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Tractor tire aspect ratio effects on soil bulk density and cone index

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Abstract

A 580/70R38 tractor drive tire with an aspect ratio of 0.756 and a 650/75R32 tire with an aspect ratio of 0.804 were operated at two dynamic loads and two inflation pressures on a sandy loam and a clay loam with loose soil above a hardpan. Soil bulk density and cone index were measured just above the hardpan beneath the centerline and edge of the tires. The bulk densities were essentially equal for the two tires and cone indices were also essentially equal for the two tires. Soil bulk density and cone index increased with increasing dynamic load at constant inflation pressure, and with increasing inflation pressure at constant dynamic load. In comparisons of the centerline and edge locations, soil bulk density and cone index were significantly less beneath the edge than beneath the centerline of the tires. Soil compaction is not likely to be affected by the aspect ratio of radial-ply tractor drive tires when aspect ratios are between 0.75 and 0.80.
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1. Introduction

Soil compaction often prohibits crop roots from extending to reach more soil for water, nutrients, and anchorage. Compaction can also reduce infiltration of water into soil, causing an increased potential for runoff and erosion. Radial-ply tractor drive tires with aspect ratios, which are ratios of the cross-sectional height to width [1], greater than 0.75, are commonly used. Also, radial-ply tractor drive tires with aspect ratios less than 0.75 are commonly available. Soil compaction and tractive performance characteristics of these low aspect ratio tires may differ from those of tires with conventional aspect ratios.

Soil stresses and changes in soil bulk density have been determined for conventional aspect ratio tires such as an 18.4R38 with an aspect ratio of 0.82. Octahedral stresses in soil beneath the centerline of an 18.4R38 tractor drive tire operating at 10% travel reduction increased as dynamic load increased while inflation pressure was held constant [2]. When dynamic load was held constant, stresses increased as inflation pressure increased. The major principal stress, octahedral normal stress and octahedral shear stress in a sandy loam soil at a depth of 150 mm beneath the centerline of an 18.4R38 tractor drive tire operating at 20% travel reduction were generally 50% greater than the corresponding stresses measured beneath the edge of the tread [3].

Koolen and Kuipers [4] reported that tires with low aspect ratios allow for lower contact stresses and larger contact areas. Yong et al. [5] said low section height tires have improved flotation relative to conventional tires, without increasing the overall diameter or weight of the tire.

Bias-ply tractor drive tires with aspect ratios of 0.85 and 0.78 were operated with inflation pressures of 80 kPa and 20% travel reduction in 37 fields [6]. The 0.78 aspect ratio tire was 5% wider and 1.5% smaller in overall diameter than the 0.85 aspect ratio tire. There were no obvious differences in performance between the tires, but the rolling resistance was somewhat greater for the 0.78 aspect ratio tire than for the 0.85 aspect ratio tire.

Tractive performances of two 13.6-38 tractor drive tires with aspect ratios of 0.75 and 0.69 were determined on fields with various soil textures, soil moisture contents and surface conditions, some cultivated and some with

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Table 1
Tire dimensions and tire load limits recommended by manufacturer for each inflation pressure.

Tire	Overall diameter[a] (mm)	Section width[a] (mm)	Section height[a] (mm)	Aspect ratio[b]	Tire carcass thickness at central plane of tire[c] (mm)	Mean thickness of sidewall[d] (mm)	Ratio of section height to mean sidewall thickness	Lug height at central plane of tire (mm)	Total number of lugs on tire	Tire load limit at 40 kPa inflation pressure[e] (kN)	Tire load limit at 120 kPa inflation pressure[e] (kN)
580/70R38	1834	575	434	0.756	23	23	19	57	38	17.2	30.9
650/75R32	1815	623	501	0.804	26	25	25	59	38	20.2	36.7

[a] Measured when inflation pressure was 120 kPa. Terms defined by The Tire and Rim Association, Inc. [12].
[b] Aspect ratio = (Overall diameter − Nominal rim diameter)/(2 * Section width).
[c] Thickness from undertread face to inner surface of tire carcass.
[d] Mean of eight thickness measurements beginning at rim flange and progressing radially outward at 50 mm arc length increments along tire sidewall.
[e] For maximum speed of 40 km/h. Source: The Goodyear Tire & Rubber Company [13].

crop residues [7]. Tractive performances of tires at the same inflation pressure were not affected by small changes in aspect ratio.

