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Tine options for alleviating compaction in wheelings

J.C. Niziolomski, R.W. Simmons*, R.J. Rickson, M.J. Hann

Cranfield Soil and AgriFood Institute, School of Energy, Environment and AgriFood, Building 52a, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

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ABSTRACT

Repeated trafficking and harvesting operations lead to high levels of compaction in inter-row wheelings used in asparagus (*Asparagus officinalis*) production. This reduces soil porosity and infiltration resulting in water ponding on the soil surface. Even on gently sloping land this can result in runoff generation and an increased risk of soil erosion. A winged tine (WT) is currently used by a leading asparagus grower to loosen compacted inter-row wheelings. In order to test the effectiveness of this tine for alleviating compaction and implications for runoff and soil erosion control, it was evaluated alongside several other tine configurations. These were a narrow tine (NT); a narrow tine with two shallow leading tines (NSLT); a winged tine with two shallow leading tines (WSLT); and a modified para-plough (MPP). Testing was conducted under controlled conditions on a sandy loam soil in the Soil Management Facility at Cranfield University, Bedfordshire, UK. Tine performance was assessed at 3 depths (175, 250 and 300 mm) by draught force; soil disturbance (both above and below ground); specific draught for a given level of soil disturbance; surface roughness; and estimated change in soil bulk density. The effectiveness of tines for compaction alleviation and potential for mitigating runoff and soil erosion varied with depth. The most effective tines were found to be the MPP NSLT and the WSLT at 175 mm, 250 mm and 300 mm depth, respectively.

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1. Introduction

Compaction, alongside soil erosion, is the costliest and most environmentally damaging consequence of conventional agriculture (FAO, 2003). Graves et al. (2015) estimated the cost of soil compaction in England and Wales at £472 million a year. This figure includes the on-site costs of the loss of nutrients and crop productivity, the increased fuel required to work compacted soils and the environmental cost of nutrient and sediment pollution, as well as enhanced greenhouse gas emissions. Compaction degrades agricultural land. In Europe alone, compaction has degraded an estimated 33 million ha of agricultural land (Oldeman et al., 1991), of which 3.9 million ha are deemed at risk in England and Wales (Graves et al., 2015).

Row crop systems are particularly prone to compaction. This is a result of regular vehicle trafficking of inter-row wheelings located between the crop rows for repeated field operations. These exist in addition to sprayer tramlines. In hand-harvested crops such as asparagus these same areas are also foot-trafficked and/or harvested using 'picking rigs' under a range of climatic conditions for a 3-month period. This can result in shallow surface compaction and soil smearing of inter-row wheelings when undertaken in very wet conditions. In addition, herbicide use to control weeds results in the surface of asparagus rows being exposed to the kinetic energy associated with raindrop impacts resulting in surface sealing and on de-hydration, capping (Romkens et al., 1986). This significantly reduces infiltration (Philip, 1998; Assouline, 2004) into the asparagus rows with runoff shed to already compacted inter-row wheelings.

Tillage can instantaneously alleviate compaction by breaking through the compacted layer and increasing soil porosity. Tine configuration and arrangement can affect the extent of compaction alleviation. Compaction alleviation is greatest when tines work well above critical working depth (Arvidsson et al., 2004). Critical depth refers to the depth at which loosening operations are limited by confining forces that prevent the upward movement of compacted soil (Spoor and Godwin, 1978). Depth of operation and thus area of soil disturbance can be increased with a decrease in tine rake angle, the addition of wings, and shallow leading tines (Godwin and Spoor, 1977; Spoor, 2006). The resulting increased porosity allows water to infiltrate into the soil reducing surface water ponding and the risk of runoff generation. The additional pore space results in an increased soil volume creating an area of loosened soil on the surface. This loosened soil can further reduce

* Corresponding author.
E-mail addresses: j.c.niziolomski@cranfield.ac.uk (J.C. Niziolomski), r.w.simmons@cranfield.ac.uk (R.W. Simmons), j.rickson@cranfield.ac.uk (R.J. Rickson), m.hann@cranfield.ac.uk (M.J. Hann).

