Field Crops Research 203 (2017) 47–54

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

The effect of sowing depth and soil compaction on the growth and yield of rapeseed in rice straw returning field

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ARTICLE INFO

Article history:
Received 12 October 2016
Received in revised form
19 December 2016
Accepted 19 December 2016
Available online 27 December 2016

Keywords:
Rapeseed
Seedling growth
Lodging
Weed
Yield

ABSTRACT

The seed emergence and yield of rainfed rapeseed (*Brassica napus* L.) are commonly limited by soil water availability during the growing season. The return of straw to the field helps maintain soil moisture status, but can cause long hypocotyls of seedlings and result in yield reduction. Using the swede rape hybrid Huayouza 62 as material, the effects of sowing depth and soil compaction on seedling growth and yield under conditions of straw return to the field were investigated. The bulk density and water content for the soil layers of 0–10 and 10–20 cm significantly increased and total porosity decreased under the compaction of shallow (2 cm) and deep sowing (3 cm), and the effect was greater for the 0–10 cm layer. Without soil compaction, the seedling emergence rate was substantially improved with increased sowing depth, but was dramatically decreased in the case of compacted soil. The soil compaction significantly elevated the seedling emergence rate with shallow sowing, and increases were 15.57 and 17.08% for 2013–2014 and 2014–2015, respectively; however, with deep sowing, compaction had no significant effect. The variation in seedling density was consistent with that of the seedling emergence rate. Compared to shallow sowing, deep sowing induced a thinner rapeseed stem, but soil compaction had an opposite effect. Increasing the sowing depth or soil compaction improved the overall yield by elevating the root/shoot ratio of seedlings and lodging resistance, effectively eliminating weed infestation. Significant interactions were found between sowing depth and soil compaction in yield and siliques. Shallow sowing with soil compaction had a positive effect on growth and development, and dramatically increased seedling density and siliques, leading to improved yield.

1. Introduction

Rapeseed (*Brassica napus* L.) is the fifth largest crop in China with an annual planting area of 7.52 million hectares (FAO, 2014). It not only provides people with edible oil, but also is a source of protein feed for animal husbandry (Mcansh, 1973). Therefore, development of rapeseed production is of great significance. Sowing depth and soil compaction are major factors known to influence seedling emergence, stand establishment, and crop performance. Seeds must be sown sufficiently deep to ensure a continual moisture supply and good seedling anchorage (Heydecker, 1956). Deep sowing has a number of effects on seedling growth. These include an increase in the time between seed germination and seedling emergence; an increase in hypocotyl or epicotyl length, which reduces the probability of seedlings overcoming soil strength and renders them more susceptible to attack by pathogens (Parker and Taylor, 1965); a depletion of the seed reserves remaining in the emerged seedling; and a modification to seedling biochemistry, perhaps due to ethylene production (Clarke and Moore, 1986). However, rapeseed is a small shallow-seeded crop that is subject to more variable and higher seedling mortality than larger seeded crops. Due to time constraints, field logistics, and high seedling numbers, seedling emergence of rapeseed is in the range of 45%–69%. Seed yield for plants from 2.5 cm sowing depth was higher than from 5 cm (Lamb and Johnson, 2004). Thomas et al. (1994) also observed reduced rapeseed emergence at sowing depths greater than 3 cm in field studies.

Soil compaction is the physical consolidation of soil by an applied force. In general, at a whole plant level, it is assumed that soil compaction destroys structure, reduces porosity, limits water and air infiltration, restricts plant root growth and exploration, increases resistance to root penetration, and subsequently reduces crop yield (Ishaq et al., 2001; Bassett et al., 2005; Sidhu and Duiker, 2006). However, results vary depending on the climate and the time required by soils to adapt to a new management system

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http://dx.doi.org/10.1016/j.fcr.2016.12.016
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(Grzesiak et al., 2016). Post-sowing compaction can significantly increase rapeseed seedling emergence (Botta et al., 2013). Roath (1998) reported that soil packing increased seedling emergence by 14%, compared to non-packed treatments with a 13-mm sowing depth. Post-sowing compaction also benefited tall fescue and ryegrass with surface or very shallow sowing (Brock, 1973). This might be due to firmness of the seedbed, more accurate seed placement, and improved seed/soil contact resulting in greater seed hydration with the packed treatment. The great variability of responses to soil compaction is also dependent on the variable and the species studied (Alameda and Villar, 2009). Gomez et al. (2002a) found that the effect of soil compaction on growth of *Pinus ponderosa* saplings ranged from negative to positive, depending on the texture or water content of the soil. Therefore, it is very difficult to extrapolate compaction results to other soil conditions.