The availability of radial-ply drive tires with lower aspect ratios caused us to consider effects of aspect ratio on soil bulk density and soil cone index. Tire dynamic load and inflation pressure were thought to potentially influence the centerline-to-edge distribution of soil bulk density and cone index. Therefore, an experiment was developed with the following objectives:

1. To determine effects of two radial-ply drive tires, each with a different aspect ratio, on soil bulk density and cone index.
2. To determine effects of dynamic load and inflation pressure of the tires on soil bulk density and cone index.
3. To compare the tire tread centerline and edge locations of soil bulk density and cone index, as affected by the tires, their dynamic loads and inflation pressures.

Effects of the two tires, dynamic loads, and inflation pressures used in this experiment, on soil stresses and rut depths, are described in Way et al. [8]. The octahedral shear stress and rut depth were not significantly different for the tires. The peak octahedral normal stress was not significantly different for the two tires when the dynamic load was 17.2 kN, but was significantly greater for the 650/75R32 tire, which had the greater aspect ratio, when the dynamic load was 30.9 kN. Soil stresses and rut depths increased with increasing dynamic load at constant inflation pressure, and with increasing inflation pressure at constant dynamic load. In comparisons of the centerline and edge locations, soil stresses were significantly less beneath the edges than beneath the centerlines of the tires. Soil dynamics is a relatively complex phenomenon, so even though Way et al. [8] found that soil stresses and rut depths were generally not significantly different for these two tires, we believed it would be useful to investigate effects of the two tires on soil bulk density and cone index. Also, the soil bulk density and cone index results in this article, and the soil stress results from this same experiment which are presented in Way et al. [8], may be useful in developing models that relate these variables to one another.

2. Materials and methods

The experiment was conducted at the National Soil Dynamics Laboratory (NSDL), a facility of the USDA Agricultural Research Service in Auburn, Alabama, using the NSDL single wheel Traction Research Vehicle (TRV) operating in soil bins [9,10,11]. Two tractor drive tires were used: a Goodyear[1] DT 810 580/70R38 155A8[2] R-1W radial-ply tire and a Goodyear DT 820 650/75R32 167A8 R-1W radial-ply tire. The tires were chosen to get the greatest difference in aspect ratio while keeping approximately the same overall diameter and section width for both tires. The actual aspect ratios, calculated from the tire overall diameters, bead diameters and section widths, were 0.756 for the 580/70R38 tire and 0.804 for the 650/75R32 tire (Table 1). The thickness of the tire carcass at the tire central plane and the mean sidewall thickness were slightly less for the 580/70R38 tire than for the 650/75R32 tire (Fig. 1 and Table 1). The tires had small differences in other characteristics including section width and lug shape.

Each tire was operated at four combinations of dynamic load and inflation pressure (Table 2). The 17.2-40 and 30.9-120 treatments had correct inflation pressures corresponding to the dynamic loads for the 580/70R38 tire. The 650/75R32 tire specifications recommended a slightly greater load for a given inflation pressure than the 580/70R38 tire specifications (Table 1). Dynamic load and inflation pressure have been shown to affect soil bulk density and cone index [14]. Therefore, the load and inflation pressure combinations used in the experiment were chosen to be the same for the two tires. The dynamic loads of the 580/70R38 tire were used for both tires. The 17.2-120 treatment

[1] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.
[2] Load Index = 155 and Speed Symbol = A8.

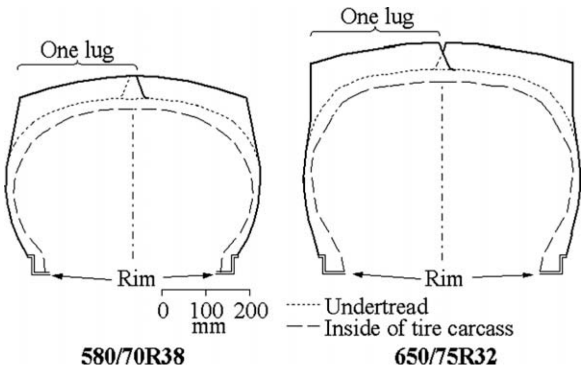

Fig. 1. Circumferential projections of lugs and undertread of unloaded tire sections onto a cross-sectional plane when inflation pressures were 120 kPa.

Table 2
Dynamic load and inflation pressure combinations.