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runoff volume by increasing surface depression storage. Tillage increases soil surface roughness which can impart friction to overland flow and increase flow tortuosity. This will reduce runoff volume (by allowing time for the runoff to infiltrate) and reduce runoff velocity and erosivity of overland flow (i.e. energy to detach and transport soil particles). This effect on runoff and erosion is demonstrated in established runoff prediction equations where the roughness of cultivated surfaces can reduce peak flow (Rational Method, Morgan, 2004) and reduce runoff sediment transport capacity (Smith et al., 2011).

In asparagus production shallow soil disturbance is currently undertaken in inter-row wheelings at 175 mm depth to alleviate compaction, whilst limiting damage to the asparagus root system, which determines crop health. Root damage risks crop diseases (*Phytophthora asparagi* and *Fusarium)* that can dramatically affect the marketable yield, as well as lead to 'asparagus decline' (Snowdon, 1991). However, current tillage practice is not addressing on-site compaction adequately, as large-scale runoff and erosion issues still persist. Furthermore an on-site penetrative resistance survey (with an Eijkelkamp Penetrologger) conducted by the authors in April 2012 demonstrated compaction beyond 175 mm, extending to 500 mm with maximum resistance around 200 mm.

On-site erosion and runoff control can be achieved through a combination of shallow soil disturbance using a winged tine (WT) and application of surface mulch. This outcome has been observed on fully replicated and instrumented runoff erosion plots set up in asparagus inter-row wheelings situated in Herefordshire, UK (Niziolomski et al., 2014). Whilst different surface mulch options have already been investigated (Niziolomski et al., 2014), the efficiency of the current shallow soil disturbance practice has not. This study aims to address this knowledge gap. This in turn can aid the prevention of onsite soil degradation from compaction, contribute to improving the water quality of the local catchment and have wider implications of reversing and preventing soil degradation from compaction in row crops. In order to achieve this, a novel soil bin experiment was set up to evaluate the effect of tine configuration on alleviating soil compaction through above and below ground soil disturbance whilst considering implications for runoff and soil erosion control.

2. Material and methods

Five tine configurations were selected for testing (Table 1, Fig. 1) based upon their suitability for alleviating compaction in wheelings. With the exception of the winged tine (WT), all configurations were designed and built for this experiment. These were a narrow tine (NT); the currently adopted winged tine (WT); a narrow with two shallow leading tines (NSLT); a winged tine with two shallow leading tines (WSLT); and a modified para-plough (MPP).

2.1. Soil testing

Testing was undertaken at the Cranfield University Soil Management Facility, Bedfordshire, UK. A soil bin ($20 \times 1.7 \times 0.7$ m) filled with a sterile, light sandy loam soil (64% sand, 18% clay and 18% silt), was prepared in 50 mm layers to the planned depth of cultivation. Each layer was wetted to an approximate moisture content of 8.2% and subsequently rolled 13 times using a 700 kg roller to create compaction of approximately 1.6 g cm^{-3}. This bulk density and soil type closely reflected the field condition, i.e. a sandy loam soil (69% sand, 15% clay and 16% silt) with a bulk density of 1.7 g cm^{-3}. Once prepared, each tine configuration was mounted in turn onto the soil bin processor and tested.

Testing was carried out in triplicate at depths of 175, 250 and 300 mm below the ground surface. These were selected to simulate the current depth of operation and depths that would address the observed deeper onsite compaction. This was conducted in two phases; the first phase tested each tine at 175 mm depth, and the second phase at 250 and 300 mm depth. All testing was completed on one tine before moving onto the next. The order in which the tines were selected for testing was randomised. During the second phase, the depth of cultivation for each tine was randomised between 250 and 300 mm. Two tine runs were conducted along the length of each soil bin preparation giving an approximate plot size of 1.7×6.0 m (± 0.3 m). Tines were pulled through at 2.1 km h^{-1}. For each soil bin preparation, soil bulk density samples were taken in triplicate down the centre of the soil bin at 0–5 cm depth prior to tine testing in order to ensure consistency.