In the Yangtze Valley, in a rice-rapeseed cropping system, the optimal winter rapeseed sowing date often does not coincide with adequate soil conditions for field preparation and sowing. A delay in sowing beyond mid-October, however, is associated with continuous decreases in seed yield. Thus, farmers tend to prepare the field and sow when the soil can be sensitive to soil compaction. Rapeseed development and growth is considerably influenced by compacted soil structures. Previous efforts have been made to study the effect of sowing depth or soil compaction, no data have been published from sowing depth and soil compaction interaction studies for rapeseed grown in the fields with rice straw added. Our main objectives were to quantify the interaction of sowing depth and mechanical soil compaction post-sowing on soil physical quality and the performance of rapeseed in a field with rice straw added.

2. Materials and methods

2.1. Field sites and experimental design

Split plot experiments were performed using the swede rape hybrid Huayouza 62 in the Ezhou Experimental Station of Huazhong Agriculture University during 2013–2014 and 2014–2015. Two sowing depths (2 and 3 cm) were set as primary plots, and with or without soil compaction as subplots (soil compaction applied with a cylindrical hollow iron roller of diameter 35 cm, length 190 cm, and weight 100 kg). The length of plots was 40 m and the width was 2 m, each containing three replicates of six rows. The previous crop for the area was rice, and rice straw mulch was applied at 7500 kg ha^{-1} (rice straw from the previous season was manually crushed into 5-cm pieces and the field was uniformly mulched). The average atmospheric temperature and precipitation in the two growing seasons were similar (Table 1).

The average atmospheric temperatures in the corresponding months of different years were comparable, with differences within 1 °C. Compared to 2013–2014, the growing season in 2014–2015 had more precipitation during May and October–December. Seeds were sown at a rate of 3.75 kg ha^{-1}on 12 October with the 2BFQ-6 type rapeseed combined drill in both growing seasons. The combined fertilizer of nitrogen (N), phosphorus, and potassium (15%–15%–15%) at 900 kg/hm^2 and 7.5 kg/hm^2 of borax was applied as base fertilizer. Urea as the N source was applied at 75 and 60 kg/hm^2 at seedling and bolting stages, respectively. The soil moisture content when sowing in the two growing seasons was 20.15 and 20.72%, respectively, and other management followed the usual routine.

2.2. Measurement of soil characteristics

Soil was collected at 7 d post-sowing at two depths (0–10 and 10–20 cm) to measure the soil characteristics. In each plot, the soil samples were collected using a soil-sampling probe (internal diameter 5 cm) at five points randomly selected from within the plot and bulked, and a composite sample was obtained. The soil samples were passed through a 2-mm screen to remove roots and other debris. Each sample was air-dried and stored at room temperature until soil physical and chemical properties could be determined. Soil bulk density (BD, g cm^{-3}) of each soil layer (0–10 and 10–20 cm) was measured using a soil bulk sampler with a 5 cm diameter and a 5 cm high stainless steel cutting ring at points adjacent to where soil samples were collected for chemical analysis. Soil BD was calculated depending on the inner diameter of the core sampler, sampling depth and the oven dried weight of the composite soil samples. The original volume of each soil core and its dry mass after oven-drying at 105 °C were measured. Soil water content was measured gravimetrically and expressed as a percentage of soil water to dry soil weight. Particle density (PD) was determined by the pycnometer method. The formula for calculating total porosity (TP) was $[(\mathrm{PD} - \mathrm{BD})/\mathrm{PD} \times 100]$. Each analysis was performed for three replicates (Deng et al., 2014; Korkanç, 2014).

2.3. Measurement of plant characteristics

2.3.1. Evaluation of seedling growth

The following indicators were determined 61 d after sowing. Each analysis was performed for three replicates.

The continuous field of 3 m was selected at each plot. The seedling numbers were counted for 3 m × 2 m (i.e. 6 m^2), and the seedling density was calculated using the following equation: seedling density (plants ha^{-1}) = 6-m^2 seedling number/6 × 10^4. Based on seedling density, planting rate, and thousand-seed weight, the seedling emergence rate was obtained using the following equation: rate of emergence (%) = seedling density/(sowing rate/thousand-seed weight × 10^3) × 100. The rhizome diameter was determined by measuring the diameter at 10 mm below the cotyledonary node on the stem of rapeseed seedlings using a vernier caliper. Ten plants from each plot were collected and dug out, then the soil on the root was washed away. The seedlings were separated at the cotyledonary node, and dried to determine the dry weight of aboveground and underground portions.

2.3.2. Yield and yield components

Plots were harvested when approximately 2/3 of the seeds were brown. Ten plants were randomly sampled from each plot by slowly uprooting, so that the taproot and large lateral roots were retained. Next, the yield components and seed yield per plant were determined. The following measurements and observations were made for each plant: height (cm), number of siliques per plant, number of seeds per silique, and thousand-seed weight. Plant tissue samples were separated from the cotyledonary node into roots and aboveground tissues. After determining the fresh weight, the roots and aboveground tissues were dried in an oven for 30 min at 105 °C to deactivate enzymes, and then dried again at 80 °C until constant weight to determine the dry weight.

