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Influence of Recurrent Rolling/Crimping of a Cereal Rye/Crimson Clover Cover Crop on No-Till Bush Bean Yield

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Abstract: A no-till experiment was conducted in Auburn, AL U.S.A. to evaluate the effectiveness of an experimental two-stage roller/crimper in reoccurring rolling over the same area planted with a cereal rye/crimson clover cover crop mix and its influence on bush bean yield. Cover crop termination was much greater with rolling/crimping when compared to the non-rolled (untreated) control. During the three growing seasons, rolling three times had significantly higher termination rates compared to all other treatments, exceeding 90% in 2020. These results suggest that there may be an advantage to rolling/crimping three times so that planting of the cash crop could potentially be performed one week earlier, under favorable soil moisture conditions. However, for growing seasons 2018 and 2020 at three weeks after rolling, there were no differences between rolling treatments. In 2019, rolling three times over the same cover crop area was the only treatment that achieved above 90% termination rate indicating a clear advantage of recurring rolling/crimping in 2019. Rolling/crimping proved to be effective as yield was significantly higher compared to not rolled when averaged over all three growing seasons. This is possible due to the difficulty in planting into a standing cover crop which could have negative effects on seed to soil contact, but more importantly explained with the slight soil moisture advantage given to the rolled plots over the standing cover crop plots. Thus, optimum soil moisture when planting beans is key for successful germination and good main crop stand.

Keywords: roller/crimper; cover crop; no-till drill; conservation tillage

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1. Introduction

The demand for fresh produce grown by small local farms is steadily increasing along with the push for more sustainable no-till agricultural production methods. Cover crop utilization while minimizing inversion tillage has grown in popularity and become a standard practice no-till system for row crop producers. Roller/crimping to kill the cover crop by causing physical injury by crushing plant tissue can be successful if the roller/crimper is aggressive enough to effectively injure the cover crop at the appropriate growth stage [1–4]. The crimping action injures the cover crop by applying a massive vertical pressure to cover crop tissue from the crimping bars against the firm soil surface. The crimping drum with crimping bars equally spaced around the drum's perimeter mechanically injures the plant at equal intervals, leaving a thick layer of residue mulch [2,3]. The crimping effectiveness is directly related to the soil surface firmness and weight of the roller. Soil with higher moisture content is softer which can lead to the crimping bar imprinting the plant into the soil surface instead of crushing it. The advantages of this thick residue layer include retained soil moisture, reduced soil erosion, decreased soil compaction and runoff water, minimized weed seed germination, increased soil organic matter over time, reduced tractor usage and emissions, and carbon sequestration [5–9]. A field experiment conducted in Italy with organically grown zucchini [10] has shown that terminating a barely (*Hordeum distichum* L.) cover crop with a roller/crimper significantly reduced weed pressure (from 6 to 8 times) generating only 770 kg ha^{-1} of weed biomass compared with incorporated cover crop (4840 kg ha^{-1}) or fallow without covers (6020 kg ha^{-1}). However, adoption of these methods is slow for small vegetable farms as there is minimal commercially available equipment options to properly manage cover crop residue, particularly cover crop roller/crimpers that are effective with limited power lighter tractors. Some specific challenges are encountered for organic growers that are not allowed to use commercial pesticides and herbicides in their farm management toolbox [11]. These growers can be overwhelmed with no-till techniques if problems arise such as weed pressure, insects, or disease that must be managed differently than other production systems, such as conventional tillage. For example, with conventional tillage, weeds are often managed with sweep type cultivators to lightly disturb the soil and keep it loose but with no-till methods the soil is covered with desiccated cover crops that are still rooted in the soil making it very difficult to cultivate or hoe weeds. Additionally, no-till using cover crops can increase areas where insects can hide, particularly grasshoppers, that can decimate small transplants [12].

The objective of this experiment was to test the mechanical termination performance of a prototype 1.2 m-wide patented two-stage roller/crimper in a cereal rye and crimson clover cover crop mixture. A bush bean crop was no-till seeded into the rolled residue and pod yield was collected. Without using herbicide, rolling was performed one, two, or three times successively over the same area to see if termination would be accelerated with recurring passes of rolling/crimping operations over the same cover crop area compared to a single pass.

2. Materials and Methods

Cover crops (mixture of cereal rye and crimson clover) were planted in October of each year. Prior to planting the cover crops each year, P_2O_5 fertilizer were applied and incorporated with a rotary tiller at the rates of 65, 20, and 80 kg ha^{-1} on 13 October 2017, 12 October 2018, and 23 October 2019, respectively, according to the soil report for general analysis. Cover crops were planted with a Hoss Garden seeder (Hosstools, Norman Park, GA, USA) with 19 cm row spacing. The planter was calibrated for seeding rates of 50.4 kg ha^{-1} for cereal rye (*Secale cereale*, L., var. Wintergrazer 70) and 14 kg ha^{-1} of pre-inoculated crimson clover seeds (*Trifolium incarnatum*, L., var. Dixie). Rye was planted first and then clover was planted in between each row of rye. Cover crops were terminated between anthesis and early milk growth phase.

A patented 2-stage roller/crimper [13] was designed and specifically built for the Oggun I tractor (CleBer, LLC, Paint Rock, AL, USA) 3-point hitch mid-mount platform (Figure 1). The Oggun I 4-wheel tractor is a power source with a hydrostatic drivetrain (2 rear wheels powered only) by a 16.5 kW Honda GX690 engine and weighs approximately 816 kg (Honda, Tokyo, Japan). The Oggun's mid-mount 3-point hitch feature (Figure 1) can be used for combined operations with another tool mounted on the rear category I, three-point hitch for a single pass. The 2-stage roller has a smooth drum located in the front-most position of the frame (1st stage) and provides stability to the roller frame and serves as the vibration dumper (transferring vibration from the roller's frame into the ground) as it rolls over the cover crop. The crimping drum is constructed from a 11.4 cm (OD) steel tube with 6 pieces of 5.08 cm × 7.62 cm angle iron welded equally spaced on the drum's circumference along its length. Such design provides an aggressive crimping action from the crimping bars, contrary to elliptical (chevron) type rollers that are commercially available. Each of the drums has a 2.54 cm diameter solid steel shaft running through the middle that is supported by compatible pillow block bearings. This crimping drum (2nd stage) is connected with tubular arms that have rubber isolators in the pivot connector and a spring-loaded rod on the opposite end. The drum with crimping bars can pivot independently of the main frame with variable pressure provided from the adjustable spring-loaded rod assembly with a 21 kg cm^{-1} spring rate. For our field testing, the compression spring was preloaded to a distance of 2.54 cm (53 kg force from one spring; 106 kg force from 2 springs) along a crimping bar surface area of 77.4 cm^2, thus applying a static pressure of 1.4 kg cm^{-2} to the cover crop. These springs can be compressed 7.62 cm total. In addition to the force from the springs, the additional downward force comes from the crimping drum assembly weighting 80 kg. Therefore, the total downward force applied to the cover crop is 186 kg every 13.6 cm along the plant's length with downward pressure of 2.4 kg cm^{-2}.