2.2. Variables and data collection

Tine performance was assessed using seven indicators: draught force (D); soil disturbance (both above (D_{AG}) and below ground (D_{BG})); specific draught for a given level of soil disturbance (SD_D); surface roughness (both in-line (SR_I) and perpendicular (SR_P) to the direction of cultivation); and bulk density reduction. These were selected to assess implement dynamics and quantify the extent of compaction alleviation and soil properties beneficial to increasing infiltration.

Draught force was measured using a calibrated Extended Octagonal Ring Transducer (EORT), through a series of strain gauges on the tine mounting point (Godwin, 1975). These measurements were recorded using data logging software (Data Acquisition System Laboratory Ver. 8.00.04). The draught force measurements made it possible to infer tractor power requirements and fuel costs for each tillage system; with higher draught force associated with a greater power requirement and higher fuel cost.

In order to assess the efficiency of each tine in relation to compaction and potential runoff/erosion control, the traditional specific draught calculation was adapted to include both above and below ground disturbance. The resulting equation was:

Table 1
Technical properties of the tested tine configurations.

Description	Code	Geometry	Configuration
Winged tine	WT	Rake angle; 45°, wing inclination; 30°.	Single tine, in-line.
Narrow tine	NT	Rake angle; 45°	Single tine, in-line.
Modified para-plough	MPP	Tine and rake angle; 45°.	Two tines, in parallel.
Winged tine with two shallow leading tines	WSLT	Rake angle; 45°, wing inclination; 30°.	Two leading shallow tines spaced 220 mm apart, 350 mm ahead of main tine.
Narrow tine with two shallow leading tines.	NSLT	Rake angle; 45°.	Two leading shallow tines spaced 220 mm apart, 350 mm ahead of main tine.

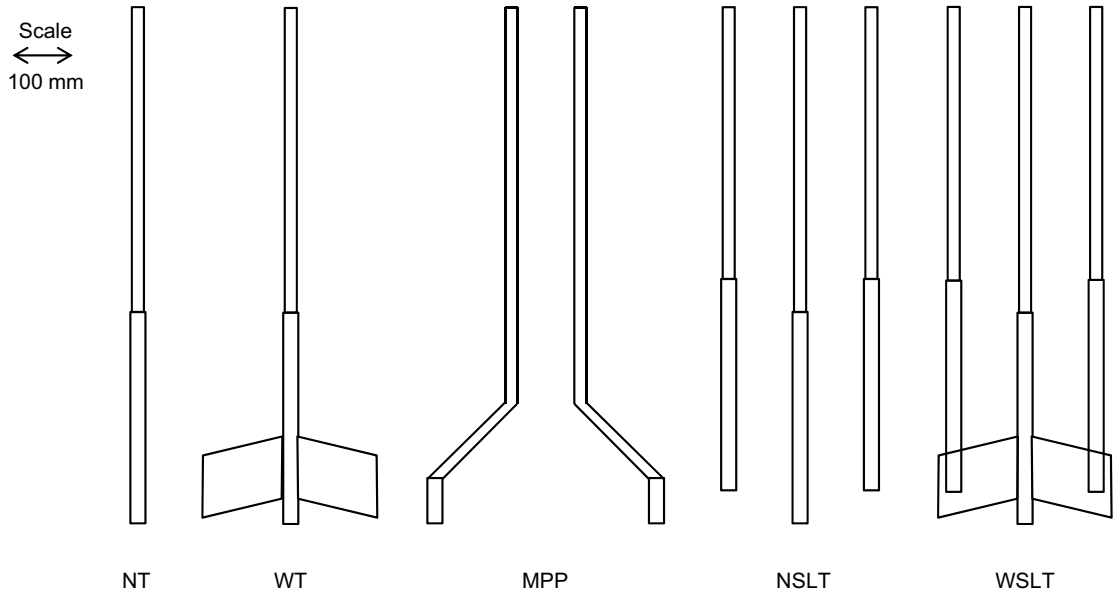


Fig. 1. Plan view of the tested tine configurations. NT: narrow tine, WT: winged tine, MPP: modified para-plough, NSLT: narrow tine with two shallow leading tines, WSLT: winged tine with two shallow leading tines.

$$SD_D = D/D_{AG} + D_{BG}. \quad (1)$$

where SD_D is the specific draught for a given area of soil disturbance, D is draught force, D_{AG} is soil disturbance above ground and D_{BG} is soil disturbance below ground.