Treatment	Dynamic load (kN)	Inflation pressure (kPa)
17.2–40	17.2	40[a]
17.2–120	17.2	120[b]
30.9–40	30.9	40[c]
30.9–120	30.9	120[a]

[a] Correct inflation pressure to match load for 580/70R38 tire. The 650/75R32 tire was slightly overinflated in these treatments.

[b] Both tires were overinflated in this treatment.

[c] Both tires were underinflated in this treatment. This combination of load and inflation pressure is not recommended by the tire manufacturer.

overinflated both tires. Farmers have commonly used overinflated radial-ply tractor tires because the tires are often inflated until there is little or no sidewall bulge, so the tires look like bias-ply tires [15]. The 30.9-40 treatment underinflated the tires and is not recommended by the manufacturer because underinflation results in rapid and uneven tread wear and can cause cracking in tire sidewalls.

The experiment was conducted in the Norfolk sandy loam (a fine loamy siliceous thermic *Typic Paleudults*) and Decatur clay loam (a clayey kaolinitic thermic *Rhodic Paleudults*) indoor soil bins at the NSDL. The composition of the sandy loam was 72% sand, 17% silt, and 11% clay, and the composition of the clay loam was 27% sand, 43% silt, and 30% clay. A hardpan was established in each soil bin by first rotary tilling the soil to a depth of 400 mm. Each hardpan was formed across the whole area of the bin using a single moldboard plow followed by a weighted steel wheel operating in the plow furrow. The loose soil above the hardpan was then rotary tilled and leveled with a scraper blade. The depth of the top of the hardpan beneath the loose soil surface was 202 mm in the sandy loam soil and 270 mm in the clay loam soil. Initial conditions of the soils are given in Table 3.

A randomized complete block design with four blocks was used. Each soil bin was divided into four blocks (replications), each containing eight plots, one for each treatment. The eight treatments resulting from 2 tires × 2 dynamic loads × 2 inflation pressures were randomly assigned to the plots in each block. The tires were operated so the four plots in each block (one plot per treatment) for each tire in each soil were completed in one day. The soil surface of the blocks not being used was covered with polyethylene film to minimize changes in soil moisture content.

During each tire pass, the computer control of the TRV maintained constant inflation pressure, constant dynamic load, and a constant travel reduction of 10%. The forward velocity was 0.15 m/s for all tire runs. Zero conditions [1] for travel reduction calculations consisted of each tire operating at zero net traction on concrete.

Stresses in soil beneath each tire pass were determined using stress state transducers (SSTs) as described in Way et al. [8]. One SST was buried in the soil beneath the centerline and one beneath the edge of the tire path before the tire was operated and each SST was buried with its base resting on top of the hardpan. The center of pressure measurement of each SST was 14 mm beneath the top of the SST, and its mean initial depth beneath the untrafficked soil surface was 166 mm in the sandy loam and 234 mm in the clay loam.

After the tire passes were completed, soil core samples were collected beneath a lug imprint at the tire track centerline and at the edge of the tread, to determine dry bulk density (Fig. 2). The depth of the center of each sample was the final depth of the center of pressure measurement of the corresponding SST. Soil samples were also collected in

Table 3
Mean initial conditions of soils.

Soil	Water content above hardpan (% dry basis)[a]	Dry bulk density[b]		Soil cone index[c] Depth beneath untrafficked surface (mm)		
		In loose soil (Mg/m^3)	In hardpan (Mg/m^3)	0–202 (NSL) 0–270 (DCL) (MPa)	146–186 (NSL) 214–254 (DCL) (MPa)	212–252 (NSL) 280–320 (DCL) (MPa)
NSL	6.7	1.18	1.36	0.147	0.196	1.02
DCL	12.8	1.19	1.51	0.272	0.434	1.91

[a] Water content at maximum Proctor density is 11.2% and 18.4% dry basis for the Norfolk sandy loam and the Decatur clay loam, respectively [16].

[b] Depths of centers of loose soil samples beneath untrafficked soil surfaces were 166 mm in the Norfolk sandy loam (NSL) and 234 mm in the Decatur clay loam (DCL). Depths of centers of soil samples in hardpans were 30 mm beneath the top of the hardpan in each soil. Each bulk density is the mean of 32 soil samples.

[c] Base area of cone penetrometer = 323 mm^2. Each cone index is the mean of 16 cone penetrations. Depth of top of hardpan beneath untrafficked soil surface was 202 mm in the Norfolk sandy loam and 270 mm in the Decatur clay loam.