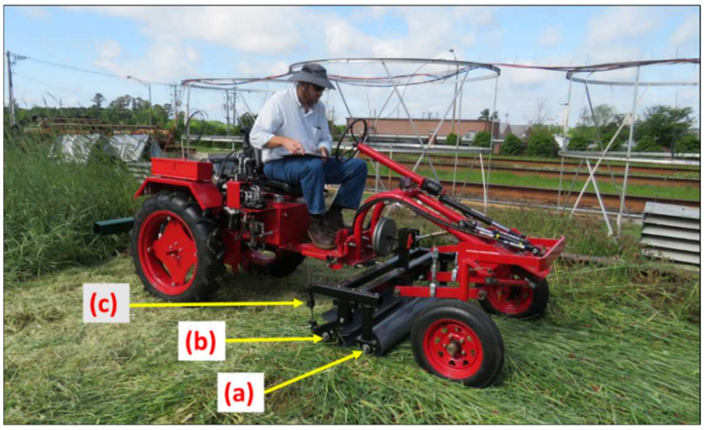

Figure 1. Oggun tractor with mid-mounted patented 2-stage roller/crimper [13]. (**a**) smooth drum for flatting cover crop and serves as the base for roller's stability; (**b**) secondary drum with crimping bars to injure cover crop in equal intervals; (**c**) compression spring to maintain down force for increased crimping efficiency.

Bush beans (*Phaseolus vulgaris*, L., var. Provider) were planted with a Morrison seeder (WHT Foundation, Durham, NC, USA) that was customized to fit on a 3-point hitch (Figure 2). The Morrison seeder is a single row planter unit originally designed for a two-wheel walk-behind tractor to plant a cash crop in no-till systems. This planter was also modified to fit a patented variable depth cutting coulter (Figure 2b) that is powered by a hydraulic motor and roller chain drive with the depth controlled with an electric linear actuator [14]. The variable depth cutting coulter system was designed to improve cutting of heavy cover crop residue for small scale planters where power and weight of the implement would limit cutting effectiveness compared to larger machines.

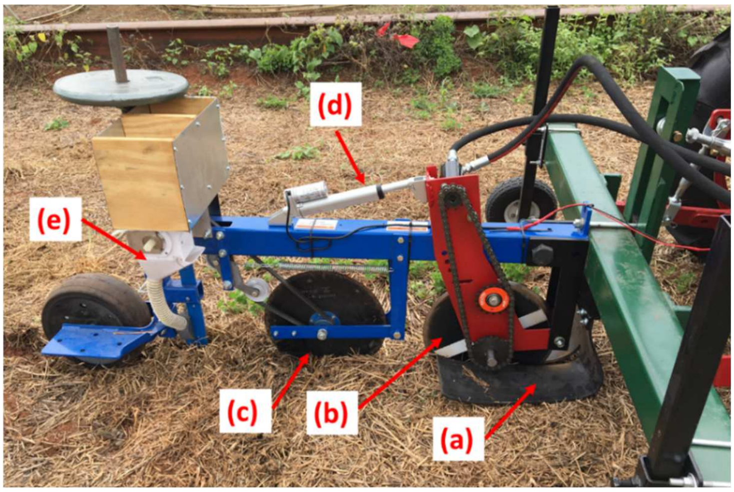

Figure 2. Modified Morrison no-till drill with powered coulter for effective cover crop cutting. (**a**) rubber shield to press cover crop against the soil; (**b**) powered coulter with hydraulic motor drive to cut the cover crop residue and topsoil [14]; (**c**) secondary coulter with welded spikes (on opposite side: not shown) for better engagement with the soil and to power the metering unit of the drill; (**d**) electric linear actuator to control the depth of the powered coulter in the soil; (**e**) metering unit assembly with seed discharge tube, seed dispensing box, and rubber closing wheel.

The experiment was conducted at the National Soil Dynamics Laboratory in Auburn, AL, USA, (32.61° N, −85.48° E) on a Davidson Clay soil having 25% sand, 31% silt, 44% clay (a clayey kaolinitic thermic (oxidic) Rhodic Paleudults). The experiment started with planting cover crops in October of 2017 and was concluded in July of 2020 for a total of 3 complete growing cycles (seasons). Rolling treatments were applied according to the plot layout with standing plots used as a control. The experimental layout, depicted in Figure 3, consisted of four different treatments in a randomized complete block design (RCBD) configuration. The four treatments included R1 (rolled once), R2 (rolled twice), R3 (rolled three times) over the same cover crop area, with the control (C) for comparison (standing control: untreated. Treatments were randomized within each block. All rolling/crimping treatments were completed in the same day. Due to space constraints, the standing plots were 4.57 m and the rolled plots were 6.1 m. Four border plots were included to allow space for equipment maneuvering with a length of 3.05 m.

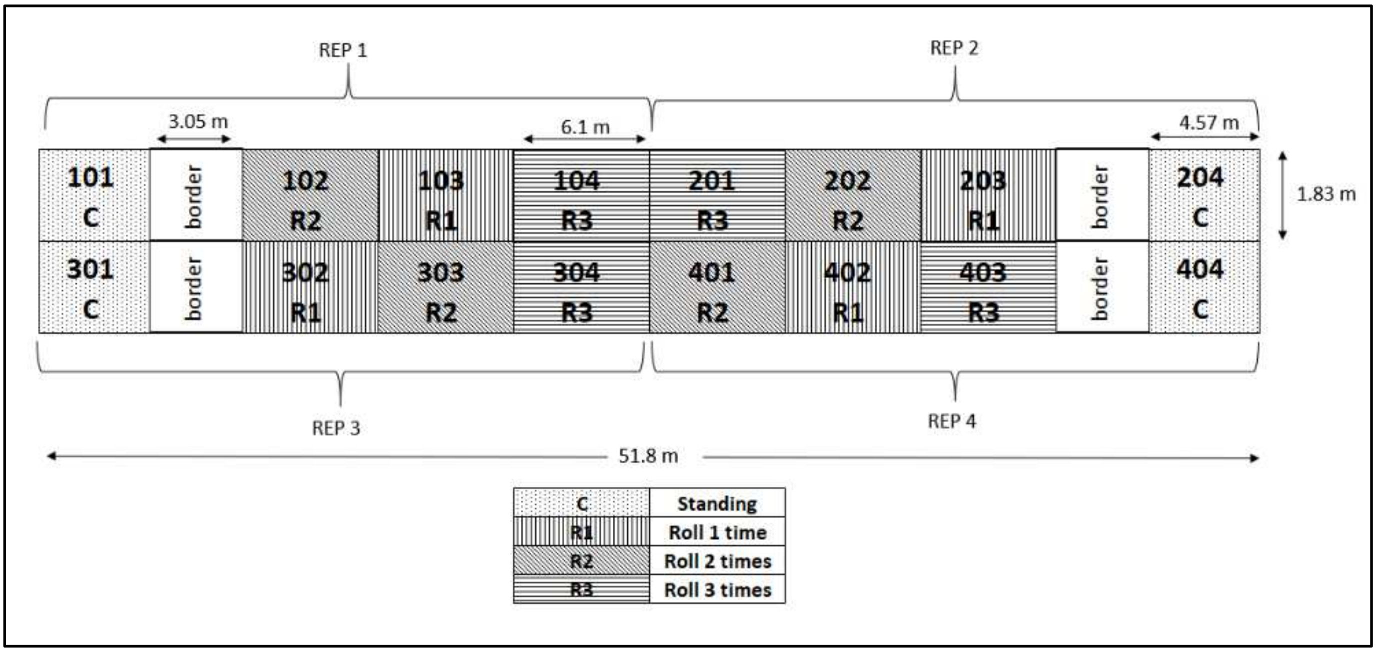

Figure 3. Experiment layout: the randomized block design with four replications.

