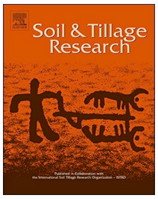
Soil & Tillage Research 191 (2019) 131–141

Contents lists available at ScienceDirect

Soil & Tillage Research

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



BEETSOIL: a decision support tool for forecasting the impact of soil conditions on sugar beet harvest

Miguel A. Gabarron-Galeote[a,b], Jacqueline A. Hannam[a,*], Thomas Mayr[a], Patrick J. Jarvis[b]

[a] School of Water, Energy and Environment, Cranfield University, Bedfordshire, MK43 0AL, UK
[b] AB Sugar plc, Sugar way, Peterborough, PE2 9AY, UK

ARTICLE INFO

Keywords:
Decision support tool
Soil trafficability
Soil compaction
Sugar beet
Harvesting

ABSTRACT

Sugar beet in the UK is harvested in autumn and winter, when soil moisture is usually close to field capacity. This, together with the heavy machinery used can lead to serious environmental problems such as topsoil disturbance, subsoil compaction and soil erosion. BEETSOIL is a decision support tool (DST) developed to help plan the sugar beet harvest campaign by assessing if soil conditions are suitable for harvest whilst minimising the occurrence of soil damage. The core of BEETSOIL is a soil water balance model that, using a rainfall source selected by the user, predicts soil water content in a determined prediction window. The resulting soil water content is used to predict soil trafficability, wheel sinkage, soil stickiness and soil loss due to harvest on a daily basis. The soil water balance module was validated with measured soil water content at three field sites with contrasting clayey, silty and sandy textures and showed RMSE of 0.91%, 0.96% and 0.52%, respectively. The sensitivity of the trafficability modules of BEETSOIL were tested using several scenarios using different initial soil water contents at the start of the harvest campaign combined with rainfall amounts that simulate wet, median and dry conditions during the harvest period. Analysis of the scenarios showed the trafficability module was very sensitive to changes in texture, initial soil water content of the simulation and rainfall. This information can be used to assess the suitability of new sugar beet growing areas, where the proportion of time during which fields can be trafficked by vehicles (harvested effectively) can be predicted under different scenarios and therefore give an indication of any consistent harvest difficulties. The model outputs of sinkage, trafficability and soil loss by harvest have yet to be validated, but the first outputs provide indications of how the DST can be used across the whole growing area to schedule harvest operations to target areas that can be harvested most effectively.

1. Introduction

In the UK late-harvested crops such as sugar beet have significant impact on soil conditions during harvest causing soil compaction and impacting the yields of the following crops. Sugar beet is harvested between October and February (known as the campaign), when rainfall usually exceeds evapotranspiration and soil moisture levels are consequently high (Edwards et al., 2016). At the same time, the industrialisation of agriculture in the UK, due to the increasing pressure to improve production and reduce costs, has led to the extensive use of heavy machinery for a variety of agricultural operations. Sugar beet harvesters can weigh up to 35 tons unloaded and 65 tons when they are full of crop. The pressure triggered by these loads on the soil surface is transmitted through the profile, causing top and subsoil compaction (Arvidsson et al., 2003; Chamen et al., 2015). There are three main problems associated with harvesting during wet conditions 1) subsoil compaction, 2) reduced access to fields due to poor trafficability and 3) soil adhering to the beet (Arvidsson et al., 2003; Earl, 1997; Edwards et al., 2016; Rücknagel et al., 2015; Ruysschaert et al., 2005, 2007).

Soil compaction is defined as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Soil Science Society of America, 1996). The main factors influencing soil compaction are the characteristics of machinery (vehicle load, wheel configuration and tyre characteristics) and soil (texture, soil organic carbon soil surface state, soil structure and water content) (Défossez and Richard, 2002). Due to its pervasiveness, soil compaction is an important problem in the subsoil (Etana and Håkansson, 1994) and its

---

* Corresponding author.
E-mail addresses: Miguel.Gabarron@absugar.com (M.A. Gabarron-Galeote), j.a.hannam@cranfield.ac.uk (J.A. Hannam), t.mayr@ntlworld.com (T. Mayr), Patrick.Jarvis@absugar.com (P.J. Jarvis).

https://doi.org/10.1016/j.still.2019.04.001
Received 26 March 2018; Received in revised form 27 February 2019; Accepted 3 April 2019

Fig. 1. Structure of the BEETSOIL decision support tool.

main effects are reduced infiltration causing flooding and erosion, and rooting restrictions linked to yield reductions (Raper, 2005; Schjønning et al., 2012).

