicide applications on lentil growth (Figure 1A). This could be attributed to the low disease pressure observed at all site-years due to the generally hot and dry weather conditions.

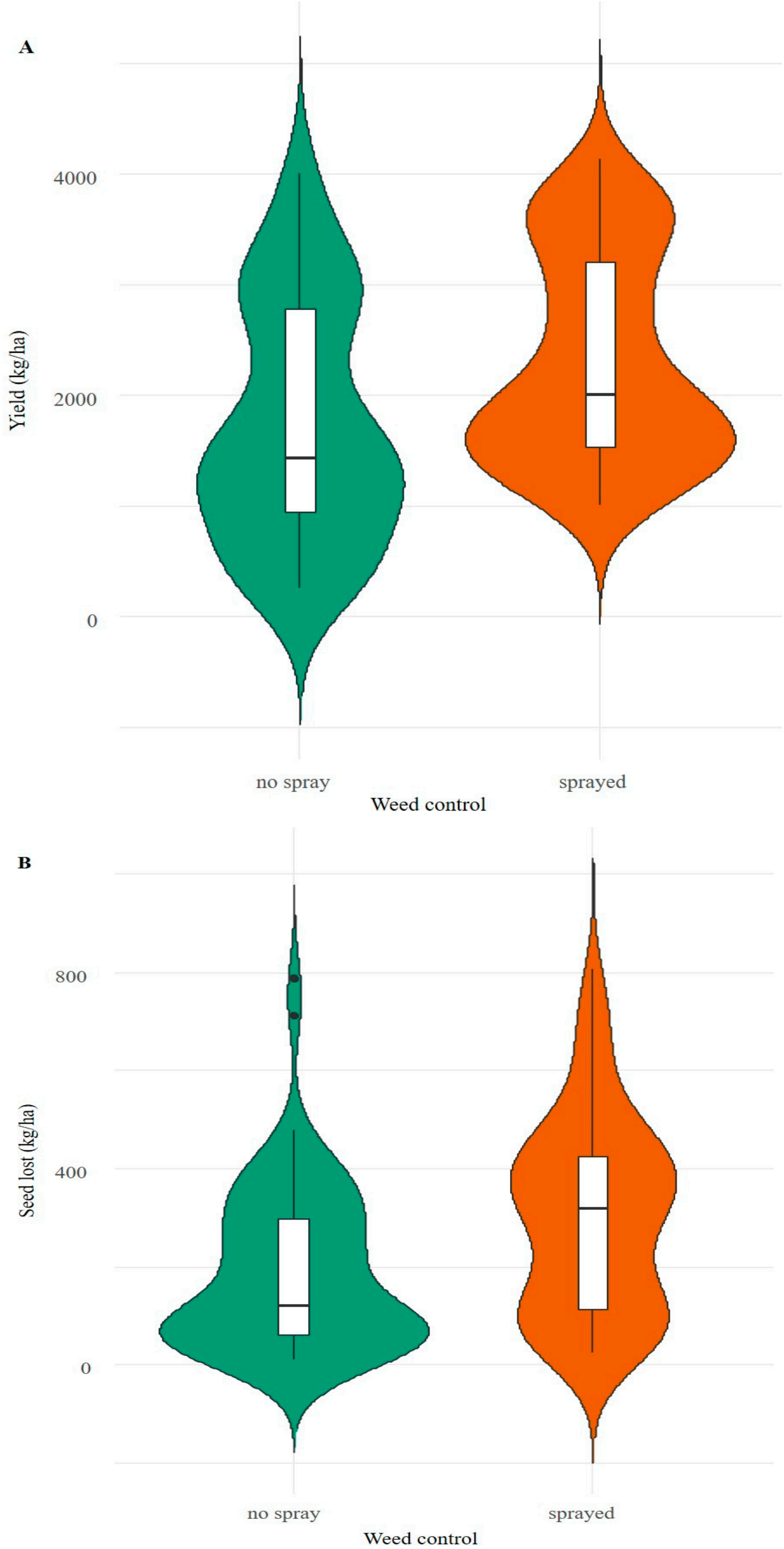

Figure 4. Weed control impacts on (**A**) lentil yield and (**B**) lentil seed lost.