Immediately prior to applying termination treatments, cover crop production data was collected including biomass and plant heights. A single 0.25 m^2 biomass sample was collected per plot along with 6 heights for each cover crop per plot (i.e., 6 per rye; 6 per clover for each plot). Biomass samples were cut, placed in paper bags, then the samples were placed in a programmable electric shelf oven with forced air flow by convection for 24 h at a temperature of 55 °C (Model No. SC-400 manufactured by Grieve Corporation, Round Lake, IL, USA) to dry down and remove water content from the sample. After the drying process, the cover crop samples were then weighed and recorded. Plant heights were collected using a foldable measuring stick from the soil surface to the top of the seed head of both rye and clover.

Termination data were collected utilizing the SPAD 502 chlorophyll meter (Spectrum Technologies, Aurora, IL, USA). Since cover crop species were not separated for individual biomass data, it was assumed that rye accounted for 80% of the plot cropping area and the clover accounted for the other 20% of the plot cropping area. These percentages were used to give weighted termination values by crop to the termination data collected with the SPAD chlorophyll meter. This was a way to give more weight to the rye compared to the clover regarding percentage kill data (termination) which is more representative of each of the crop's contribution to the mixture. To evaluate the cereal rye and crimson clover termination rates, data collected with a handheld SPAD chlorophyll meter was converted utilizing a linear regression equation and procedure described by Kornecki et al. (2012) [15]. Volumetric soil moisture content (VMC) using the time domain reflectometry soil moisture meter TDR300 (Spectrum Technologies, Aurora, IL, USA). All data were collected weekly for 3 weeks after the termination was complete. Plant chlorophyll content data from 0 to 50 scale, where 0 is 100% of termination (no chlorophyll activity) and 50 is 0% termination rates (plant green with full chlorophyll activity) were collected 3 times per plot with individual leaf samples of each species (3 per species per plot) and VMC was collected 3 times per plot.

After week 3, a single row of bush beans was planted into each plot using a Morrison planter (Figure 3) with the patented variable depth cutting coulter system [14]. Successive harvests were collected approximately two times per week depending on plant production. In 2018 and 2020, there were 6 bean harvests, whereas 7 harvests occurred in 2019. The harvested beans were then weighed, and the weight was recorded by plot. The field activities during three growing seasons are presented in Table 1.

Table 1. Detailed field activities of the experiment during three growing seasons 2018–2020.

Field Activities	Growing Season		
	2018	**2019**	**2020**
Cover crop planting	20 October 2017	12 October 2018	24 October 2019
Collect biomass and plant heights	17 April 2018	15 April 2019	3 April 2020
Collect mc, chlor-wk0	18 April 2018	16 April 2019	6 April 2020
Termination treatment applied	18 April 2018	16 April 2019	6 April 2020
Week 1 termination data	25 April 2018	24 April 2019	14 April 2020
Week 2 termination data	2 May 2018	30 April 2019	20 April 2020
Week 3 termination data	9 May 2018	7 May 2019	27 April 2020
Planted bush beans	7 June 2018	16 May 2019	22 May 2020
Harvested beans #1	20 July 2018	2 July 2019	8 July 2020
Harvested beans #2	25 July 2018	8 July 2019	14 July 2020
Harvested beans #3	30 July 2018	12 July 2019	17 July 2020
Harvested beans #4	3 August 2018	18 July 2019	22 July 2020
Harvested beans #5	8 August 2018	24 July 2019	28 July 2020
Harvested beans #6	17 August 2018	31 July 2019	31 July 2020
Harvested beans #7	-	6 August 2019	-

Weather data (AWIS, 2021) [16] are presented in Table 2 which show cumulative precipitation and the average ambient minimum and maximum temperatures for specific periods of agronomic activities during growing seasons (from 2017 to 2020) which had an influence on cover crop production and bush bean yields.

Cover crop plant length and biomass, termination data, volumetric soil moisture content, and bean yield were subjected to analysis of variance and treatment means were separated using the Fisher's protected Least Significant Differences (LSD) test at the 0.10 (10%) probability level. Cover crop mixture and roller/crimper were considered fixed effects and years were considered random effects [17]. Where interactions between treatments and weeks or years occurred, data were analyzed separately and where no interactions were present, data were combined using SAS [18], ANOVA Analyst's linear model.

Table 2. Rainfall amounts and ambient temperatures (minimum and maximum) in each growing season during specified periods of agronomic field activities.

Time Period for Specific Agronomic Field Activities	Cumulative Rainfall (mm)			Average Minimum Temperature (°C)			Average Maximum Temperature (°C)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
Time within one month before cover crop planting *	126	160	53	17.7	21.9	18.0	27.9	30.9	29.2
Time within one week before cover crop planting *	0	101	30	14.5	21.7	11.2	25.5	29.6	21.9
Time between planting cover crop and its termination *	601	670	861	5.0	7.7	7.5	17.1	18.2	18.3
Time within one month before cover crop termination	212	54	28	6.6	10.1	12.8	22.4	21.8	24.0
Time within one week before cover crop termination	100	29	5	4.8	16.2	10.3	23.3	27.0	24.1
Time within three weeks of termination	37	80	224	12.1	14.1	12.1	24.7	25.9	23.5
Time from third week of termination to beans planting	96	73	29	20.1	17.4	13.6	29.5	27.1	25.3
Time from planting cash crop to its first harvest	754	82	157	20.7	20.9	20.6	31.5	31.3	30.0
Time between first harvest and last harvest	59	92	86	22.1	22.1	22.8	31.3	32.4	32.3

* Planting of cover crops was accomplished in preceding fall periods (e.g., cover crop for 2018 growing season was planted in October of 2017).