In addition to issues with compaction, a primary concern for processing and production are topsoil conditions causing difficulty in access to land for effective beet harvest (trafficability). Trafficability is the capacity of land to be driven on without undue sinkage (ruts < 5 cm deep), slippage or adhesion of soil to the tyres (Earl, 1997). Reduced trafficability can considerably increase production costs of farms due to greater draught forces required (Chamen et al., 2015), together with causing operational problems with efficiently planning the campaign. In some years topsoil conditions are not trafficable during the campaign, beet is difficult to harvest and the supply of sugar beet to processing factories is interrupted. In extreme cases this causes factory shut down during the campaign, with large costs to the industry.

When conditions are wet in soils with higher clay contents the soil adheres to the beet and is transported to the sugar factory. In the 2016–17 campaign a total of 334,172 Tm of dirt tare were extracted at the four British factories, equating to 4.2 Mg ha^{-1}. It is firstly an environmental problem, since this kind of erosion can be in the same order of magnitude of water and tillage erosion (Ruysschaert et al., 2005). Secondly, it is an operational problem, since the beet has to be cleaned before being processed and the resulting excess topsoil disposed of.

In order to minimise these detrimental effects, agricultural operations must be carefully planned. Decision Support Tools (DST) are important instruments in agricultural planning, since they help users to make effective decisions by leading through successive stages or scenarios and showing the results of different decision paths (Rose et al., 2016). Several DSTs exist to predict compaction, trafficability and removal of soil by harvesting. Subsoil compaction is by far the most studied aspect and there are abundant estimation and risk assessment tools. Terranimo (Stettler et al., 2014) predicts the risk of soil compaction with different machinery and soil conditions. It uses the precompression stress to quantify soil strength, which is compared with the stress caused by the vehicle through the soil profile. The SoilFlex model predicts stress propagation and changes in soil bulk density (Keller et al., 2007). Pre-compression stress was also used as a criterion to assess risk of subsoil compaction in other risk assessment methods developed by Arvidsson et al. (2003) in Sweden and Rücknagel et al. (2015) in Germany. Regarding trafficability, Audsley (1984) published a model to select the optimum machinery for ploughing and drilling from a cost perspective. This model estimated the best tractor to use given the soil and climate characteristics of a place, but did not give daily recommendations about the possibility of conducting the operation. Most of the DSTs in this topic have been developed in the military field and based on experimental work performed at the Waterways Experimental Station (WES) of the US Army. Two semi-empirical models arising from this work are Mobility Numerics (Freitag, 1966) and Mean Maximum Pressure (Rowland, 1975), further developed by Maclaurin (1997) and Larminie (1988, 1992). Lastly, literature on harvest erosion is not abundant and it consists mainly on the work performed by Ruysschaert et al. (2005, 2007).

Although there exist many DSTs in agriculture, to our knowledge there are none available that have integrated the issues with sugar beet harvesting from a soil management perspective, to include predictions of trafficability and soil tare in forecasting mode. Therefore, the main aim of this work was to develop a DST to plan sugar beet harvesting operations, taking into account trafficability conditions, soil stickiness and forecasting conditions on a daily basis. The DST (BEETSOIL) is intended to work as a strategic rather than operational tool at a regional scale to determine when and where to harvest sugar beet for the whole sugar beet growing area. It would therefore be used in the context to guide harvest operators to the best places to harvest to minimise trafficability issues and soil damage based on a forecast of soil conditions on a weekly or monthly basis. The sugar beet growing area in the UK extends across Eastern and Central England and covered > 100,000 ha in 2017 (Farmer's Weekly, 2018). The DST was also developed as a strategic tool for the sugar beet processing industry to evaluate how the harvesting operations in different areas are sensitive to weather conditions (*e.g.* for average, wet and dry years), for example when considering where to expand into new sugar beet growing areas. Therefore, we have prioritised simple and easy to parametrise methods for the different modules within the BEETSOIL DST.

2. Description of the DST

2.1. General structure

BEETSOIL is a DST that uses weather, soil and vehicle properties to help plan the sugar beet harvesting campaign, by estimating the evolution of soil trafficability and soil loss in a determined window of prediction. The prototype version of BEETSOIL is coded in an Excel spreadsheet and its general functioning is presented in Fig. 1. The DST contains six modules that successively i) require the input options to be selected by the user; ii) estimate or read the daily rainfall; iii) estimate daily soil water content using a soil water balance model; iv) compare vehicle pressure with soil strength to estimate soil trafficability and, v) vehicle sinkage; and vi) calculate consistency index and soil loss due to harvest.