D_{AG} was measured at three random points along the line of cultivation using a 1 m long profile meter with pins set at 2 cm intervals and one fixed length pin at each end. This captured the 2D profile of D_{AG}. Once the pins were clamped in place the shape was traced onto paper. The distance of each pin from the soil surface baseline (indicated by the fixed length pins) was then measured, and the cross sectional area calculated.

Surface roughness was measured both following and perpendicular to the direction of cultivation (SR_I and SR_P respectively). This took into account the two runoff pathways identified in the field; from the raised asparagus beds into the inter-row wheelings (perpendicular) and channelled downslope in the centre of the inter-row wheelings (following the direction of cultivation). Measurements were made at three points along each plot. SR_P measurements were made at the same points as the earlier D_{AG} measurements. Using the chain method (Saleh, 1993), a chain of known length was carefully placed across the disturbed surface and the horizontal distance covered by the chain measured (Gilley and Kottwitz, 1996). This was divided by the original chain length and subtracted from 1, to provide an index of roughness in which 0 equated to a completely smooth surface.

Once these measurements were completed, the three measurement areas were carefully excavated of loose soil to reveal the extent of the D_{BG}. The cross sectional area was measured using a profile meter, as with D_{AG}.

Changes in bulk density were calculated using the pre-testing bulk density and the total cross sectional area of disturbance. The pre-testing soil bulk density (between 0 and 5 cm depth) was multiplied by the cross sectional volume of D_{BG} (cm^3). The resulting mass was subsequently divided by the new soil volume; the sum of D_{BG} and D_{AG} (cm^3).

Results were analysed using STATISTICA 12. Data was first checked for normality using residual analysis, and then analysed

Table 2
Above ground disturbance (D_{AG}), below ground disturbance (D_{BG}), perpendicular surface roughness (SR_P), in-line surface roughness (SR_I), draught force and specific draught for a given area of soil disturbance (SD_D) and change in bulk density for each tine configurations at all three tested depths. Different letters following results for each variable within each cultivation depth denote significant differences ($p = < 0.05$).

Cultivation depth	Tine[a]	D_{AG} (m^2)	D_{BG} (m^2)	SR_P	SR_I	Draught force (kN)	SDD (kN m^{-2})	Changes in bulk density (g cm^{-3})
175 mm	NT	1.46b	2.68a	0.21a	0.45c	1.31b	0.32a	0.54a
	WT	2.21a	3.41b	0.24a	0.34a	2.55a	0.45b	0.63ab
	MPP	3.11c	5.07c	0.23a	0.3ab	2.08d	0.25a	0.57a
	NSLT	1.90a	2.92a	0.31a	0.36a	1.68c	0.35a	0.59a
	WSLT	2.25a	2.82a	0.22a	0.22b	2.75a	0.55c	0.71b
250 mm	NT	2.42b	3.78b	0.15a	0.44c	14.3a	2.35a	0.60a
	WT	3.38ac	6.28a	0.17a	0.32ab	22.7b	2.34a	0.55a
	MPP	3.59a	6.67a	0.26a	0.28a	22.0b	2.15a	0.54a
	NSLT	2.71bc	5.43c	0.23a	0.38bc	14.7a	1.80a	0.51a
	WSLT	3.93a	6.53a	0.24a	0.31a	25.7c	2.46a	0.58a
300 mm	NT	3.10b	4.62b	0.21ab	0.37a	22.3a	2.94a	0.62b
	WT	4.20a	8.38a	0.18ab	0.31b	32.0b	2.55a	0.52a
	MPP	4.21a	8.02a	0.12a	0.30b	37.0c	3.07a	0.55ab
	NSLT	3.00b	5.66b	0.24bc	0.38a	19.7a	2.29a	0.53a
	WSLT	4.01a	8.47a	0.34c	0.40a	32.3b	2.59a	0.48a

[a] NT: narrow tine, WT: winged tine, MPP: modified para-plough, NSLT: narrow tine with two shallow leading tines, WSLT: winged tine with two shallow leading tines.

using Factorial ANOVA. This was followed, when significant effects were observed ($p = 0.05$), by post-hoc Fisher LSD analysis.