3. Results and Discussion

3.1. Plant Length and Biomass Production for Cereal Rye and Crimson Clover Mixture

Plant lengths for both variables: CROP (cover crop) and YEAR (growing season) were highly significant with their respective $p < 0.0001$ and 0.0004. In addition, there were significant interactions between CROP and YEAR variables with $p < 0.0001$ (Table 3), so analysis was performed separately for each cover crop and each year. Results for the plant length are presented in Table 4. For cereal rye, the length was significantly greater for the 2020 growing season reaching 166.1 cm followed by 151.1 cm in 2019 and 159.6 cm in 2018. The crimson clover had a significantly greater length of 74.1 cm in 2018, followed by 67 cm in 2019, and the shortest length of 56.8 cm was observed in 2020. The length of the clover decreased consecutively every year which was most likely explained by its declining stand establishment and contribution to the total biomass. However, the biomass samples were not separated by species, as the total combined weight of cover crop mixture was assessed. Across all growing seasons, average plant length was 158.9 cm and 66 cm for cereal rye and crimson clover, respectively. Results from on-farm replicated field experiment in central Alabama [12], have shown that the length for cereal rye and crimson clover in mixture was 149.4 and 54.4 cm, respectively. Similar results for crimson clover were found in previous research [19] at northern Alabama generating average plant height of 165.4 cm for cereal rye and 54.1 cm for crimson clover.

Table 3. ANOVA results with respect to cover crop plant length and biomass mixture.

Cereal Rye and Crimson Clover Length			Cover Crop Mixture Biomass		
Effect	F-Value	*p*-Value	Effect	F-Value	*p*-Value
REP	3.19	0.0276	REP	1.08	0.3721
YEAR	8.67	0.0004	YEAR	33.21	<0.0001
CROP	3524.65	<0.0001	TRT	0.25	0.8620
CROP*YEAR	27.27	<0.0001	YEAR*TRT	0.64	0.7000

Table 4. Plant length in the mixture of cereal rye/crimson clover and combined biomass mixture.

YEAR	Cereal Rye Length (cm)	Crimson Clover Length (cm)	Mixture Biomass kg ha^{-1}
2018	159.6 b *	74.1 a	11,646 a
2019	151.1 c	67.1 b	7398 b
2020	166.1 a	56.8 c	7659 b
p-value	0.0002	<0.0001	<0.0001
LSD	5.4	3.5	989

* Same lower-case letters indicate no yield difference in each column among growing seasons.

There were significant differences in biomass amounts of cover crop mix among the years ($p < 0.0001$, Table 3) indicating that different weather and climatic conditions affected the biomass production presented in Table 4, especially the biomass of clover in the mix. The first year, 2018, produced the highest amount of biomass measured at 11,646 kg ha^{-1} and significantly more than other years. Both 2019 and 2020 showed statistically similar biomass amounts with 7398 and 7659 kg ha^{-1}, respectively, but both were significantly lower than that produced in 2018. These results represent average biomass production in Alabama cited in previous study [19–21], and these biomass amounts were weather related.

During the three-year field experiment conducted on-farm in central Alabama with different cover crops [12], the dry biomass of cereal rye and crimson clover mixture ranged between 4712 and 8120 kg ha^{-1} with average biomass of 6965 kg ha^{-1} across 2009 to 2011 growing seasons. In another experiment [22] conducted in Indiana at three sites and 2 growing seasons, similar biomass production of cereal rye and crimson clover mixture was between 5451 and 8144 kg ha^{-1}, with average biomass of 6703 kg ha^{-1} across years and sites. According to researchers [23] who conducted a multiyear field experiment in North Carolina, USA, the biomass of cereal rye and crimson clover mixture was between 3820 and 6610 kg ha^{-1}, but they stated that these levels were below expectation of >8000 kg ha^{-1} to provide adequate weed control. In fact, under optimum weather conditions and fertilization, researchers [24] reported that in that region, cereal biomass can exceed 9000 kg ha^{-1}, whereas biomass for crimson clover can reach 5500 kg ha^{-1}. Despite some similarities in biomass production, the range of differences in growing seasons and locations were mainly dependent on different weather and soil moisture conditions.

The higher biomass for the 2018 season can be explained by the higher soil available moisture during the most vigorous cover crop growth in the spring (March and April). As showed in Table 2, during one month before cover crop termination the highest rainfall amount of 212 mm was reported in 2018 growing season compared with 54 mm in 2019 (74.5% less than in 2018) and the lowest rainfall of 28 mm in 2020 (86.8% less than in 2018). These similar rainfall trends continued one week before applying rolling treatments to terminate cover crop mixture. In 2018, one week before cover crop termination rainfall amount was 100 mm compared to lower amounts of 29 mm in 2019 and only 5 mm in 2020. Biomass results for the cereal rye during the three growing seasons do not correspond with cereal rye heights as the tallest stems do not produce higher biomass, i.e., shorter plants can be thicker and might generate larger biomass amounts. In contrast, these rainfall amounts impacted crimson clover heights with the tallest plant of 74 cm in 2018 indicating greater biomass production, compared to 67 cm and 56 cm for 2019 and 2020, respectively, generating lower biomass.

3.2. Cover Crop Mixture Termination

The rate at which the cover crop died was assessed with a chlorophyll meter. This meter was used to collect the chlorophyll activity on three individual leaves of each cover crop (rye and clover) to obtain an accurate assessment. The initial analysis of variance results presented in Table 5 indicates that significant differences in cover crop termination were reported for variable YEAR, WEEK, and TRT all with $p < 0.0001$. In addition, the interactions between WEEK*TRT variables were also significant ($p < 0.0001$). Therefore, the analysis of variance was performed separately by YEAR and then presented by week for each rolling treatment.

Table 5. Analysis of variance with respect to cover crop mixture termination.

Effect	F-Value	*p*-Value
REP	2.49	0.0620
YEAR	30.47	<0.0001
WEEK	1102.42	<0.0001
TRT	554.76	<0.0001
YEAR*TRT	1.71	0.1210
YEAR*WEEK	1.72	0.1189
WEEK*TRT	66.93	<0.0001

3.2.1. 2018 Termination Rates

For 2018, week 0 termination ranged from 9.7% (standing) to 15.9% (rolled once) (Table 6). For week 1, all rolling treatments were statistically similar with an average of 56.8% compared to a significantly lower Standing amount of 13%, illustrating that the rolling treatments were very effective at advancing the termination of the cover crops at one week after rolling. However, 56.8% termination rate is not sufficient for planting the subsequent cash crop, as it is recommended that planting of the main cash crop be done at rates of 90% or greater [1]. The results for week two after rolling showed significant difference for the rolling three times treatment with the highest reported termination rate of 86.8% followed by 73.3% for rolling twice and 63.7 % for rolling once. Rolling multiple times causes more injury with every pass and is illustrated with the termination rates being in a step sequence. The standing control was significantly less compared to all rolling treatments at 18.8%. The rolling three times treatment at week 3 was the only treatment to achieve greater than 90% termination rate measured at 91.2%. Similar results were obtained by [25] when in one growing season, termination rates for mixture (cereal rye, crimson clover and hairy vetch) rolling three times with two-stage roller/crimper exceeded 95%. However, rolling twice and rolling once treatments were not different statistically with 87.6% and 88.8%, respectively, indicating that these where at a high enough death percentage for adequate planting conditions without competition between the cash crop and cover crop for moisture and nutrients.