2.2. Initial conditions and model inputs

At start-up the DST requires the user to select the mode in which BEETSOIL will be run, the vehicle configuration, the soil parameter file to use in the simulation, and the initial soil water content. The differences between the three modes are the prediction window, the origin of the rainfall input and the format of the results. The three modes are:

a) *Forecast*: the DST estimates the results for the short term future (daily up to 28 days, depending on weather forecast availability) according to the rainfall forecast. The weather forecast module produces 300 rainfall realisations, allowing for a probabilistic result.
b) *Long-term*: results are estimated for the whole harvesting campaign (up to 151 days) assuming historical average rainfall. The use of 1000 rainfall realisations statistically identical to the long-term average rainfall also allows for probabilistic results in this mode.
c) *Input Rainfall*: daily rainfall and consequent prediction window are decided by the user. Given that the model is run with a single rainfall realisation, results in this mode are deterministic.

The DST allows for selecting between 4 different vehicles, including a 2-axle and a 3-axle harvester and tractor and trailer combinations of two different sizes. These were selected after reviewing the most common vehicles used for sugar beet harvest in the UK. The user can select the appropriate combination of tractor and trailer from this list. For future refinements of the model it would be possible to change these specifications but this level of detail was not needed at this stage of development. Changing the vehicles selected can also be used for scenario testing *e.g.* "If we harvested using these vehicle types on these soils during this week what is the effect on harvest trafficability?". The user's choice of the vehicle type and the soil type determines the selection of a number of soil, vehicle and weather properties that are used in the DST modules that predict trafficability, sinkage and stickiness (see Table SM1 and Fig. 1). The prototype model has been developed for 10 dominant soil mapping units within the UK sugar beet growing area, identified from the national soil map and associated data (LandIS: Hallett et al., 2017). The rationale for selecting these units was to indicate how the DST could be up scaled to the whole sugar beet growing region by relating the input soil parameter files to major soil mapping units in the national soil map. Thus the model outputs are dependent on the scale of the available soil data. A representative field within each mapping unit was selected and two pairs of tensiometers were installed at 15 cm and 35 cm depth. The tensiometers provided real time initial soil water conditions for the simulations. In further developments of the model, it is expected that the initial soil water content could be provided by satellite data or other available data collected from local weather stations owned by farmers. For clarity we report results from 3 soil units that have the largest spatial coverage and span the diversity of soils in the region.

2.3. Weather forecast

The weather forecast is only executed when BEETSOIL is run in the Forecast mode and it uses two weather forecast files to estimate daily rainfall amounts for a period of up to 28 days.

Daily rainfall for the first week of prediction is estimated from a 6-day local forecast file representative of the field location received from the U.K. Meteorological Office (Met Office). It contains a rainfall range (in mm) and the associated rainfall probability for each day. From this rainfall forecast the model produces 300 rainfall realisations that are input to the water balance. For each day, 300 random numbers between 0 and 1 are produced. If the number falls below the rainfall probability associated to the day, the day is classified as rainy and another random number is produced within the associated rainfall range, and this is the resulting rainfall amount for that day of the forecast. If the first random number falls above the rainfall probability associated to the day, it is classified as not rainy and the prediction on the day for that realisation is 0 (Table 1).

Daily rainfall for weeks 2 to 4 are predicted based on a Monthly Outlook forecast produced by the Met Office. It consists of a regional forecast (*e.g.* Eastern England) of total weekly rainfall (in mm) for week 2 and for weeks 3 + 4 and an indication of being 'well below',' below',' on',' above' or 'well above the average' (Table 2). The following procedures were implemented to convert the monthly outlook into a daily rainfall forecast for weeks 2, 3 and 4. BEETSOIL incorporates a database

Table 1
Format of the weather forecast file for week 1 in the Forecast mode of the DST. R_{mi} and R_{Mi} are the limits of the expected rainfall range and $Prob_i$ is the rainfall probability of day *i*.

Day	Rainfall	Probability
1	$R_{m1} - R_{M1}$	$Prob_1$
2	$R_{m2} - R_{M2}$	$Prob_2$
…	…	…
6	$R_{m6} - R_{M6}$	$Prob_6$

Table 2
Format of the weather forecast forecast for weeks 2 and 3 + 4. R_i is the expected rainfall and P_i is probability of rainfall being in the following ranges: *wba* (well below average), *ba* (below average), *a* (average), *aa* (above average), *waa* (well above average).