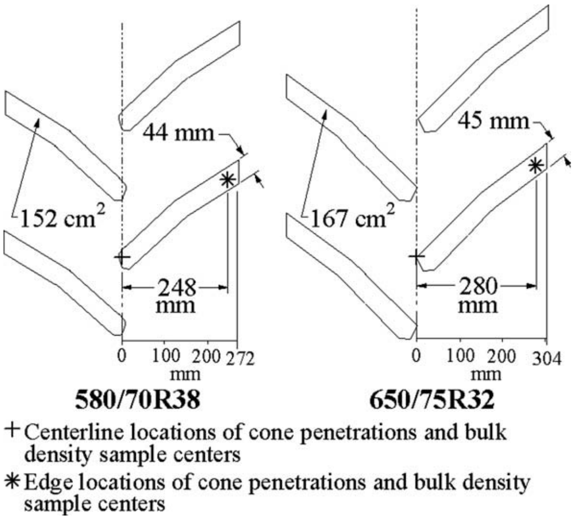

Fig. 2. Lug patterns, lug widths and lug face areas of the tires. Also represents top view of tire path showing locations of cone penetrations and centers of soil core samples for bulk density measurements.

undisturbed soil at the initial depth of the SST and in the hardpan beneath undisturbed soil. Each soil core sample was cylindrical with a height of 40 mm and a diameter of 69 mm. Soil cone indices were measured using a cone penetrometer [17] with a 323 mm^2 base area in a lug imprint at the tire track centerline and at the edge of the tread (Fig. 2), and in undisturbed soil in each plot. Soil cone indices were calculated for depths of the cone base ranging from the top to the bottom of the corresponding 40 mm-high soil bulk density samples.

3. Results and discussion

Mean values of the soil bulk density for the four blocks of the treatments are given in Table 4. Mean soil cone indices are presented in Table 5.

The experiment was viewed as a split-plot-in-space experiment with the combinations of tire, dynamic load, inflation pressure, and soil as the main plot treatments and the centerline and edge locations within each plot of soil as the subplot treatments [18]. The treatments consisted of combinations of two tires, two dynamic loads, two inflation pressures and two soils. The data were analyzed with a repeated measures analysis using the REPEATED statement in PROC GLM of SAS programs [19]. Two repeated measures analyses were conducted, one for each dependent variable: soil bulk density and soil cone index. In each analysis, block was nested within soil because the depths of the hardpans differed in the two soils. Main effects and four-way interactions of all factors were investigated. Effects involving the soil factor were disregarded because we had only one soil bin for each soil type, so we did not have error terms appropriate for testing effects involving the soil factor.

The block factor was considered to be a random effect because the blocks actually included in the experiment were assumed to be a random sample from a population of blocks [20]. The other factors (tire, dynamic load, inflation pressure, and soil) were considered to be fixed effects. Summaries of the mixed model analyses of variance are presented in Table 6.

Table 4
Mean soil dry bulk densities in trafficked soil beneath the centerline and edge of the tire tread.

Dynamic load (kN)	Inflation pressure (kPa)	Norfolk sandy loam				Decatur clay loam			
		580/70R38		650/75R32		580/70R38		650/75R32	
		Centerline (Mg/m^3)	Edge (Mg/m^3)	Centerline (Mg/m^3)	Edge (Mg/m^3)	Centerline (Mg/m^3)	Edge (Mg/m^3)	Centerline (Mg/m^3)	Edge (Mg/m^3)
17.2	40	1.55	1.36	1.54	1.34	1.32	1.23	1.33	1.24
17.2	120	1.66	1.41	1.60	1.32	1.35	1.23	1.32	1.22
30.9	40	1.62	1.43	1.63	1.40	1.34	1.24	1.36	1.26
30.9	120	1.68	1.43	1.66	1.40	1.41	1.27	1.41	1.25

Table 5
Mean soil cone indices in trafficked soil beneath the centerline and edge of the tire tread[a].

Dynamic load (kN)	Inflation pressure (kPa)	Norfolk sandy loam				Decatur clay loam			
		580/70R38		650/75R32		580/70R38		650/75R32	
		Centerline (MPa)	Edge (MPa)	Centerline (MPa)	Edge (MPa)	Centerline (MPa)	Edge (MPa)	Centerline (MPa)	Edge (MPa)
17.2	40	0.84	0.46	1.15	0.81	0.94	0.96	1.21	0.76
17.2	120	1.41	0.61	1.09	0.58	1.29	1.22	1.25	0.86
30.9	40	1.21	0.58	1.30	0.65	1.43	0.98	1.41	0.91
30.9	120	1.70	0.75	1.57	1.08	1.65	1.12	1.66	1.35

[a] Base area of cone penetrometer = 323 mm^2.