Table 6. Cover crop termination results (%) during 2018, 2019, 2020 growing seasons for cereal rye/crimson clover mixture.

Rolling Treatment	Week 0	Week 1	Week 2	Week 3
		2018		
Standing	9.7 b *	13.0 b	18.8 d	45.5 b
Rolling once	16.0 a	58.3 a	63.7 c	88.8 a
Rolling twice	14.6 a	55.7 a	73.3 b	87.6 a
Rolling three times	12.7 ab	56.5 a	86.8 a	91.2 a
p-value	0.0776	<0.0001	<0.0001	<0.0001
LSD	3.94	11.13	7.20	5.82
		2019		
Standing	9.3	12.9 c *	14.5 c	28.7 d
Rolling once	10.4	45.0 b	69.9 b	75.5 c
Rolling twice	5.6	49.1 ab	72.5 b	83.6 b
Rolling three times	4.7	54.8 ab	80.4 a	91.1 a
p-value	0.3924	<0.0001	<0.0001	<0.0001
LSD	N/S	9.10	5.06	4.15
		2020		
Standing	12.1	21.6 c *	16.6 d	31.4 b
Rolling once	13.6	51.9 b	68.2 c	96.5 a
Rolling twice	14.4	58.5 b	79.1 b	94.7 a
Rolling three times	13.8	70.9 a	91.7 a	97.9 a
p-value	0.7701	<0.0001	<0.0001	<0.0001
LSD	N/S	7.88	5.05	7.00

* Same lower-case letters indicate no yield difference in each column at each week of the evaluation.

3.2.2. 2019 Termination Rates

Termination data by treatment and week are presented in Table 6. For 2019, week 0 termination, no significant differences were found among all rolling treatments and the control ranging from 4.7% to 10.4%. These numerical values were associated with the slight differences in cover crop maturity within the experimental area, since at week 0, termination data were collected before rolling treatment application. At week 1 after rolling, a significantly higher termination rate was obtained for rolling three times at 54.8 % compared to rolling once (45.0%) but rolling twice at 49% was not significantly different than rolling three times. The control was significantly lowest for week one after rolling at 12.9%. The rolling three times treatment for week two was significantly highest at 80.4%. The once and twice rolled termination rates were similar at 69.9% and 72.5%, respectively, with the control being the lowest at 14.5%. At week three after rolling, termination rates for all rolling treatments were significantly different. The rolling three times treatment has the highest termination rate at 91.1%. These results follow findings from previous field experiment conducted in northern Alabama, USA with cover crop mixture (cereal rye crimson clover and hairy vetch) [25] generating 97% termination rates rolling three times at three weeks after rolling. The rolling twice treatment was lower than rolling three times at 83.6% followed by rolling once having termination rate of 75.5%. The lowest termination rate was associated with the control at only 28.7%.

3.2.3. 2020 Termination Rates

For the 2020 season at week 0, no differences existed between any of the treatments and the control (Table 6). Week 1 showed an advantage in the rolling three times treatment at 70.9%, which is the highest kill rate for week 1 for all years. The once and twice treatments were similar at 51.9% and 58.5%, respectively. The untreated control had the lowest termination rate at 21.6%. The rolling three times treatment generated a termination rate of 91.7%, already at the second week after rolling, again having the highest kill rate for week 2 out of all years and treatments. The rolling two times treatment was second best at

79.1% followed by rolling once at 68.2% compared to the control at 16.6%, all significantly different. For week 3, the rolling treatments measure similarly with an average of 96.4% compared to the lower control at only 31.4%. For 2020, rolling three times showed a significant advantage over only rolling once or twice providing a termination rate of 91.7% at 2 weeks after rolling signifying that the cash crops could be planted earlier compared to the other treatments.

Overall, results from all growing seasons indicate that cover crop termination rates for week two or three after rolling illustrates the advantage of rolling three times by generating termination rates exceeding 90% that according to Ashford and Reeves (2003) [1] are sufficient rates to plant a cash crop into desiccated residue cover. According to [21] rolling cereal rye three times with a two-stage roller/crimper generated termination rates consistently above 90% (91–100%) after 7, 14, and 21 days, indicating that planting of main crop can be accomplished earlier than three weeks after cover crop termination. These results also agreed with other studies [26–28] showing that three times rolling over the same cover crop area accelerates termination rates using rollers/crimpers which is very important in organic no till-systems with cover crops, as using commercial herbicides is prohibited and efficient termination of cover crops is solely dependent on mechanical termination by rollers/crimpers. The advantages of earlier cash crop planting can be a reduced weed, insect, and disease pressure compared to later planting.

3.3. Soil Volumetric Moisture Content (VMC)

Volumetric moisture readings were collected weekly starting at week 0 (day of termination) up to week 3 (3 weeks after termination) to compare the soil moisture amounts between the standing control plots and the rolling treatments. The initial results (Table 7) show difference for YEAR, WEEK, and TRT with $p < 0.0001$. The interactions of YEAR*WEEK and WEEK*TRT were also significant ($p < 0.0001$), therefore, the statistical analysis for this experiment was separated by YEAR and then presented by week for all treatments.

Table 7. Analysis of variance for the soil VMC.

Variable	F-Value	*p*-Value
REP	11.27	<0.0001
YEAR	131.75	<0.0001
WEEK	110.30	<0.0001
TRT	51.01	<0.0001
YEAR*TRT	0.71	0.6424
YEAR*WEEK	131.67	<0.0001
WEEK*TRT	4.34	<0.0001

3.3.1. Soil VMC in 2018 Growing Season

VMC results from 2018 growing season are shown in Table 8. The VMC for week 0 showed no significant difference between any of the treatments and the control, which was expected as data were collected before rolling treatment application. For week one, significantly higher VMC of 15.5 % was observed for rolling three times (R3) and 16.5% for rolling twice (R2) without significant difference between rolling three times treatment (R3) and rolling once treatment (R1) having VMC of 14.8%. The lowest volumetric soil moisture content was measured for the standing cover crop at 11.6%, which is realistic, considering that the standing cover crop is still actively growing, and the soil surface is not completely covered, allowing more moisture loss to the air (i.e., more soil evaporation). For week 2, the rolling treatments were all statistically similar ranging from 12.9% (R3) down to 11.89% (R1). The lowest for week 2, was again the standing control treatment at 9.4%. For week 3, the results experienced significant but decreased separation with a $p = 0.0702$, which shows that the cover crops, including the standing, are consuming less soil moisture for growth as plants mature and its termination rates have advanced. The R1, R2, and R3 treatments were statistically similar with the R2 treatment also being similar to the untreated control (standing) cover crop. Similar results were obtained by researchers [3] who examined rolling/crimping effect of different rollers/crimpers on volumetric soil moisture content. Utilizing mechanical termination and comparing with standing cover rye crop, an average VMC in 2006 was 10.5% using two-stage roller/crimper vs./7.1% for standing rye cover crop. In 2007, when a severe drought occurred during the evaluation period of 3 weeks after rolling, VMC with two-stage roller was 3.3% compared to 1.8% VMC for untreated cover crop. In 2008, the soil VMC with two-stage roller was 6.9% compared with 4.1% for an untreated (standing) rye cover crop. These results clearly indicate that covering soil surface with flattened and terminated cover crop residue conserves soil water.