Region	Forecast	*wba*	*ba*	*a*	*aa*	*waa*
Region 1	R_1	P_{wba1}	P_{ba1}	P_{a1}	P_{aa1}	P_{waa1}
Region 2	R_2	P_{wba2}	P_{ba2}	P_{a2}	P_{aa2}	P_{waa2}
…	…	…	…	…	…	…
Region n	R_n	P_{wban}	P_{ban}	P_{an}	P_{aan}	P_{waan}

containing 1000 annual daily rainfall realisations for at least one location per region. These realisations are produced using the LARS Weather Generator (Semenov and Barrow, 2002) and are generated from a long-term (at least 25 years) daily data series, and are statistically identical to the observed data. The model selects the 300 realisations that have the closest weekly rainfall totals (Euclidean distance) to the weather forecast and assigns them a probability score depending on where it falls around the average on both periods week 2 and weeks 3 + 4 (Table 2).

For the Long-term mode the model used the 1000 rainfall realisations generated from the historical datasets using the LARS weather generator. In the absence of forecast data this mode provides the user of an indication of weather over the campaign based on long-term records. This mode is used as a strategic tool to assess and test scenarios such as determining trafficability across the whole campaign based on historical data and to assess any potential trafficability issues for soils in new growing areas that may be under consideration. For the Input Rainfall mode, a single dataset is input by the user that represents a daily annual rainfall data, for example where the user has access to local weather station data.

2.4. Water balance

A modified version of the WaSim water balance model (Hess and Counsell, 2000) has been integrated within BEETSOIL. It is a one-dimensional, daily, soil water balance model that simulates soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to weather, irrigation and canal seepage where relevant. Water is stored in a maximum of five layers (Fig. 2) between the surface (upper boundary) and the impermeable layer (lower boundary), which limits are established at 0.15 m, root depth, water table depth and drain depth. Both water table and drainage system can be removed from the scheme so it is simplified to three layers.

2.5. Trafficability

BEETSOIL estimates soil trafficability by comparing soil strength, represented by the Cone Index (CI) with vehicle pressure, represented by the Mean Maximum Pressure (MMP). CI has been calibrated against SWC for 10 representative soil units of the growing area, following Eq. (1) developed by Sullivan and Anderson (2000):

$$CI = EXP(a - b\ln SWC) \tag{1}$$

where*a* and *b* are empirical coefficients and *SWC* is the volumetric soil water content (%). Local calibrations were developed for SWC and *CI*, illustrated in Fig. 3 for three selected field sites that were with instrumented with tensiometers, representing the spectrum of soil textures in the growing region (Table 3). Each site was visited seven times over the growing season (between drilling in March and harvest in late Autumn) to cover a range of soil moisture conditions. Ten measurements of *CI* were taken within each field at random locations using a digital penetrologger (Eijkelkamp). According to Saarilahti and Anttila (1999), the critical depth for trafficability and sinkage is between 15 and 30 cm, so the average *CI* within this range was calibrated against the average soil water content of the corresponding day. The average of the *SWC* measurements at 15 and 35 cm (derived from converting water tension from tensiometers, see Eq. 11) installed in the same field were used to develop the calibrations for each soil based on Eq. 1 (Table 4, Fig. 3). The standard deviation (SD) of ten *CI* measurements ranged from 0.11 to 0.66 MPa in the clay soil, 0.12–0.54 MPa in the silt soil and 0.25– 0.66 MPa in the sandy soil. Thus, the estimation error of the model was not higher than the field variability of the property.

We did not use equations that incorporated bulk density or texture to predict *CI* because the local calibrations with SWC take into account any variation in these soil properties. The rationale for using Eq. 1 was