Table 6
Tests of hypotheses for main plot effects in repeated measures analyses of variance[a].

Source	Numerator[b]		Denominator		F-value	Pr > F
	DF	MS	DF	MS		
Soil bulk density						
Tire	1	0.00608	6	0.00239	2.55	0.1614
Load[c]	1	0.07732	6	0.00022	357.71	0.0001
Ipr[c]	1	0.02205	6	0.00036	61.40	0.0002
Tire × Load	1	0.00320	6	0.00079	4.06	0.0905
Tire × Ipr	1	0.00711	6	0.00040	17.78	0.0056
Load × Ipr	1	0.00041	6	0.00171	0.24	0.6416
Tire × Load × Ipr	1	0.00118	6	0.00567	0.21	0.6629
Soil cone index						
Tire	1	0.0280	6	0.1222	0.23	0.6485
Load	1	1.8887	6	0.0261	72.49	0.0001
Ipr	1	1.6108	6	0.0369	43.68	0.0006
Tire × Load	1	0.0347	6	0.0233	1.49	0.2680
Tire × Ipr	1	0.1553	6	0.0101	15.35	0.0078
Load × Ipr	1	0.1938	6	0.0500	3.87	0.0967
Tire × Load × Ipr	1	0.4268	6	0.0768	5.56	0.0564

[a] Main plot effects are between-subjects effects.
[b] Degrees of freedom (DF) and mean squares (MS) used in calculating the F-values and determining the probability of a larger F (Pr > F). The denominator mean squares are those specified by the output of the RANDOM statement in SAS's PROC GLM. For each variable, the denominator mean square used to test Tire, Load, Ipr, Tire × Load, Tire × Ipr, and Load × Ipr was the mean square of the corresponding Source × Block(Soil). For example, the mean square used to test Tire was Tire × Block(Soil). The denominator mean square used for Tire × Load × Ipr was MS Error.
[c] "Load" is dynamic load and "Ipr" is inflation pressure.

3.1. Main plot treatment effects

3.1.1. Soil bulk density

The analysis of variance for soil bulk density showed that the interaction between tire and inflation pressure significantly affected bulk density at the 5% significance level (Table 6). The method described by Cody and Smith [21] for handling a significant interaction was used, so bulk density was graphed as a function of inflation pressure (Fig. 3). The graph shows the bulk density has a greater slope for the lower aspect ratio 580/70R38 tire than for the higher aspect ratio 650/75R32 tire. Two subsequent repeated measures analyses of variance were conducted for the bulk density, one for each of the two tires (Table 7). The dynamic load and inflation pressure each significantly affected the soil bulk density for both the 580/70R38 tire and the 650/75R32 tire. The interaction of dynamic load and inflation pressure was not significant at the 5% level for either tire. For the 580/70R38 tire, the mean bulk density of 1.39 Mg/m^3 at the 17.2 kN load was significantly less than the mean of 1.43 Mg/m^3 at the 30.9 kN load. For the 650/

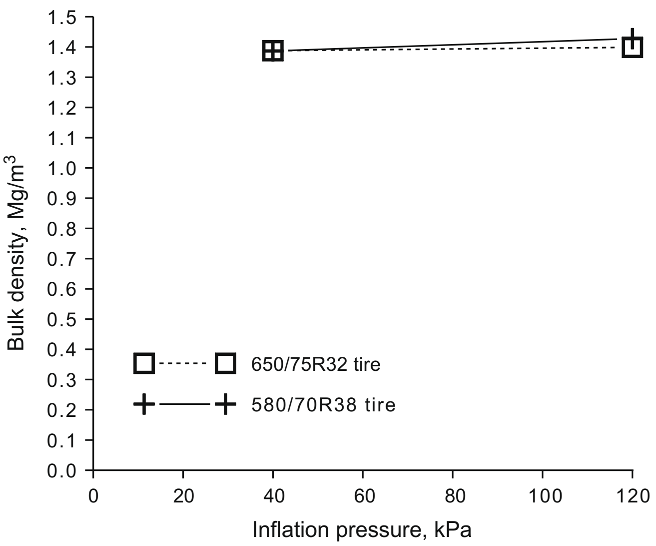

Fig. 3. Interaction of tire and inflation pressure for soil bulk density.