4. Discussion

4.1. Optimized Timing of Rolling Can Reduce Lentil Seed Lost

The results from this study indicated that the timing of land rolling had an impact on lentil growth. Based on a meta-analysis study of Warne et al. (2019) [2], land rolling is the third most prevalent management practice in lentil production. It has been applied to more than 70% of lentil fields globally, especially in conventional fields. Land rolling mainly affects plant growth by interfering with physical soil conditions, such as reducing the air pockets and increasing resistance to soil penetration in topsoil. These changes in physical soil conditions can further modify soil micro-climate conditions. Previous research reported that land rolling can tighten topsoil structure and reduce evaporation from the soil surface, thus increasing soil water content and reducing soil temperature [6,16].

Land rolling had a significant impact on lentil seed loss at Scott in 2017, which was a relatively dry and hot year compared with the other site-years in this study (Figure S1). Therefore, land rolling before seedling emergence can optimize soil water content and temperature compared with a no rolling practice, and create micro-climate conditions that are more suitable for lentil growth. Notably, we found land rolling before seedling emergence increased lentil plant density, but land rolling after seedling emergence had the opposite effect, suggesting the timing of rolling is also critical for lentil growth. The timing of land rolling can increase topsoil resistance to a seedling's emergence. The high mechanical resistance of the compacted soils can increase root-soil contact during root development, thus modifying lentil plant density. This is in agreement with findings from previous studies [6,17,18]. Although increased soil penetration can help lentil root establishment during the growing season and lead to higher plant density and taller plants, it can also restrict lentil root development, consequently decreasing yield and seed loss [19,20]. These previous findings can explain why land rolling practices before emergence increased lentil plant density and plant establishment during the growing season but did not necessarily lead to higher yield. On the contrary, although land rolling after emergence did not change the lentil plant morphological structure, it did prevent lentil seed loss at harvesting, which may be due to the physical termination of weak lentil plants during rolling. By eliminating the weaker plants, the stronger plants are subjected to less competition for resources such as available soil moisture and nutrients.

4.2. Stubble Management Can Impact Seed Loss by Affecting Lentil Plant Height and Lowest Pod Position

In this study, we found that stubble had an impact on lentil plant morphological structure. Stubble management can influence crop growth by modifying the micro-climate. Usually, in Western Canada, a certain amount of stubble is maintained during the harvesting of cereal crops in the fall to improve snow trapping capability to provide moisture for subsequent legume and other crops [8]. Cereal stubble also plays a major role in retaining soil moisture during precipitation by reducing the evaporation rate. For example, Cutforth and McConkey [9] reported that tall stubble can reduce evaporation from topsoil by up to 25%. Under semi-arid climate conditions, such as the Prairie region of Canada, soil moisture is usually the critical factor that limits crop growth, thus increasing soil water content from stubble practices can contribute to better crop growth [8]. Moreover, stubble can affect crop micro-climate conditions, such as temperature, and thus further modify crop morphological structures—such as plant density, root diameter development, crown diameter development, and the number of tillers in cereal crops [21,22]. These findings from previous studies can explain the lentil plant morphological structure changes that we observed in this study. In particular, lentil grown in cereal stubble had a higher plant height and the lowest pod height. However, we only detected these effects in 2018, which had relatively low precipitation and high temperature during the growing season. The weather in 2018 combined with low airflow in the stubble plots may have created hot micro-climate growing conditions for lentil plants, thus promoting growth resulting in taller plants and increased lowest pod height positioning. This could be a coping strategy for the lentil plants in response to the hot environment. This is supported by findings in a previous study [21]. However, we did not detect similar results in 2017, which was also a hot and dry year, suggesting that other environmental factors may have influenced the effect of stubble on plant growth. This requires further investigation to establish the effect of other environmental factors on the effect of stubble.

4.3. Pesticide Application Can Influence Lentil Seed Loss

Fungicide and herbicide applications are commonly used in lentil fields to prevent the outbreak of fungal disease and weeds [12,14]. Usually, pesticide efficacy depends on the types of applied chemicals, application timing, seeding rates, crop cultivars, and environmental conditions [13,14]. Improper fungicide or herbicide usage can negatively impact lentil yield, milling quality, seed vigor, and unacceptable chemical residues in the seed [15,23,24]. In this study, we did not detect any significant interactions between fungicide or herbicide applications, and land rolling or stubble management, under all tested site-year conditions. In our study, the conditions during most of the test site-years were dry and hot, which are unfavorable conditions for fungal disease development. This would explain the non-significant effects of fungicide applications and the fact that there was no interaction between rolling or stubble, and fungicide applications under the prevailing conditions of this study.