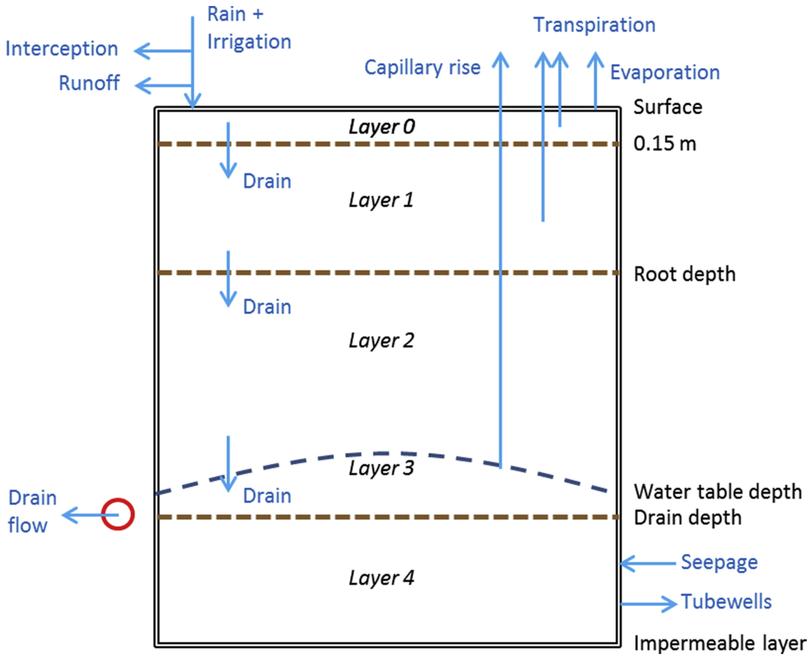


Fig. 2. Schematic of modified WASIM model (after Hess and Counsell, 2000) integrated in BEETSOIL. Blue arrows represent flows of water and dashed lines boundaries between soil layers.

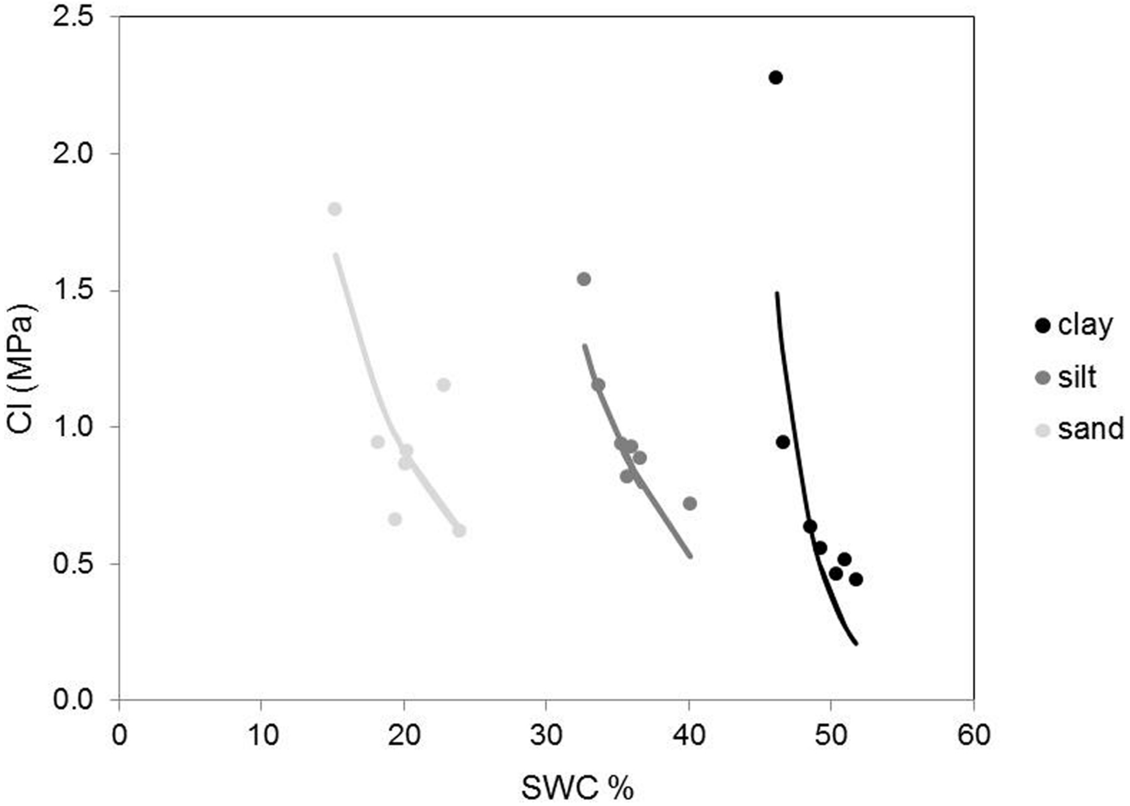


Fig. 3. Calibrations of Cone index (*CI*) using Soil water content (*SWC*) as predictor for three selected field sites. Calibrations represent average CI values between 15 and 30 cm depth and corresponding volumetric SWC derived from tensiometer measurements.

Table 3
Summary of soil properties from the 3 instrumented field sites. ρ: Dry bulk density; *OC*: organic carbon; *Cf*: coarse fragments.