Table 7
Tests of hypotheses for main plot effects in repeated measures analyses of variance, for soil bulk density, for each of the two tires[a].

Source	Numerator[b]		Denominator		F-value	Pr > F
	DF	MS	DF	MS		
580/70R38 Tire						
Load[c]	1	0.02453	6	0.00036	68.11	0.0002
Ipr[c]	1	0.02710	6	0.00058	46.53	0.0005
Load × Ipr	1	0.00010	6	0.00588	0.02	0.8922
650/75R32 Tire						
Load	1	0.05599	6	0.00064	86.84	0.0001
Ipr	1	0.00206	6	0.00018	11.65	0.0143
Load × Ipr	1	0.00149	6	0.00150	0.99	0.3582

[a] Main plot effects are between-subjects effects.
[b] Degrees of freedom (DF) and mean squares (MS) used in calculating the F-values and determining the probability of a larger F (Pr > F). The denominator mean squares are those specified by the output of the RANDOM statement in SAS's PROC GLM. For each variable, the denominator mean square used to test Load and Ipr was the mean square of the corresponding Source × Block(Soil). The denominator mean square used for Load × Ipr was MS Error.
[c] "Load" is dynamic load and "Ipr" is inflation pressure.

75R32 tire, the mean of 1.36 Mg/m^3 at the 17.2 kN load was significantly less than the mean of 1.42 Mg/m^3 at the 30.9 kN load. For each tire, the mean for each load is the average across the two soils, the two inflation pressures, the centerline and edge locations, and four replications. Also for each tire, the greater dynamic load generated the greater soil bulk density, and this result is consistent with the greater mean octahedral stresses at the greater load for these two tires as presented by Way et al. [8]. The tire inflation pressure results exhibited a pattern similar to the dynamic load results. For the 580/70R38 tire, the mean bulk density of 1.39 Mg/m^3 at the 40 kPa inflation pressure was significantly less than the mean of 1.43 Mg/m^3 at the 120 kPa inflation pressure. For the 650/75R32 tire, the mean of 1.39 Mg/m^3 at the 40 kPa inflation pressure was significantly less than the mean of 1.40 Mg/m^3 at the 120 kPa inflation pressure.

Differences in soil bulk density in a relatively narrow range, such as the differences found in this experiment, may have a relatively strong influence on plant seedling emergence, crop stand, and yield. The bulk density of a sandy loam in the range of 1.3–1.5 Mg/m^3 and of a silty clay loam in the range of 1.2–1.4 Mg/m^3 was found to strongly affect the emergence of tomato seedlings [22]. When the soil water content was 1/3 of the plant-available water for the sandy loam, the seedling emergence was 79%, 26%, and 3% for bulk densities of 1.3, 1.4, and 1.5 Mg/m^3, respectively. When the soil water content was 1/4 of the plant-available water for the silty clay loam, the seedling emergence was 95%, 82%, and 34% for bulk densities of 1.2, 1.3, and 1.4 Mg/m^3, respectively. The bulk density of a fine sandy loam in the range of 1.25–1.56 Mg/m^3 in the 0–60 mm depth range was found to affect the stand and yield of grass and legume cover crops [23]. When the bulk density was 1.25, 1.40, and 1.56 Mg/m^3, the cover crop stand was 58%, 49%, and 37%, respectively. The cover crop yields were 4.44, 4.42, and 3.36 t/ha, respectively, with the 3.36 t/ha value here being significantly less than the 4.44 and 4.42 t/ha values. These results from previous research indicate that the soil bulk density results in our experiment may affect crop seedling emergence, crop stand, and yield.

3.1.2. Soil cone index

The statistical analysis of the main plot treatment effects for cone index were similar to those for bulk density, as the interaction between tire and inflation pressure significantly affected the soil bulk density at the 5% significance level (Table 6). A graph of the cone index as a function of inflation pressure shows the cone index has a greater slope for the lower aspect ratio 580/70R38 tire than for the higher aspect ratio 650/75R32 tire (Fig. 4).