Table 8. Soil volumetric moisture content (%) in 2018, 2019, 2020 growing season assessed from rolling treatment application up to three weeks after rolling.

Rolling Treatment	Week 0	Week 1	Week 2	Week 3
2018				
Standing	13.0	11.6 c *	9.4 b	8.3 b
Rolling once	13.4	14.8 b	11.8 a	9.6 a
Rolling twice	13.2	16.5 a	12.1 a	9.4 ab
Rolling three times	13.4	15.5 ab	12.9 a	10.4 a
p-value	0.3848	<0.0001	0.0071	0.0702
LSD	N/S	1.06	1.38	1.21
2019				
Standing	11.6 b *	11.9 b	11.7 b	14.1 b
Rolling once	12.5 ab	14.7 a	13.1 ab	16.5 a
Rolling twice	11.7 b	14.9 a	13.7 a	17.1 a
Rolling three times	13.2 a	15.7 a	14.5 a	17.1 a
p-value	0.0840	0.0261	0.0349	0.0017
LSD	1.12	1.93	1.48	1.08
2020				
Standing	9.7	14.0 b *	19.3 b	11.4 b
Rolling once	9.4	17.6 a	21.7 a	14.3 a
Rolling twice	10.7	18.9 a	22.0 a	14.2 a
Rolling three times	10.5	18.1 a	21.7 a	14.3 a
p-value	0.2026	0.0074	0.0738	0.0007
LSD	N/S	2.00	1.77	0.94

* Same lower-case letters indicate no soil VMC difference in each column at each week of the evaluation.

3.3.2. Soil VMC in 2019 Growing Season

In contrast to 2018, the 2019 growing season noticed statistical differences for week 0 even though the treatments were not applied yet which could be contributed to in-field variability (Table 8). For week 1, the rolled treatments showed no statistical differences, however VMC numerical values were greater compared to the standing control plots. Similar results were detected for weeks 2 and 3, however for week 2, similarities were observed for the rolling once treatment compared to the standing control plots. A deeper look into week 3 shows the average VMC for the rolling treatments to be 16.9% which is 20% more soil moisture compared to the standing plots. VMC results by treatment within each week seemed to follow a trend for 2019 in which the VMC was numerically higher for rolling three times and then decreasing order according to the number of roll/crimp passes. Faster termination occurred with the 3X rolling which noticed an increase in VMC compared to the other treatments, although it was not significantly different than the rolling twice or rolling once treatment. The standing control plot was significantly less than all the rolling treatments for weeks 1, 2, and 3 while the cover crop is still actively growing and consuming soil moisture to develop compared to the rolled/crimped treatments. Results from another field experiment in Northern Alabama conducted in 2011 [28] supports these findings, as the VMCs for rolled/crimped rye residue by two-stage roller/crimper were significantly higher: 18.2%, 13.3% and 19.0% compared with the untreated control of 12.6%, 6.6% and 11.9%, at 1, 2, and 3 weeks after rolling, respectively.

3.3.3. Soil VMC in 2020 Growing Season

In 2020, no treatment differences were observed for week 0 (Table 8). The same trend existed for weeks 1, 2, and 3 with all rolling treatments being similar within weeks but statistically different than the standing cover control treatment. Rainfall events did occur between week 0 and 1 readings along with a rainfall event in the amount of 144 mm [16] occurring on the day when the week 2 VMC readings were collected (Table 2) which explains the increase in the average VMC at week 2 for rolled/crimped treatments of 21.8% compared to 19.3 for the standing (control). Similar results with increased VMC were reported by researchers [28] where in 2010 three weeks after rolling, VMC for rolled/crimped rye residue by the two-stage roller/crimper was 26.0% compared to 21.9% for the control after two rainfall events with the total rainfall amount of 43 mm.

Overall, volumetric soil moisture results obtained during three growing seasons, consistently showed that rolling down cover crops against soil surface conserves soil water. In contrast, for an untreated cover crop mixture (standing cereal rye and crimson clover), there was more bare soil exposed between plants, allowing for more soil evaporation. In addition, evapotranspiration of still-living rye and clover plants further depleted soil moisture, thus not conserving soil water. These findings agreed with several previous field studies with cover crops [2,3,5–7,27] in which benefits from cover crops residues were identified, such as increased water holding capacity due to a mulch effect.

3.4. Bush Bean Yield

Based on ANOVA results (Table 9) from three growing seasons, there was significant difference in the bush bean yield with respect to YEAR (p = 0.0002) and TRT (p = 0.0668) variables. However, there were no significant interaction between YEAR and TRT, therefore differences for main effects (YEAR and TRT) are analyzed separately and reported by year with respect to rolling treatments.

Table 9. Analysis of variance results for bush beans yield.

Variable	F-Value	*p*-Value
REP	1.02	0.3948
YEAR	11.56	0.0002
TRT	2.63	0.0668
YEAR*TRT	0.72	0.6371

The bush bean yield for the 2018 season averaged over all rolling treatments was significantly higher producing 23,160 kg ha^{-1} when compared to lower yield of 19,892 kg ha^{-1} in 2020 (14.1% lower than in 2018) and the lowest yield of 16,838 kg ha^{-1} (27.3% lower than in 2018) was obtained in 2019 (Table 10). The main reason for the yield difference in each growing season was the amount of available water to grow plants. In fact, the total rainfall amount in 2018 from planting the beans to their first harvest was 754 mm, compared to a much lower rainfall of 157 mm (20.8 % of 2018 rainfall) in 2020 and the lowest rainfall amount of 82 mm (10.2% of 2018 rainfall) that was received in 2019 (Table 2). As shown in Table 11, for both growing seasons of 2018 and 2019, no significant differences in the yield were observed among rolling treatments and the control. For 2020, the rolling treatments showed statistically higher yield with an average of 21,153 kg ha^{-1} compared to the lower yield of the control at 16,109 kg ha^{-1}.

Table 10. Bush bean yield (kg ha^{-1}) at each growing season averaged over rolling treatments.

YEAR	Bush Bean Yield
2018	23,160 a *
2019	16,837 c
2020	19,892 b
p-value	0.0002
LSD	2225.5

* Same lower-case letters indicate no yield difference in the second column among growing seasons.

Table 11. Bush beans yield (kg ha^{-1}) in each growing season and average yield over all growing seasons with respect to rolling treatments.

Rolling Treatment	2018	2019	2020	Average over Years by Treatment
Standing (untreated)	23,126	13,032	16,109 b *	17,422 b
Rolling once	21,718	18,084	21,013 a	20,272 a
Rolling twice	23,751	17,647	21,430 a	20,943 a
Rolling three times	24,044	18,587	21,015 a	21,215 a
p-value	0.4551	0.2777	0.0270	0.0668
LSD	N/S	N/S	2951.9	2570.0

* Same lower-case letters indicate no yield difference in each column among rolling treatments.