Field	Topsoil characteristics					
	ρ (g cm^{-3})	Clay (%)	Silt (%)	Sand (%)	*OC* (%)	*Cf* (%)
Clay (Ramsey)	1.07	79.0	16.3	4.7	9.5	0.0
Silt (Moulton)	1.55	32.1	42.5	25.4	1.3	0.0
Sand (Eagle)	1.46	6.0	10.0	84.0	1.9	21.3

Table 4
Parameters, significance and coefficients of adjustments of the calibration equations for Cone Index using soil water content as predictor. The relationship is significant if p-value < 0.05. R^2: Regression coefficient; RMSE: Root mean squared error.

Field	*n*	Parameter *a*	Parameter *b*	*p-value*	R^2	RMSE (MPa)
Clay (Ramsey)	7	66.7	17.3	< 0.05	0.83	0.30
Silt (Moulton)	7	15.6	4.4	< 0.01	0.90	0.01
Sand (Eagle)	7	6.2	2.1	< 0.05	0.66	0.23

to develop calibrations that can be easily derived from direct field measurements (*e.g.* using a soil moisture probe and penetrometer), which could be undertaken by growers themselves without the need for taking samples for laboratory analysis of bulk density and soil texture. In the absence of local CI calibrations alternative equations for CI prediction could be used that take into account texture, organic matter content and bulk density, where this information was available.

The *MMP* has been calculated according to Larminie (1988, 1992), who developed Eqs. (2) and (3) for wheeled vehicles in clayey and sandy soils:

$$MMP_{clay} = \frac{k'L}{\sum_1^i B_{ti}^{0.85} D_{ti}^{1.15} (\delta_{ti}/D_{ti})^{0.5}} \tag{2}$$

$$MMP_{sand} = \frac{STL}{\sum_1^i B_{ti}^{1.5} D_{ti}^{1.5} (\delta_{ti}/H_{ti})} \tag{3}$$

where*k'*, *S*, and *T* are empirical factors, *L* is the vehicle weight and B_{ti}, D_{ti}, δ_{ti} and H_{ti} are respectively the tyre width, diameter, deflection and section height corresponding to each wheel *i*. According to Larminie (1992), the *CI* threshold for a soil to bear one vehicle pass is (4):

$$CI_1 = 0.827MMP \tag{4}$$

Generally, sugar beet fields are harvested by a combine harvester supported by a number of tractor + trailer vehicles, which take the loads out of the field to the clamp (temporary storage area at the edge of fields). Based on observations during harvest operations a harvester commonly does not traffic the same area more than five times, however field access points can be trafficked as much as 50 times by the supporting tractors and trailers. Thus, different soil strength thresholds have been defined according to the vehicle type and the section of the field (Table 5).

In the Forecast and Long-term modes, if the field is trafficable in more than 80% of the rainfall realisations of the day, it is considered suitable; if the probability is between 40% and 80%, marginal; and if it

Table 5
Number of passes and Cone Index thresholds for field trafficability in the Forecast and Long-term modes. *CI*: Cone Index, *MMP*: Mean maximum pressure.

	Harvester		Tractor + trailer	
	Passes	*CI* threshold	Passes	*CI* threshold
Field	1	CI_1 = 0.827MMP	5	CI_5 = 1.53CI$_1$
Headlands and access (H & A)	5	CI_5 = 1.53CI$_1$	50	CI_{50} = 2.8 CI$_1$

Table 6
Number of passes and Cone Index thresholds for field trafficability in the Input Rainfall mode. *CI*: Cone Index, *MMP*: Mean maximum pressure; H + A: Headlands and Access.

Threshold	Harvester		Tractor + trailer	
	Field	H & A	Field	H & A
Suitable – Marginal	$CI_1 = 0.827MMP$	$CI_{10} = 1.85\ CI_1$	$CI_1 = 0.827MMP$	$CI_{10} = 1.85\ CI_1$
Marginal – Unsuitable	$CI_5 = 1.53CI_1$	$CI_{25} = 2.35\ CI_1$	$CI_5 = 1.53CI_1$	$CI_{50} = 2.8\ CI_1$

is less than 40%, unsuitable. These thresholds were selected as a starting point to represent likely trafficability scenarios based on the distribution of rainfall amounts. These hypothetical thresholds take into account the difference in frequency between many small rainfall events that would likely not cause issues with trafficability compared with fewer large events that are more likely to result in untrafficable conditions. In the Input Rainfall mode the results are deterministic and two soil strength thresholds have been defined for each vehicle and field section, defining suitable, marginal and unsuitable regions for trafficability (Table 6). Different areas of the field will also receive variation in the number of vehicle passes.