3. Results and discussion

3.1. Soil disturbance

3.1.1. Disturbance area

The MPP generated significantly greater D_{AG} and D_{BG} as compared with all other tines, when tested at 175 mm depth (Table 2). This greater D_{BG} can be attributed to the spatial configuration of the tine, with two tines running parallel, creating two separate entry points into the soil profile, so disturbing two distinct areas (Fig. 2).

It would be expected that winged tines generate a greater disturbance area compared to narrow tines as a result of the lateral disturbance created by the wings (Spoor and Godwin, 1978). However, this was only observed at 250 and 300 mm depth when the MPP, WSLT and WT all generated significantly greater D_{BG} as compared with both narrow tine configurations (NT and NSLT; Table 2). This suggests that the tines' wings disturbed the soil more effectively with depth. This is supported by an observation that the wing inclination was such that at 175 mm the wings were not fully submerged beneath the soil surface.

The addition of shallow leading tines to the NT (in the NSLT) increased D_{BG} by 8, 30 and 18% at 175, 250 and 300 mm respectively, as compared with the NT (Table 2). This effect was not observed with the WSLT, where D_{BG} increased by just 4 and 1% at 250 and 300 mm respectively as compared with the WT (Table 2). This is because there was little difference in operating width between the WT and WSLT, meaning that little additional lateral soil disturbance occurred.

At 250 mm, D_{AG} was only significantly greater for the WSLT and MPP as compared with the NT and NSLT (Table 2). At 300 mm, the MPP, WSLT and WT all generated significantly greater D_{AG} than the NT and NSLT configurations (Table 2). This was to be expected as wings and multiple tines increase the compaction alleviation and soil porosity which is manifest in the resulting D_{AG}.

3.1.2. Change in bulk density from baseline condition

A reduced bulk density ranging from 32 to 44% was achieved with all tines, at all tested depths as compared with the baseline condition. Statistically significant differences were only observed at 175 and 300 mm depths (Table 2). At 175 mm, the WSLT significantly reduced bulk density as compared with the MPP, NSLT and NT. However, the mean pre-tillage soil bulk density was also significantly higher for this tine with a difference of 0.10–0.07 g cm^{-3} as compared with all other tines. At 300 mm, the NT significantly reduced bulk density as compared with the NSLT, WT and WSLT (Table 2). This was most likely a result of the nature of disturbance. The NT generates heave as it fractures and lifts the soil, whilst the WT rearranges and breaks-up the soil as the tine point first fractures the soil, after which the disturbed soil is re-oriented by the wings as it is lifted and dropped (Spoor and Godwin, 1978).

3.2. Surface roughness

Narrow tine configurations most consistently increased SR_I, with shallow leading tines resulting in increased surface roughness