Across treatments and years, the overall average pod yield was 19,963 kg ha^{-1}. Similar results were obtained from a field experiment conducted by a researcher [29] in Oregon, USA, who examined water availability effect on bush beans, and reported pod yields between 15,864 kg ha^{-1} and 19,348 kg ha^{-1}. In another field experiment conducted [30] in India with different biostimulants, the total produced pod yield was 12,600 kg ha^{-1}, which was about 37% lower than yield obtained from this study and [29]. A yield of main crops under organic no-till farming with cover crops is also very dependent of the geographical location. In fact, a significant cabbage yield reduction (68–100%) with cover crops terminated by a roller/crimper was reported by European researchers [31] from a multi-location study in Denmark, Estonia and at three locations in Belgium (northern and western Europe). Results from [31] indicated that the main reason in seven out of nine cases was mainly due to slower mineralization/degradation of cover crop residues and reduced soil mineral nitrogen availability. In contrast, rapid cover crop degradation in Alabama's subtropical climate with higher temperatures allow to release soil nitrogen that is available to main crops.

On average over all growing seasons, the rolled three times treatment had slightly higher numerical value for yield (21,215 kg ha^{-1}) when compared to other treatments, but these numerical values were not statistically different. This is most likely due to the increased cover crop death rate that allowed for slightly better planting conditions including soil moisture and cover crop plant brittleness. However, averaged across all years, rolling treatments yielded more beans compared to the standing treatments. This emphasizes the importance of cover crop management using roller/crimpers to retain soil moisture for better bush bean establishment.

3.5. Economic Considerations

In the middle of 2022, the United States national average price for regular grade gasoline is US $1.04 L^{-1} [32] which is higher due to international tensions and inflation. The Oggun tractor having a hydrostatic drive, will be operated at full throttle with a fuel consumption rate of 6.7 L h^{-1} at 3600 rpm [33]. The roller/crimper is 1.22 m wide and would cover approximately 0.67 ha h^{-1} operating at a speed of 6.44 km h^{-1} with 75% field efficiency [34]. Based on these parameters and gasoline physical properties (density) [35], the total gasoline consumption is 7.2 kg ha^{-1}, which is more than the total fuel/lubricant usage of 4.8 kg ha^{-1} reported by European researchers in Italy [36]. This difference is related to the 27 percent lower energy value for gasoline than from diesel fuel [35] along with the 75% field efficiency adjustment to account for overlap and turning around after each pass.

Using the procedures outlined in [34], both fixed and direct machinery costs for the tractor and roller/crimper were included in the economic calculations per pass with the roller/crimper. Total cost (fixed and direct) was US \$56.01 ha^{-1} for a single pass with the roller/crimper at this travel speed and would take approximately 1.5 h to complete a rolling one hectare of cover crop area. Rolling two and three times would take 3 and 4.5 h to complete at a cost of US \$112.02 and US \$168.02 ha^{-1}, respectively.

According to the USDA National Agriculture Statistics Service [37], the 5-year average retail price for fresh market bush beans was USD 1.36 kg^{-1}. Based on bush bean yield (Table 11), it would provide USD 27,569.92 ha^{-1}, USD 28,482.48 ha^{-1}, and USD 28,852.40 ha^{-1} income for 1, 2, and 3 rolling passes, respectively. An increase of USD 912.56 ha^{-1} and USD 1282.48 ha^{-1} would be given with two passes and three passes of rolling, respectively, compared to a single pass in income per ha^{-1}. However, since bush bean yield difference among rolling passes is not statistically different, benefits from rolling three times v/s once or twice are related to cover crop termination results. Cover crop termination data suggests that rolling three times could provide optimum conditions (above 90% termination rate and increased soil moisture) for planting the cash crop one week sooner than rolling one and two times. That additional week of planting opportunity could result in faster cash crop establishment and ultimately increased crop yield which could overcome the additional costs (e.g., fuel, labor, depreciation) to perform the multiple rolling/crimping operations. Our calculated additional cost of each pass does not include the opportunity cost of the producer's time. Some diversified mixed vegetable producers may have draws on their time from the other crops that they manage worth more than the additional profit we estimated for fresh market bush beans.

4. Conclusions

Cover crop termination rate was significantly higher for the rolling/crimping treatments compared to the non-rolled control. For all three years, the three times rolled treatment had significantly higher kill percentage compared to all other treatments at two weeks after rolling treatments were applied, with over 90% in 2020. This shows an advantage to rolling/crimping three times to allow successful cash crop that could potentially be performed one week earlier compared to the recommended 3-week interval, under certain conditions. The advantages of planting a week earlier are important in no-till to avoid increased weed and pest pressure as well as higher temperatures that occur later in the season. This could help get crops to market earlier. Rolling/crimping proved to be effective as yield was significantly higher compared to not rolled when averaged over all 3 growing seasons. Although statistical significance was not observed for yield and monetary benefits, rolling three times could provide better planting conditions and shorter harvest times by being able to sow earlier compared to the other rolling treatments. Difficulty planting into a standing cover crop exists which negatively effects seed to soil contact, but more importantly the higher soil moisture advantage on the rolled plots over the standing (untreated) cover crop plots was an important advantage of rolling/crimping. Soil moisture, when first planting, is the key to successful germination and establishing a good crop stand. Greater termination rates of the cover crop mixture resulted in better soil conditions for planting such as higher soil moisture and more brittle cover crop residue to be effectively cut and parted away from the planting path.