2.6. Sinkage

The sinkage also affects trafficability but its effects can also clearly be seen in the field (vehicles becoming stranded and deep rutting). We estimate the sinkage parameter separately as it is a concept more easily recognised than the trafficability for harvest operators. Sinkage has been estimated according to the WES (US Army Research Centre Waterways Experiment Station) -method, based on the wheel numeric (N_{CIi}) Eq. (5).

$$N_{CIi} = \frac{CI \bullet B_{ti} \bullet D_{ti}}{L_{wi}} \bullet \left(\frac{\delta_{ti}}{H_{ti}}\right)^{0.5} \bullet \frac{1}{1 + \frac{B_{ti}}{2 \bullet D_{ti}}} \tag{5}$$

where *CI* is Cone index and N_{CIi}, B_{ti}, D_{ti}, L_{wi}, δ_{ti} and H_{ti} are wheel numeric, tyre width, tyre diameter, wheel load, tyre deflection and tyre section height of the corresponding wheel. There are several models based on this method (Maclaurin, 1990; Saarilahti and Anttila, 1999) and the one developed by Saarilahti and Anttila (1999) has been selected for BEETSOIL. Although it was developed for moraine soils, it has produced good results when tested for this work (see Section 3). The model takes into account the wheel configuration of the vehicle. It calculates the sinkage caused by each wheel depending whether it is the first or subsequent pass over the same area. For the first pass Eq. (6) is used:

$$z_1 = 0.019 + {}^{0.21}\!/_{N_{CIi}} \tag{6}$$

For subsequent passes, sinkage is calculated using the Eq. (7) and (8):

$$mpc = 1.5 \bullet N_{CIi}^{0.7} \tag{7}$$

$$z_n = z_1 \bullet n_p{}^{(1/mpc)} \tag{8}$$

where *mpc* is the multi-pass coefficient and n_p is the pass done by the wheel. After sinkage has been calculated for each wheel, daily average and maximum sinkage (in cm) are calculated and displayed in the output sheet.

2.7. Stickiness

The most important aspect of soil stickiness with regards to sugar beet harvesting operations is its effect on soil tare. Soil tare is soil adhering to sugar beet after harvest, thus representing harvest erosion. As soil adhering to sugar beet (soil tare) affects beet quality the soil is washed from the beets at the processing factory. This creates costly requirements for additional infrastructure such as settling ponds and the disposal of large volumes of soil... Eq. (9), developed by Ruysschaert et al. (2007) to estimate Soil Loss Caused by Harvest (*SLCH*), has been incorporated into the model:

$$SLCH = 0.0404 - 0.53SWC_g + 2.61SWC_g^2 \tag{9}$$

where *SWCg* is the gravimetric soil water content (g g^{-1}). This only estimates loss in clay and clay loam soils only, although these are the dominant soil texture types in the growing area.

In addition, an alternative approach to evaluate soil stickiness has been included in the model. Consistency index (I_c) has been calculated according to Eq. (10) (Zumsteg and Puzrin, 2012):

$$I_c = \frac{LL - SWC}{LL - PL} \tag{10}$$

where *LL* and *PL* are plastic and liquid limits. The highest clogging potential of clays is thought to be reached when $0.75 < I_c < 1.25$ (Zumsteg and Puzrin, 2012). This model is also only for clay rich soils as plastic limits are not applicable in sandy soils. As for trafficability, 80% and 40% define the proportion of realisations for a day in which clays are outside the highest clogging potential range for it to be considered suitable and marginal, respectively. Both SLCH and the consistency index thresholds are shown in the model output, the former to indicate the amount of soil tare and the latter to indicate clogging potential of the harvester or other harvest vehicles.

2.8. Final output

The output of the DST is a traffic light system for each of the modules, which identifies green, yellow and red colours with suitable, marginal and unsuitable conditions, respectively. The output of the model differs between the modes where Forecast and Long-term modes are probabilistic, and Input Rainfall is deterministic. Table 7 shows the output on a daily basis for each module.

3. Model evaluation and scenario testing

We were unable to obtain reliable measurements of the model outputs directly (trafficability, sinkage and stickiness) in sufficient quantity and quality to perform adequate validations. Instead we have evaluated the soil water content predictions as these are central to predicting trafficability, sinkage and stickiness in the BEETSOIL DST (Fig.1). The DST was developed to assess harvest efficacy and as a planning tool, for example when assessing new areas for beet production and the likely harvest efficacy. As a result we also tested the model under several scenarios to illustrate impacts of different rainfall scenarios (wet, dry and average rainfall during the campaign) and starting conditions (wet soil at FC and dry soil at PWP) on harvest vehicle sinkage and trafficability.