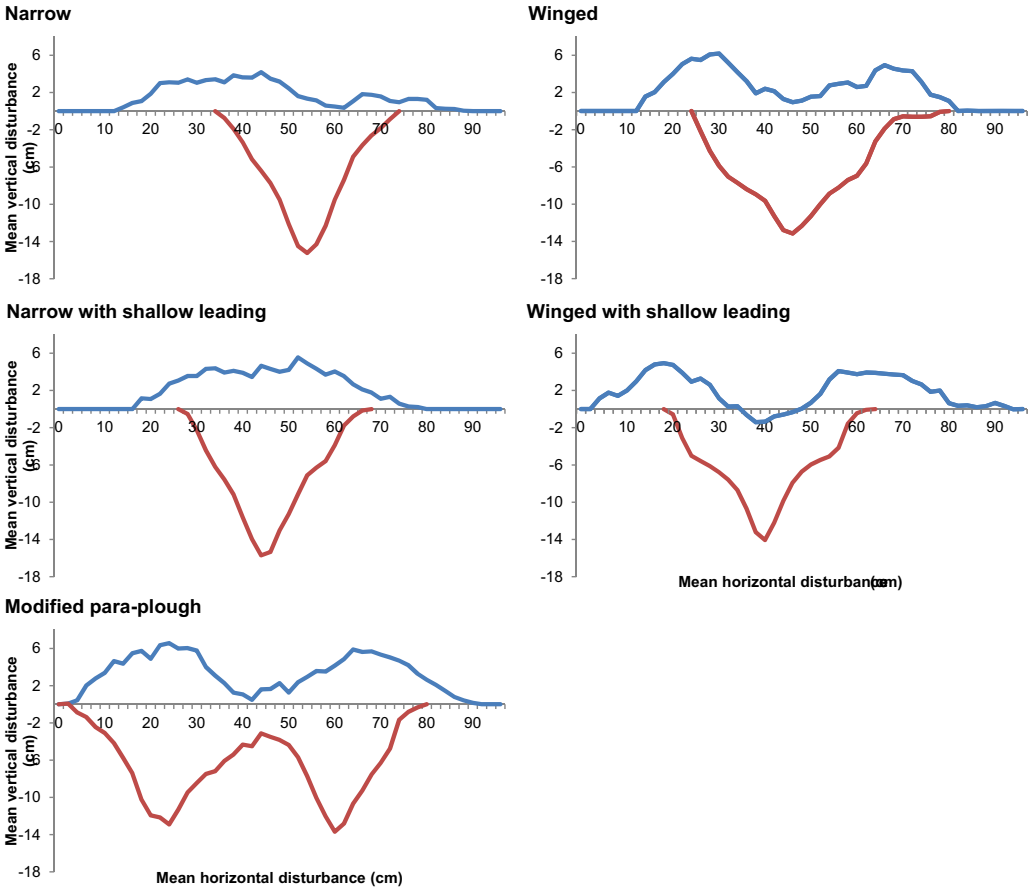


Fig. 2. Cross section profiles of each tested tine configuration at 175 mm, derived from the mean profile of three runs.

with greater cultivation depths. Only the WSLT resulted in significant increases in SR_P as compared with all other tines.

At 175 and 250 mm, only significant differences in SR_I were observed between the different tines (Table 2). The NT generated a significantly higher SR_I at 175 mm as compared with all other tines (Table 2). At 250 mm the NT continued to create the highest SR_I, but this was not significantly different from the NSLT. This higher SR_I was a result of the larger ped sizes generated by the NT, which resulted in larger surface clods with a greater surface area as compared with the WT and MPP.

At 300 mm depth, three tine configurations generated significantly higher SR_I; WSLT, the NT and the NSLT as compared to the WT and MPP (Table 2). The WSLT generated significantly higher SR_P than the NT, WT and MPP, but this was not significantly higher than the NSLT. The success of the WSLT at the greater working depth could be attributed to a larger tine leading-edge surface area (0.006–0.04 m^2 greater than all other tines) resulting in maximum soil rearrangement.

The nature of the soil disturbance undertaken by each tine configuration can also have an effect on the longevity of the compaction alleviation effect. Spoor and Godwin (1978) observed that the limited soil rearrangement by narrow tines is more likely to fall back into place and re-compact than soil that has been rearranged by winged tines. This suggests that compaction alleviation would be better sustained with winged tines.

3.3. Draught force

The WT and WSLT both exerted significantly higher draught as compared with all other tine configurations at 175 mm depth (Table 2). At 250 mm, the draught force for all tines had increased by an order of magnitude, due to the greater soil mass presenting an increase in frictional resistance. At this depth, the WSLT exerted significantly greater force than all other configurations (Table 2). The high draught forces observed with the winged tine configurations are to be expected as they had the largest leading edge surface area (0.03 m^2 greater than all other configurations) resulting in a greater frictional resistance being imparted as the WT moves through the soil.