We disregarded this overall analysis for the cone index based on the significant interaction between tire and inflation pressure. Two subsequent repeated measures analyses of variance were conducted for the cone index, one for each of the two tires (Table 8). The dynamic load and inflation pressure each significantly affected the soil cone index for

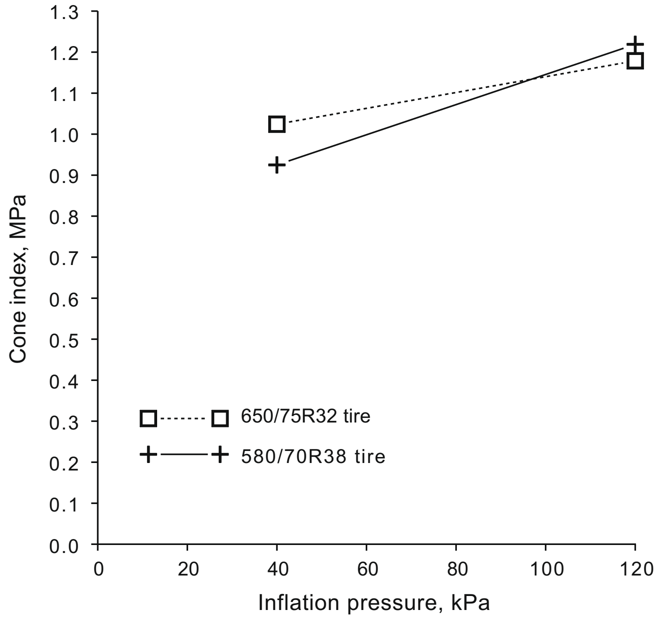

Fig. 4. Interaction of tire and inflation pressure for soil cone index.

both the 580/70R38 tire and the 650/75R32 tire. The interaction of dynamic load and inflation pressure was not significant at the 5% level for either tire. For the 580/70R38 tire, the mean cone index of 0.97 MPa at the 17.2 kN load was significantly less than the mean of 1.18 MPa at the 30.9 kN load. For the 650/75R32 tire, the mean cone index of 0.96 MPa at the 17.2 kN load was significantly less than the mean of 1.24 MPa at the 30.9 kN load. For each tire, the mean for each load is the average across the two soils, the two inflation pressures, the centerline and edge locations, and four replications. For each tire, the greater soil cone index resulted from the greater dynamic load, and this result is consistent with the greater mean octahe-

Table 8
Tests of hypotheses for main plot effects in repeated measures analyses of variance, for soil cone index, for each of the two tires[a].

Source	Numerator[b]		Denominator		*F*-value	Pr > *F*
	DF	MS	DF	MS		
580/70R38 Tire						
Load[c]	1	0.7057	6	0.02913	24.23	0.0027
Ipr[c]	1	1.3831	6	0.01301	106.34	0.0001
Load × Ipr	1	0.0227	6	0.01508	1.51	0.2651
650/75R32 Tire						
Load	1	1.2177	6	0.02021	60.25	0.0002
Ipr	1	0.3829	6	0.03399	11.27	0.0153
Load × Ipr	1	0.5979	6	0.11172	5.35	0.0600

[a] Main plot effects are between-subjects effects.
[b] Degrees of freedom (DF) and mean squares (MS) used in calculating the *F*-values and determining the probability of a larger *F* (Pr > *F*). The denominator mean squares are those specified by the output of the RANDOM statement in SAS's PROC GLM. For each variable, the denominator mean square used to test Load and Ipr was the mean square of the corresponding Source × Block(Soil). The denominator mean square used for Load × Ipr was MS Error.
[c] "Load" is dynamic load and "Ipr" is inflation pressure.

dral stresses at the greater load for these two tires as described by Way et al. [8]. The effect of tire inflation pressure on cone index was similar to its effect on bulk density. For the 580/70R38 tire, the mean cone index of 0.92 MPa at the 40 kPa inflation pressure was significantly less than the mean of 1.22 MPa at the 120 kPa inflation pressure. For the 650/75R32 tire, the mean cone index of 1.02 MPa at the 40 kPa inflation pressure was significantly less than the mean of 1.18 MPa at the 120 kPa inflation pressure.