2.3.3. Lodging angle at maturity

Crop lodging was classified as root lodging and stem lodging. The total lodging degree was represented as the degree between the line connecting the highest point of the canopy, the cotyledonary node, and the vertical direction. The degree of root lodging was represented by the degree between the stem and vertical direction, measured by a protractor with a 20 cm radius. The degree of stem lodging (the bending and breaking of the main stem) was calculated: stem lodging degree = total lodging degree – root lodging degree.

Table 1
Air temperature and precipitation during the 2013–2104 and 2014–2015 rapeseed growing seasons.

Year	Item	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Sowing-harvest
2013–2014	Air temperature (°C)	19.0	12.5	6.3	6.4	6.3	12.8	17.5	21.9	12.8
	Precipitation (mm)	10.6	2.7	3.1	24.6	93.0	63.5	103.5	194.2	61.9
2014–2015	Air temperature (°C)	19.5	12.8	5.6	6.6	7.5	11.9	16.8	23.0	13.0
	Precipitation (mm)	57.0	13.8	61.0	21.2	94.1	65.1	124.5	106.9	68.0

2.3.4. Weed infestation

The weed number and biomass was determined from an area of 1 m^2 at maturity as reported by Gronle et al., 2015. Weeds were cut 1 cm above the soil surface and dried in an oven for 30 min at 105 °C, and then dried again at 80 °C until constant weight. Each analysis was performed in three replicates.

2.4. Statistical analysis

Analysis of variance (ANOVA) was performed using SPSS Statistics 20 software (SPSS Inc., Chicago, IL, USA). Sowing depth and soil compaction were fixed factors, while year and block were random factors. Significant differences in means between the treatments were compared by the protected least significant difference (LSD) procedure at $P < 0.05$. Figures were prepared using the Origin 9.0 software program (OriginLab Corp.).

3. Results

3.1. Physical soil conditions

No significant effects of sowing depth on BD, TP and water content were observed under both compacted and non-compacted soil. Soil compaction substantially increased BD and water content in 0–10 and 10–20 cm soil layers in both shallow and deep sowing, but TP decreased with a greater effect on the 0–10 cm soil layer (Table 2).

3.2. Seedling emergency rate, seedling density, and rhizome diameter

The seedling emergence rate of the two seasons was in the range of 35.72%–42.01%. For shallow sowing, soil compaction substantially elevated the rate of emergence by 15.57% and 17.08% for 2013–2014 and 2014–2015, respectively; however, there was no significant difference between compacted and non-compacted soil for deep sowing. The seedling density of the two seasons ranged from 39.55×10^4 to 46.44×10^4 plants ha^{-1}, and the response to sowing depth and soil compaction was consistent with seedling emergence rate. With or without soil compaction, deeper sowing resulted in thinner stems. Soil compaction enhanced the rhizome diameter for both shallow and deep sowing, and the thickest stems among treatments were for shallow sowing with soil compaction. The ANOVA showed sowing depth had no great effect on seedling emergence rate and seedling density, but was extremely significant for rhizome diameter, and that the interaction of sowing depth and soil compaction had a significant effect on all three measures (Table 3).

3.3. Dry weight and root/shoot ratio at seedling stage

Without soil compaction, the overall dry weight and dry weight for different portions were substantially elevated with increased sowing depth, but were significantly reduced for increased sowing depth with soil compaction. Sowing depth had no effect on root/shoot ratio for both soil compaction treatments. With shallow sowing, the dry weight of root, aboveground tissue, whole plant, and root/shoot ratio were significantly higher for compacted than non-compacted soil, and the greatest increase was for root dry weight by 22.53% and 23.61% in 2013–2014 and 2014–2015, respectively. With deep sowing, no significant change in root dry weight was observed for compacted compared to non-compacted soil, but dry weight of aboveground tissue was reduced and root/shoot ratio increased by soil compaction with increases of 5.56% and 5.52% in 2013–2014 and 2014–2015, respectively. There were significant interactions between sowing depth and soil compaction on biomass of the root, shoot and the whole plant (Table 4).

3.4. Yield and yield components at maturity

With no soil compaction, yield was significantly improved with increased sowing depth, with increases of 8.04% and 6.21% compared to shallow sowing for the two seasons, respectively. The effect of sowing depth on yield was not significant for compacted soil. For the same sowing depth, yield was significantly increased by soil compaction, with the greatest improvement for shallow sowing, showing increases of 19.02% and 18.17% in 2013–2014 and 2014–2015, respectively, compared to non-compacted soil. The increases with soil compaction were relatively small for both seasons for deep sowing, and were 8.57% and 8.75%, respectively (Table 5).