At 300 mm draught force increased again, but to a lesser extent, for all configurations (Table 2). The MPP exerted the highest draught force. This could result from the bent-leg design (Fig. 1) that at 300 mm results in a larger area of the straight, flat-faced leg component beneath the soil surface.

Both the NT and NSLT configurations exerted the lowest draught force as compared with all other tines. At 175 mm, the NT exerted significantly less draught force than all other tines, followed by the NSLT (Table 2). At 250 and 300 mm, both narrow tine configurations exerted significantly less draught force than all other tines.

3.4. Specific draught for above and below ground disturbance

Significant differences in specific draught were only observed at 175 mm (Table 2). At this depth, the MPP, NT and NSLT were significantly more efficient (low SD_D; greatest area disturbed for the least specific draught; Table 2). As expected, these results reflect the tines that generated the greatest D_{BG} and exerted the least draught force. The lack of significant differences with greater depths was a result of the increased disturbance from the winged tine configurations and the increase in draught force across all configurations.

3.5. Tine performance ranking

Using a Pugh matrix (Nixon et al., 2013), tine performance at each tested depth was compared with that of the WT (the currently adopted practice). Each tine was assigned a value depending upon the difference observed from the WT. The values were: '0' when no significant difference existed, '+ when a significant positive change was observed (increased D_{AG}, D_{BG}, SR_P, SR_I, change in bulk density and decreased SD_D) and '−1' when a significant negative change was observed. These values were totalled for each tine at each tested depth, and the resulting value ranked.

The MPP was the highest ranking optimal tine configuration at 175 mm cultivation depth, considering D_{BG}, D_{AG}, SD_D, SR_I, SR_P and bulk density reduction. This is largely a result of the significantly greater area of D_{BG} and D_{AG} as compared with the all other tines. At 250 mm, the NSLT ranked highest overall as a result of a significantly greater area of D_{BG} as compared with all other tines. At 300 mm, the WSLT was associated with optimal performance as a result of a significantly greater SR_I and SR_P as compared with all other tines (Table 2).

3.6. Implications for runoff and erosion control

The results of this study demonstrate that compaction alleviation can create conditions conducive to reducing runoff and soil erosion. More specifically, compaction alleviation increases soil porosity within an area of disturbance resulting in increased infiltration. Infiltration is further increased by the resulting above ground disturbed soil that has the potential to reduce runoff velocity and increase the time in which the runoff can infiltrate into the soil. Therefore, the tines that rank best for compaction alleviation also result in the greatest potential increase in infiltration and thus runoff and erosion control.

These results represent the effectiveness of each tine under a single soil condition (soil type, bulk density and moisture content) on a sandy loam soil. Different soil conditions would result in differences in the parameters measured in this study. For example, as moisture content decreases the size of soil clods would increase (Davies et al., 2001). A similar effect would be observed with low moisture contents (Arvidsson et al., 2004) and soil types with increasing clay content (Munkholm, 2011).

4. Conclusion

The objective of this study was to evaluate the effectiveness of different tine configurations to alleviate compaction as compared with the currently adopted practice. The results indicate that tine effectiveness in terms of compaction alleviation and potential for mitigating runoff and soil erosion varied with depth. The most effective tines were found to be the MPP NSLT and the WSLT at 175 mm, 250 mm and 300 mm depth, respectively. Adopting specific tine configurations to address compaction at depth could benefit asparagus production and the wider environment, by reducing diffuse pollution associated with runoff. The findings of this study have potential relevance to other row crop production systems.

Before these results can be fully applied, field validation should be undertaken. This will verify whether the tine configuration performance observed under controlled pilot scale laboratory conditions can be transferred and up-scaled to the field. This has already been undertaken by the authors and will be reported separately. In addition, further research should be undertaken to investigate the efficacy of suitable measures to reduce the risk of compaction occurring. In the context of asparagus production, long-term research is required to critically evaluate the extent of root damage associated with each tine configuration in relation to impacts on marketable yield and 'asparagus decline'.

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