The significant interactions of tire and inflation pressure described above for both bulk density and cone index caused us to disregard the statistical test comparing the two tires. We did consider the means for the two tires, however. Comparing the two tires, the mean bulk density for the 580/70R38 tire with its 0.756 aspect ratio, averaged across both soils, both dynamic loads, both inflation pressures, the centerline and edge locations, and the four replications, was 1.41 Mg/m^3 and for the 650/75R32 with its 0.804 aspect ratio, the mean bulk density was 1.39 Mg/m^3. The mean cone index for the 580/70R38 tire was 1.07 MPa and for the 650/75R32 tire, it was 1.10 MPa. The mean bulk densities for the two tires were therefore essentially equal and the mean cone indices for the two tires were also essentially equal.

3.2. Location or subplot treatment effects

The location of the soil bulk density or cone index measurement (centerline vs. edge of tire tread) significantly affected the bulk density and cone index for both the 580/70R38 and 650/75R32 tires (Table 9). The soil bulk densities and cone indices were significantly greater at the centerline than at the edge of the tire tread.

Mean centerline-to-edge ratios of soil bulk density and cone index were calculated for each combination of dynamic load and inflation pressure (Table 10). The range of the bulk density ratios was relatively narrow, varying from 1.11 to 1.15. The 17.2-40 treatment had the lowest value of each of the two types of ratios and this was consistent with Way et al. [8] in which the 17.2-40 treatment had lower centerline-to-edge ratios of octahedral stresses than any of the other three treatments. We expected the 17.2-120 overinflated treatment would give a relatively high ratio due to the relatively high rigidity of the tire for this treatment and that the 30.9-40 underinflated would have a low ratio due to the low rigidity of the tire. The bulk density ratio for the 17.2-120 treatment was relatively high, at 1.14, and that of the 30.9-40 treatment was relatively low at 1.12. For the cone index ratio, however, the ratio for the 17.2-120 treatment was not particularly low, at 1.54, and the ratio for the 30.9-40 treatment was the greatest of the four ratios, at 1.72, so the cone index ratio results differed from our expectations.

Table 9
Location or subplot treatment effects on soil bulk density and cone index[a].

Dependent variable	Location	
	Centerline of tire tread	Edge of tire tread
Bulk density for 580/70R38 tire (Mg/m^3)	1.49	1.32
Bulk density for 650/75R32 tire (Mg/m^3)	1.48	1.31
Cone index for 580/70R38 tire (MPa)	1.31	0.84
Cone index for 650/75R32 tire (MPa)	1.33	0.87

[a] The two means in each row are significantly different ($p = 0.0001$). The subplot effects are within-subject effects. The validity of the univariate analysis of variance F tests for a within-subjects effect or its interactions with one or more between-subject effects requires the Huynh–Feldt condition to be met [18]. In this experiment, there were only two levels of the location (centerline and edge of tire tread), so the condition holds automatically.

Table 10
Mean centerline-to-edge ratios for soil bulk density and cone index.

Treatment	Centerline bulk density/ Edge bulk density	Centerline cone index/ Edge cone index
17.2–40	1.11	1.39
17.2–120	1.14	1.54
30.9–40	1.12	1.72
30.9–120	1.15	1.53

4. Conclusions

The following conclusions were drawn from the experiment.

1. The bulk density and cone index in soil just above a hardpan were not affected by the aspect ratio and differences in dimensions of two radial-ply tractor drive tires. One tire, a 580/70R38 had an aspect ratio of 0.756 and an average sidewall thickness of 23 mm, and the second tire, a 650/75R32 had an aspect ratio of 0.804 and an average sidewall thickness of 25 mm.
2. The bulk density and cone index in soil just above a hardpan increased with increasing inflation pressure at constant dynamic load. At constant inflation pressure, the bulk density and cone index increased with increasing dynamic load. For the conditions used in this experiment, soil compaction just above a hardpan, beneath a tire, therefore increases as the dynamic load or inflation pressure of the tire increases.
3. The bulk density and cone index in soil just above a hardpan were significantly less beneath the edge than beneath the centerline of the tire tread, so for the tires and conditions used, soil just above a hardpan is compacted less beneath the edge of a tire than beneath the tire centerline.

In summary, soil compaction is expected to be minimized if the dynamic load carried by each tractor drive tire is minimized and the tire inflation pressure is set at the correct pressure to match the load on the tire. Increases in crop productivity and reductions in soil erosion are expected to result from these practices. Soil beneath the edge of a tractor drive tire is likely to be compacted less, and to provide a better crop root environment than soil beneath the centerline of the tire. Soil compaction is not likely to be affected by the aspect ratio of radial-ply tractor drive tires for aspect ratios in the range of 0.75–0.80.

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