The results from our study indicated that herbicide weed control affected lentil yield and seed loss. Weeds can interfere with the growth of crops by directly competing for resources, such as soil moisture and plant nutrients, and indirectly through space exploitation and allelopathic effects [25]. Therefore, eliminating weed pressure with herbicides can improve soil moisture and nutrient availability for the crop and provide better growing conditions, reducing allelopathic stress for the lentil plants. This can explain the increased yield when herbicides were applied.

4.4. Interactions among Agronomic Activities

Previous studies have reported a strong interaction among agronomic practices in the control of pests and the improvement of plant growth under field conditions. For example, Mattox et al. (2018) [26] reported interactions between rolling and fungicide applications in the control of the pathogen *Microdochium nivale* in turfgrass. Jørgensen et al. (2019) [27] found that interactions between fungicide and herbicide applications were largely influenced by different farming strategies and soil conditions in winter wheat fields. Khalil et al. (2020) [28] documented that stubble height and density can impact pyroxasulfone spray coverage and its efficacy. In general, rolling practices and stubble management can increase topsoil temperature and moisture, which could increase potential pathogen and weed pressure due to the relatively wet micro-climate, which in turn can interfere with the effectiveness of the pesticide. However, we did not detect such interactions in our study. Based on the environmental data, there was not much difference in seasonal temperature between the years of our tests, and the 15-year monthly average at both locations (data not shown). However, precipitation was lower than the 15-year average at both locations, especially in 2017 and 2018. Previous research has shown that the efficiency of many agronomic activities such as pesticide applications can be modified by environmental abiotic factors such as topsoil temperature, moisture, soil salinity, pH, greenhouse gas concentration in the micro-climate near topsoil, ultraviolet-B radiation, and airflow [29]. Therefore, we can deduce that the non-significant interactions observed among our tested agronomic practices is likely attributed to the dry growing conditions experienced during the years of the study.

In Western Canada (Saskatchewan, Manitoba, and Alberta), including lentils in various cropping systems, along with application of several popular agronomic activities—such as rolling practices and herbicide applications—are methods widely adopted by local farmers to increase dryland production, improve nutrition consumption, and bring numerous environmental and economic benefits [2,30,31]. Our results in this study confirmed findings from some of these previous studies, and provided useful knowledge for local producers to optimize their field activities for better yield with relatively less labor and chemical inputs. In modern agriculture, with the popularity of AI-based smart farming studies [32,33], the comprehensive data collected from lentil-based cropping system research could provide useful information to help lentil-involved smart farming become established in Western Canada. This could further provide critical knowledge on optimized cropping system design—that targets increasing soil nutrients and water use efficiency—improving crop yields, environmental conditions, and economic profits. Therefore, our evaluation of common agronomic practices in lentil fields could further benefit human society by providing more plant-based protein sources with better nutrition, and increase the sustainability of agro-ecosystems in the long-term by reducing both physical and chemical disturbances.

5. Conclusions

The results from this study showed that stubble management and the timing of land rolling practices can modify lentil morphological structure, consequently impacting lentil yield and seed loss. These effects were influenced by some environmental conditions such as precipitation. Although there was no significant interaction between fungicide or herbicide applications and the timing of land rolling or stubble management in this study, we found that pesticide applications can modify lentil growth and yield—depending on prevailing environmental conditions. In general, we concluded that common agronomic practices—such as land rolling, stubble management, fungicide applications, and herbicide applications in lentil fields—can affect lentil growth by modifying plant morphological structures, thus influencing yield and seed loss, which are largely influenced by environmental conditions. Therefore, optimizing agronomic activities under different eco-zones with varied environmental conditions is critical for enhancing yield and minimizing seed loss in lentils.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/4/1896/s1, Figure S1: Monthly temperature and precipitation during growing season in 2017–2019, Table S1: Details of experimental treatments in field, Table S2: ANOVA tests for all main factor effects on tested variables.

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Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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