The effect of sowing depth and soil compaction on plant height was not substantial. Except for a slightly lower number for shallow sowing with soil compaction, there were no other significant differences in siliques per plant among treatments. There was no difference in population silique number for different sowing depths without soil compaction, but with soil compaction a significant reduction with increased sowing depth with the reduction amplitude of 4.77% and 5.10% in 2013–2014 and 2014–2015, respectively, for deep compared to shallow sowing. Shallow sowing with compacted soil significantly increased the population silique number compared to non-compacted soil by 9.66% and 8.77% in 2013–2014 and 2014–2015, respectively. There was little effect of soil compaction on population silique number under conditions of deep sowing. Silique number per plant was elevated with increased sowing depth, regardless of soil compaction; and was substantially increased for compacted compared to non-compacted soil at the same sowing depth. The lowest thousand-seed weight was for shallow sowing without soil compaction, while the highest was for deep sowing with soil compaction (Table 5).

3.5. Lodging behavior at maturity

Lodging was significantly affected by sowing depth and soil compaction. For non-compacted soil, the degrees of root and stem lodging with 3 cm sowing depth were significantly lower than for 2 cm depth, with a stronger effect on root lodging. For compacted soil, the degrees of root and stem lodging showed no substantial alteration with increased sowing depth. Soil compaction reduced the degrees of root and stem lodging, with greater reductions for shallow than deep sowing (Figs. 1 and 2).

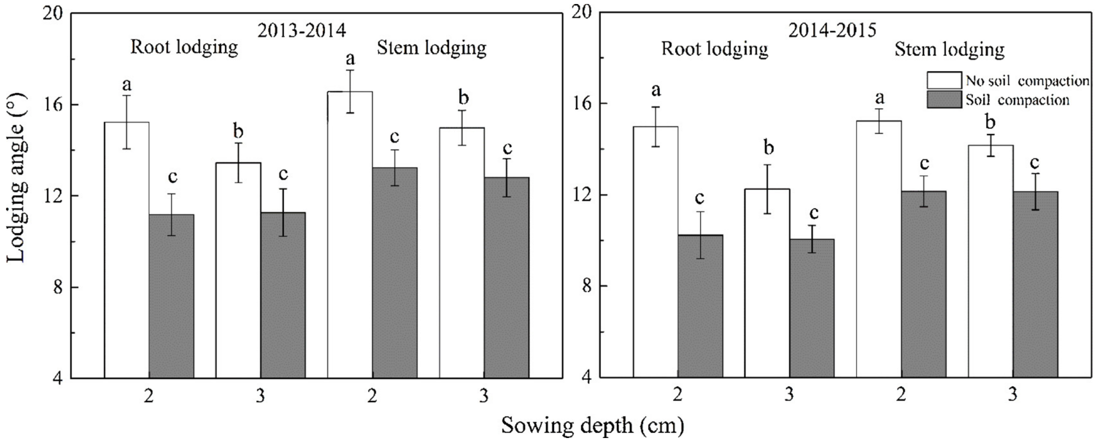


Fig. 1. Effect of sowing depth and soil compaction on lodging degree of rapeseed.