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References

1. Ashford, D.L.; Reeves, D.W. Use of a mechanical roller crimper as an alternative kill method for cover crop. *Am. J. Altern. Agric.* **2003**, *18*, 37–45. [CrossRef]
2. Kornecki, T.S.; Price, A.J.; Raper, R.L. Performance of different roller designs in terminating cover crops. *Appl. Eng. Agric.* **2006**, *22*, 633–641. [CrossRef]
3. Kornecki, T.S.; Price, A.J.; Raper, R.L.; Arriaga, F.J. New roller crimper concepts for mechanical termination of cover crops. *Renew. Agric. Food Syst.* **2009**, *24*, 165–173. [CrossRef]
4. Kornecki, T.S.; Price, A.J. Effects of different roller/crimper designs and rolling speed on rye cover crop termination and seedcotton yield in a no-till system. *J. Cotton Sci.* **2011**, *14*, 212–220.
5. Kern, J.S.; Johnson, M.G. Conservation Tillage Impacts on National Soil and Atmospheric Carbon Levels. *Soil Sci. Soc. Am. J.* **1993**, *57*, 200–210. [CrossRef]
6. McGregor, K.C.; Mutchler, C.K. Soil loss from conservation tillage for sorghum. *Trans. ASAE* **1992**, *35*, 1841–1845. [CrossRef]
7. Reeves, D.W. Advances in Soil Science: Crops Residue Management. In *Cover Crops and Rotations*; Hatfield, J.L., Stewart, B.A., Eds.; Lewis Publishers: Boca Raton, FL, USA, 1994; pp. 125–172. [CrossRef]
8. Raper, R.L.; Reeves, D.W.; Burmester, C.H.; Schwab, E.B. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. *Appl. Eng. Agric.* **2000**, *16*, 379–385. [CrossRef]
9. Raper, R.L.; Reeves, D.W.; Schwab, E.B.; Burmester, C.H. Reducing soil compaction of Tennessee Valley soils in conservation tillage systems. *J. Cotton Sci.* **2000**, *4*, 84–90.
10. Ciaccia, C.; Canali, S.; Campanelli, G.; Testani, E.; Montemurro, F.; Leteo, F.; Delate, K. Effect of roller-crimper technology on weed management in organic zucchini production in a Mediterranean climate zone. *Renew. Agric. Food Syst.* **2016**, *31*, 111–121. [CrossRef]
11. Kornecki, T.S.; Balkcom, K.S. Organic Kale and Cereal Rye Grain Production Following a Sunn Hemp Cover Crop. *Agronomy* **2020**, *10*, 1913. [CrossRef]
12. Kornecki, T.S.; Price, A.J. Management of high-residue cover crops in a conservation tillage organic vegetable on-farm setting in Alabama. *Agronomy* **2019**, *9*, 640. [CrossRef]
13. Kornecki, T.S. Multistage Crop Roller. U.S. Patent 7,987,917 B1, 2 August 2011.
14. Kornecki, T.S.; Kichler, C.M. Modular Device for Cutting Cover Crop Residue. U.S. Patent US 10,959,363 B2, 30 March 2021.
15. Kornecki, T.S.; Arriaga, F.J.; Price, A.J. Evaluation of methods to assess termination rates of cover crops using visual and non-visible light active sensors. *Trans. ASABE* **2012**, *55*, 733–741. [CrossRef]
16. AWIS. Agricultural Weather Information Service, Inc. 2021. Available online: http://www.awis.com/mesonet/index.html (accessed on 4 November 2021).
17. Gomez, K.A.; Gomez, A.A. *Statistical Procedures for Agricultural Research*, 2nd ed.; John Wiley & Sons, Inc.: New York, NY, USA, 1984.
18. SAS. *Proprietary Software Release 9.2.*; SAS Institute, Inc.: Cary, NC, USA, 2013.
19. Kornecki, T.S.; Arriaga, F.J. Impact of different cover crops and types of transplanter mounted subsoiler shanks on tomato yield. *HortScience* **2011**, *46*, 715–720. [CrossRef]
20. Kornecki, T.S.; Price, A.J.; Balkcom, K.S. Cotton Population and Yield Following Different Cover Crops and Termination Practices in an Alabama No-Till System. *J. Cotton Sci.* **2015**, *19*, 375–386.
21. Kornecki, T.S. Effects of Different Rollers and Rye Termination Methods on Soil Moisture and Cotton Production in a No-Till System. *J. Cotton Sci.* **2020**, *24*, 197–210. [CrossRef]
22. Hodgskiss, C.L.; Young, B.G.; Armstrong, S.D.; Johnson, W.G. Evaluating cereal rye and crimson clover for weed sup-pression within buffer areas in dicamba-resistant soybean. *Weed Technol.* **2021**, *35*, 404–411. [CrossRef]
23. Vann, R.A.; Reberg-Horton, S.C.; Edmisten, K.L.; York, A.C. Implications of Cereal Rye/Crimson Clover Management for Conventional and Organic Cotton Producers. *Agron. J.* **2018**, *110*, 621–631. [CrossRef]
24. Reberg-Horton, S.C.; Grossman, J.; Kornecki, T.S.; Meijer, A.D.; Price, A.J.; Place, G.T.; Webster, T.M. Utilizing cover crop mulches to reduce tillage in organic systems in the southeast. *Renew. Agric. Food Syst.* **2012**, *27*, 41–48. [CrossRef]
25. Kornecki, T.S.; Arriaga, F.J.; Price, A.J.; Balkcom, K.S. Effects of recurrent rolling/crimping operations on cover crop termination, soil moisture, and soil strength for conservation organic systems. *Appl. Eng. Agric.* **2013**, *29*, 841–850. [CrossRef]

26. Kornecki, T.S. Rye termination by different rollers/crimpers developed for no-till small-scale farms. *Appl. Eng. Agric.* **2015**, *31*, 849–856. [CrossRef]
27. Kornecki, T.S. Influence of Recurrent Rolling/Crimping on Cover Crop Termination, Soil Strength and Yield in No-Till Cotton. *AgriEngineering* **2020**, *2*, 631–648. [CrossRef]
28. Kornecki, T.S.; Kichler, C.M. Effectiveness of Cover Crop Termination Methods on No-Till Cantaloupe. *Agriculture* **2022**, *12*, 66. [CrossRef]
29. Biuk, A.A. Physiological and Yield Responses of Snap Beans (*Phaseolus vulgaris*) to Water Availability. Ph.D. Thesis, Oregon State University, Corvallis, OR, USA, 8 December 1982.
30. Priyadarshini, V.M.; Madhanakumari, P. Effect of biostimulants on the yield of bush bean (*Lablab purpureus* var. *typicus*). *Ann. Plant Soil Res.* **2021**, *23*, 66–70. [CrossRef]
31. Hefner, M.; Canali, S.; Willekens, K.; Lootens, P.; Deltour, P.; Beeckman, A.; Kristensen, H.L. Termination method and time of agro-ecological service crops influence soil mineral nitrogen, cabbage yield and root growth across five locations in northern and western Europe. *Eur. J. Agron.* **2020**, *120*, 126144. [CrossRef]
32. Heathrow, F.L. American Automobile Association. Available online: https://gasprices.aaa.com/ (accessed on 19 August 2022).
33. Honda Motor Co., Ltd. Tokyo, Japan. Available online: https://www.hondapowerequipment.co.nz/engines/gx-big-series/gx690 (accessed on 19 August 2022).
34. Ag Decision Maker: Estimating Farm Machinery Costs. Iowa State University, Extension and Outreach, File A3-29, PM 710 Revised May 2015. Available online: https://www.extension.iastate.edu/agdm/crops/pdf/a3-29.pdf (accessed on 1 September 2022).
35. Viswanathan, B. Chapter 2—Petroleum. In *Energy Sources*, Fundamentals of Chemical Conversion Processes and Applications; Elsevier: Cambridge, MA, USA, 2017; pp. 29–57. [CrossRef]
36. Canali, S.; Campanelli, G.; Ciaccia, C.; Leteo, F.; Testani, E.; Montemurro, F. Conservation tillage strategy based on the roller crimper technology for weed control in Mediterranean vegetable organic cropping systems. *Eur. J. Agron.* **2013**, *50*, 11–18. [CrossRef]
37. USDA National Agricultural Statistics Service Quick Stats Ad-Hoc Query Tool. Available online: https://quickstats.nass.usda.gov/results/25EE941F-D345-3D20-BD57-34F8D5D73FB9 (accessed on 1 September 2022).