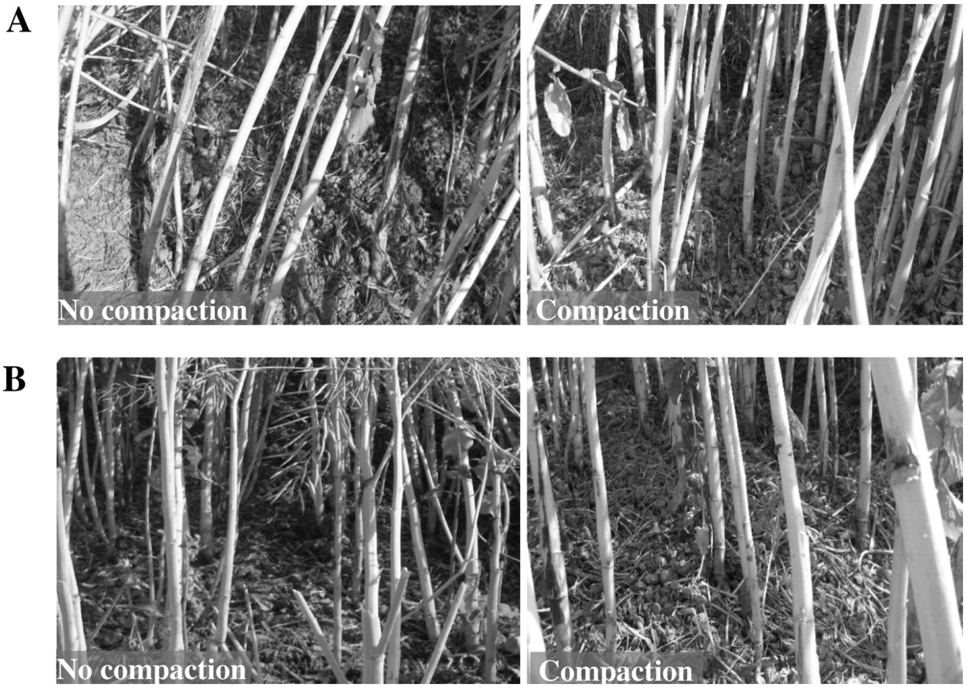
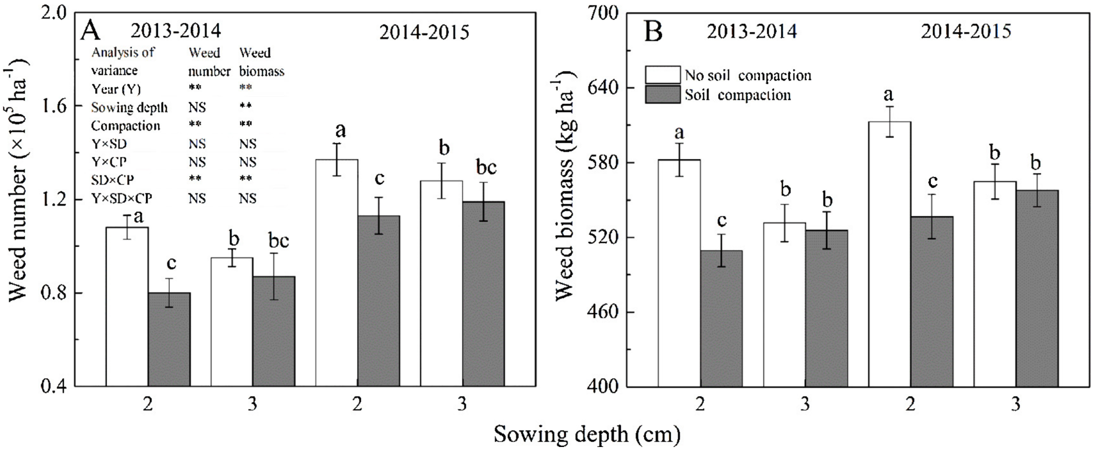


Fig. 2. Rapeseed growth at maturity under different sowing depth and soil compaction. A, sowing at 2 cm depth; B, sowing at 3 cm depth.



Analysis of variance	Weed number	Weed biomass
Year (Y)	**	**
Sowing depth	NS	**
Compaction	**	**
Y×SD	NS	NS
Y×CP	NS	NS
SD×CP	**	**
Y×SD×CP	NS	NS

Fig. 3. Weed number (A) and weed shoot biomass (B) of rapeseed field as affected by soil compaction and sowing depth in 2013–2014 and 2014–2015.

Table 2
Bulk density, total porosity and water content of the upper 0–10 cm and 10–20 cm soil as affected by sowing depth and soil compaction.

Year	Sowing depth (cm)	Soil compaction	Bulk density (g cm^{-3})		Total porosity (%)		Water content (%)	
			0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
2013–2014	2	No compaction	1.02b	1.15c	61.52a	56.47a	11.90b	15.70c
		Compaction	1.10a	1.20abc	58.49b	54.88abc	13.48a	16.65ab
	3	No compaction	1.00b	1.16bc	62.24a	56.41ab	11.83b	15.56c
		Compaction	1.12a	1.21a	58.55b	54.48bc	13.75a	16.24abc
2014–2015	2	No compaction	1.01b	1.18abc	61.84a	55.34abc	11.86b	16.06bc
		Compaction	1.08a	1.20ab	59.12b	54.8abc	13.68a	16.96a
	3	No compaction	1.02b	1.18abc	61.59a	55.64abc	12.07b	16.05bc
		Compaction	1.10a	1.22a	58.50b	53.91c	13.48a	16.54ab
Source of variance								
Year (Y)			0.86NS	0.2123NS	0.7168NS	0.276NS	0.8421NS	0.0467*
Sowing depth (SD)			0.8964NS	0.3823NS	0.9279NS	0.4971NS	0.4677NS	0.0815NS
Compaction (CP)			0.0001**	0.0001**	0.0001**	0.0001**	0.0001**	0.0002**
Y × SD			0.2018NS	0.9999NS	0.1425NS	0.9324NS	0.5327NS	0.8185NS
Y × CP			0.452NS	0.0249*	0.3213NS	0.0747NS	0.2711NS	0.6188NS
SD × CP			0.452NS	0.0249*	0.2623NS	0.0358*	0.7671NS	0.1662NS
Y × SD × CP			0.8783NS	0.206NS	0.745NS	0.1923NS	0.0111*	0.7513NS

Values followed by different letters within the same column are significantly different at 0.05 probability level according to LSD test; *,** Significant at 0.05 and 0.01 probability levels, respectively; NS, not significant.

Table 3
Effect of sowing depth and soil compaction on seedling rate, density and rhizome diameter of rapeseed at seedling stage.

Year	Sowing depth (cm)	Soil compaction	Seedling rate (%)	Density ($\times 10^4$ plants ha^{-1})	Rhizome diameter (mm)
2013–2014	2	No compaction	35.72c	39.55c	5.54c
		Compaction	41.28a	45.72a	5.82a
	3	No compaction	38.07b	42.17b	5.18d
		Compaction	37.22bc	41.22bc	5.45c
2014–2015	2	No compaction	35.88c	39.67c	5.67b
		Compaction	42.01a	46.44a	5.87a
	3	No compaction	38.29b	42.33b	5.26d
		Compaction	37.14bc	41.06bc	5.52c
Source of variance					
Year (Y)			0.0476*	0.0806NS	0.062NS
Sowing depth (SD)			0.0595NS	0.0598NS	0.0001**
Compaction (CP)			0.0001**	0.0001**	0.0001**
Y × SD			0.6618NS	0.6611NS	0.5534NS
Y × CP			0.8187NS	0.8213NS	0.1942NS
SD × CP			0.0001**	0.0001**	0.3983NS
Y × SD × CP			0.4526NS	0.4625NS	0.3983NS

Values followed by different letters within the same column are significantly different at 0.05 probability level according to LSD test; *,** Significant at 0.05 and 0.01 probability levels, respectively; NS, not significant.

Table 4
Effect of sowing depth and soil compaction on dry matter weight and root–shoot ratio of rapeseed at seedling stage.

Year	Sowing depth (cm)	Soil compaction	Root (kg ha^{-1})	Shoot (kg ha^{-1})	Whole plant (kg ha^{-1})	Root-shoot ratio
2013–2014	2	No compaction	524.3c	1582.0b	2106.4d	0.332b
		Compaction	642.4a	1788.3a	2430.7a	0.359a
	3	No compaction	592.6b	1733.5a	2326.1b	0.342b
		Compaction	591.6b	1638.4b	2230.0c	0.361a
2014–2015	2	No compaction	521.8c	1546.1d	2067.8d	0.337c
		Compaction	645.0a	1818.4a	2463.4a	0.355ab
	3	No compaction	597.8b	1736.7b	2334.5b	0.344bc
		Compaction	598.6b	1650.6c	2249.2c	0.363a
Source of variance						
Year (Y)			0.6149NS	0.8178NS	0.7288NS	0.5524NS
Sowing depth (SD)			0.0202NS	0.6472NS	0.2610NS	0.0660NS
Compaction (CP)			0.0001**	0.0001**	0.0001**	0.0001**
Y × SD			0.3874 NS	0.6906 NS	0.5735 NS	0.7693 NS
Y × CP			0.6731 NS	0.0525 NS	0.0922 NS	0.2534 NS
SD × CP			0.0001**	0.0001**	0.0001**	0.3830 NS
Y × SD × CP			0.8432 NS	0.1211 NS	0.1958 NS	0.2819 NS

Values followed by different letters within the same column are significantly different at 0.05 probability level according to LSD test; *,** Significant at 0.05 and 0.01 probability levels, respectively; NS, not significant.

3.6. Weed infestation

Weed infestation was significantly affected by sowing depth and soil compaction. For non-compacted soil, deeper sowing led to lower weed quantity and biomass; however, for compacted soil, this dramatically enhanced weed quantity and biomass. Shallow sowing with soil compaction significantly decreased weed quan-

Table 5
Effect of sowing depth and soil compaction on yield and yield components at maturity.

Year	Sowing depth (cm)	Soil compaction	Yield (kg ha^{-1})	Plant height (cm)	Number of siliques		Number of seeds per silique	Thousand-seed weight (g)
					Per plant	Per hectare (×10^{6} kg ha^{-1})		
2013–2014	2	No compaction	3113.5c	173.8a	173.3a	64.99c	15.2c	3.195b
		Compaction	3705.8a	176.2a	162.0b	71.27a	16.2ab	3.268ab
	3	No compaction	3363.7b	175.1a	169.4ab	66.99bc	15.8bc	3.272ab
		Compaction	3651.9a	176.6a	170.2ab	67.87b	16.7a	3.356a
2014–2015	2	No compaction	3147.3c	173.5a	176.3a	66.03b	15.3c	3.202b
		Compaction	3719.1a	175.8a	160.8b	71.82a	16.1ab	3.276ab
	3	No compaction	3342.6b	175.4a	171.4a	68.36b	15.5bc	3.274ab
		Compaction	3635.1a	176.1a	171.8a	68.16b	16.5a	3.347a
Source of variance								
Year (Y)			0.9326 NS	0.2697 NS	0.0587 NS	0.1007 NS	0.2136 NS	0.9499 NS
Sowing depth (SD)			0.0044**	0.2476 NS	0.259 NS	0.1608 NS	0.0010**	0.0100**
Compaction (CP)			0.0001**	0.0173*	0.0001**	0.0001**	0.0001**	0.0084**
Y × SD			0.1835NS	0.8611NS	0.8276NS	0.9685NS	0.0572NS	0.7659NS
Y × CP			0.863 NS	0.7155NS	0.2049NS	0.3194NS	0.8888NS	0.9176NS
SD × CP			0.0002**	0.3137 NS	0.0001**	0.0001**	0.9999 NS	0.9117 NS
Y × SD × CP			0.7906 NS	0.7574 NS	0.2659 NS	0.7069 NS	0.5796 NS	0.8942 NS

Values followed by different letters within the same column are significantly different at 0.05 probability level according to LSD test; *,** Significant at 0.05 and 0.01 probability levels, respectively; NS, not significant.

tity and biomass, with a similar but non-significant response for deep sowing (Fig. 3).

4. Discussion

Post-sowing rainfall and temperature vary appreciably across environments and are likely to influence seedling emergence. In this study, the average atmospheric temperature and precipitation were comparable in the two seasons, so the effect of sowing depth or soil compaction on seedling emergence rate and seedling density was similar between years. Crop seedling emergence should be high enough to allow established plants to maintain yield. Knowing the seedling emergence when selecting sowing depth is useful information for attaining an appropriate stand density and resultant optimum crop performance. Our two-season results demonstrated that the seedling emergence rate in the condition of rice straw returning was relatively low with direct-sowing. Poor root-soil contact in a loose soil resulted from rice straw returning is partly responsible for the low seedling emergence rate. Rapeseed is small, with thousand-seed weight generally in the range of 3–4 g, so few nutrients are stored in seeds, and these are basically depleted during the seed germination process. Shallow sowing is applied in rapeseed production, but the seeds are exposed in the surface soil layer making germination difficult. Under condition of non-compacted soil, increasing sowing depth effectively improved the seedling emergence rate, which is beneficial for forming a high-yielding population. An appropriate increase in sowing depth could satisfy the requirements of soil temperature and moisture, which facilitate seed germination, but a sowing depth more than 3 cm does not favor seedling establishment and final yield. Domier et al. (1992) reported that canola emergence and yield decreased for sowing depths greater than 3 cm, with similar rapeseed yields for 1 and 3 cm sowing depth but lower yield for 5 and 7 cm sowing depth as plant density decreased.

Soil compaction after sowing significantly affects the seedling emergence rate, probably due to changes in soil physical and chemical properties after soil compaction (Hillel, 1998; Grzesiak et al., 2016). Compacted soils have been shown to have higher BD and soil moisture contents, with lower porosity as observed in our study, which in this case may have been important by giving surface-sown treatments a better chance for early establishment. Increasing BD of the soil has been shown to reduce crop growth (Gifford and Jensen, 1967), but as the soil to a depth of 2 cm in this trial was dry at sowing, the degree of compaction was probably insufficient to increase BD sufficiently for mechanical impedance from crusting or lack of pore space to reduce total emergence. According to Lampurlanés and Cantero-Martínez (2003), the unrestricted extension of plant roots in moderately compact soil reflects their ability to grow in the inter-aggregate spaces, provided that soil is reasonably well structured or has preserved biochannels such as in non-tilled soils. In addition, moderate soil compaction can increase contact between root and substrate and allow greater water and nutrient absorption (Arvidsson, 1999; Gomez et al., 2002b). As soil moisture increased under compaction for 2 cm sowing depth, crust strength decreased, and the soil was more easily deformed by expanding plant organs. This allows rapid seedling emergence at lower energy cost, resulting in stronger seedlings and quicker establishment. With decreasing soil moisture, the converse occurs. Mósena and Dillenburg (2004) found an increase in *Araucaria angustifolia* biomass with higher soil compaction. For compacted soil, BD, water content, and TP did not respond to sowing depth, but seedling emergence rate and seedling density were significantly reduced by increased sowing depth. The emergence of seedlings from soil is the combined result of several processes other than soil conditions: seed germination, shoot elongation to reach the soil surface, radicle elongation to ensure water uptake, and seedling survival when encountering obstacles in soil are also important factors (Dürr et al., 2001). The degree of expression of these factors on seedling emergence is also conditioned by energy reserves and growth rate of the emerging seedling (Grzesiak et al., 2016). Emergence time was extended for deep sowing of 3 cm with soil compaction, as reported by Shanmuganathan and Benjamin (1992). In this case, more energy would be needed, which is unfavorable for seed germination and seedling emergence, leading to reductions in seedling emergence rate and seedling density. As pointed out by Pagliai et al. (1998), soil compaction after shallow sowing tends to be more stable than after deep sowing, which reduces the risk of surface crust formation, erosion, and energy limitations.

The seedling density and weed infestation affected the rapeseed yield and yield components. Compared with sowing depth, soil compaction had more effect on yield. Significant interactions were found between sowing depth and soil compaction in yield, and siliques. Shallow sowing with soil compaction had a positive effect on growth and development, and dramatically increased seedling density, siliques per plant and per hectare, leading to improved yield. However, seedling vigor was subsequently reduced as shown by reduced shoot growth with compacted soil and sowing at 3 cm. This was possibly due to resistance to lateral deformation of the soil by the expanding shoot, as compaction had no effect on seedlings sown at 2 cm. The growth of roots is closely related to the physiological metabolism and biomass accumulation of aboveground tissue, and a suitable ratio facilitates crop growth (Chen et al., 2015). The root/shoot ratio is an important indicator reflecting coordination of growth and biomass accumulation in roots and aboveground tissue. In the present study, the root/shoot ratio increased under the treatment of deep sowing or soil compaction and it had similar trends with the dry weight of underground and aboveground tissue and yield at maturity, revealing that an appropriate increase of root/shoot ratio was conducive to growth of rapeseed and high yield. Low seed yield after shallow sowing under organic and conventional conditions is often attributed to higher annual and perennial weed infestations, which are significantly influenced by soil compaction (Brandsæter et al., 2011). Weed number and biomass were obviously reduced with increased sowing depth for non-compacted soil (Fig. 2), as previously reported (Gronle et al., 2015). Soil compaction significantly restricted weed infestation for sowing at 2 cm depth. Weed infestation followed an opposite change pattern to seedling emergency rate and density (Table 3), indicating that strong rapeseed-weed competition existed. The greater biomass of shoots for plants in compacted soil when sown at 2 cm depth has previously been attributed to their ability to obtain more nutrients from soil as a result of reduced competition with weeds.

Lodging can occur by stem failure (stem lodging) (Neenan and Spencer-Smith, 1975) or anchorage failure (root lodging) (Crook and Ennos, 1993), and is a significant problem for farmers because it causes large reductions in seed yield and quality (Easson et al., 1993; Kuai et al., 2015). Plants next to wheel tracks caused by farm vehicles during application of agro-chemicals in commercial fields always remain standing, even when other plants in the field have lodged (Berry et al., 1998). Subsequent research has shown that reducing competition between plants can increase their resistance to both stem and root lodging by influencing their shoot and root growth, respectively (Easson et al., 1993, 1995; Berry et al., 1998). In addition to reduced competition, a further factor that may contribute to root lodging resistance of plants in compacted soil is the difference in soil physical conditions to non-compacted soil (Voorhees, 1992; Rowell, 1994). This may further influence their anchorage strength and hence resistance to root lodging. In the present study, rapeseed lodging had a similar trend with the root/shoot ratio. It was alleviated under the treatment of deep sowing or soil compaction, and the effect was greater for shallow sowing with soil compaction. Besides, root lodging of rapeseed was far more affected by sowing depth and soil compaction than stem lodging. An examination of the differences in soil and plant characteristics suggests that two main differences contributed to the increased root lodging resistance. These include (1) greater BD and reduced TP of the soil resulting from compaction. Depending on the mechanism of root lodging, soil strength affects either the resistance of the root–soil bond to failure by axial or shearing root movements, or the resistance of the soil matrix to failure by rotation of the root–soil cone (Easson et al., 1995) and (2) greater plant growth (increased root/shoot ratio and stem diameter) resulting from reduced competition with weeds and so greater water and nutrient absorption. Soil compaction affects root growth and thus the ability of root systems to provide anchorage to plants (Goodman and Ennos, 1999).

5. Conclusion

Sowing depth and soil compaction are two important agronomic measures for rapeseed in rice straw returning field. With no soil compaction, the seedling emergence rate and seedling density was dramatically elevated with increased sowing depth, but the seedlings tended to have a long hypocotyl. The shallow sowing with soil compaction significantly improved the seedling emergence rate, seedling density, and rhizome diameter, which alleviated the occurrence of long hypocotyls with straw returned to the field. Increasing sowing depth or soil compaction improved the root/shoot ratio and lodging resistance at maturity, eliminated weed infestation, and so improved overall yield. The most obvious effect was for shallow sowing with soil compaction. The high yield of direct-seeded rapeseed not only requires appropriate seedling numbers, which can ensure siliques, but also demands the elevated lodging resistance to guarantee efficiency of mechanical harvest. With straw returned to the field, the high yield and strong lodging resistance of direct-seeded rapeseed was achieved under 2 cm depth of sowing with soil compaction, and may promote mechanized production of rapeseed.

Acknowledgements

This research was funded by the National Key Technology Research and Development Program (2014BAD11B03), the Industry Technology Research Institute (CARS-13) and the Fundamental Research Funds for the Central Universities (2013PY001).

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