3.1. Evaluation of SWC module

3.1.1. Field sites and instrumentation

Three field sites were selected to evaluate the soil water balance model predictions of BEETSOIL during the 2016/17 harvest campaign. They were located in three of the most extensive soil units within the

Table 7
Outputs from the modules of the DST when it is used in each of the model modes. *MMP*: Mean maximum pressure; *CI*: Cone Index; I_c: Consistency index; *SLCH*: Soil loss caused by harvest.

Module	Forecast and Long-term	Input Rainfall
Trafficability	The *MMP* of the selected vehicle is displayed together with the daily median of *CI* (kPa) for all the rainfall realisations. The proportion of realisations when soil is trafficable is shown for high and low trafficked areas and colours assigned according to it.	The *MMP* of the selected vehicle is displayed together with the daily *CI* prediction (kPa). The comparison of these two variables allows producing a traffic light system for trafficability in high and low trafficked areas: Suitable (green), Marginal (yellow) and Unsuitable (red).
Sinkage	The daily median of average and maximum sinkage (cm) for all the rainfall realisations is displayed.	The daily average and maximum sinkage (cm) produced by the vehicle are displayed.
Stickiness	The daily proportion of realisations when I_c is between 0.75 and 1.25 (sticky) is shown. This proportion determines is the day is Suitable (green), Marginal (yellow) or Unsuitable (red) according to this criterion. In addition, the daily median of I_c and *SLCH* (Mg / Mg) is displayed.	The field is Unsuitable (red) if I_c is between 0.75 and 1.25 (sticky) and suitable (green) otherwise. The daily values of I_c and *SLCH* (Mg/Mg) are also displayed.

sugar beet growing area in the UK, which are characterised by contrasting texture types (Table 3).

At each field, a weather station was installed just after the beet was drilled in March, together with two pairs of tensiometers at depths of 15 and 35 cm. They recorded rainfall and soil water tension (*SWT*) at 1 h intervals. A composite disturbed soil sample was taken at the same depth the tensiometers were installed, together with three undisturbed samples using cylinders of 93 cm^3. Both the field and the zone within the field where the tensiometers were installed and the samples taken were carefully selected to be representative of the corresponding soil unit. The disturbed samples were used to analyse soil particle size distribution (pipette method ISO 11277:2015), organic carbon (organic matter by loss on ignition following Avery and Bascomb (1982) using 1.72 conversion to OC) and coarse fragments content (Table 3). Bulk density and the water release curve parameters were derived from intact soil cylinders. Water release characteristics were determined on intact soil cores following laboratory methods detailed in ISO 11274:1998 (Soil Quality Determination of the water retention characteristic). These measurements were used to update the soil parameters file in the WASIM model. To convert the tensiometer reading to SWC content the following Eq. (11), proposed by Dexter et al. (2008), was used:

$$SWC = C + A_1 e^{(-SWT/h_1)} + A_2 e^{(-SWT/h_2)} \tag{11}$$

where *SWC* is soil water content (v v^{-1}), *SWT* is soil water tension (kPa) and *C* is the residual water content, A_1 A_2, are the matrix and structural pore space, respectively,h_1, h_2 are the suctions at which the matrix and structural pore spaces empty, respectively. We used this relationship to transform the field-based soil water tension measurements into volumetric soil water content values required for the WaSim model for the initial water content and these were also used to evaluate the predicted soil water content from WaSim.

3.1.2. Model set up

Model was run in Input Rainfall mode for each field site. The daily rainfall was derived from the weather station installed at the field site and daily ET was derived from a long-term average dataset of evapotranspiration from a local weather station closest to each field site. The soil parameter file was updated with local soil parameters determined from soil samples taken from the field sites (saturation, field capacity and permanent wilting point) and the remaining soil hydrological parameters default values for each texture class were used from the WaSim database.

3.1.3. Evaluation of predictions of soil water content

The average of the soil water content calculated from the SWT at 15 and 35 cm for each field (observed) was compared to the simulated (predicted) soil water content from the first two soil layers in the WaSim model (Fig. 4). The average SWC of both probes was selected because the relevant depth for trafficability is between 15 and 30 cm. The comparison was done from the first of October to the day the field was harvested, when the instrumentation was uninstalled. This date range was selected as this represents the soil conditions during the harvest period.

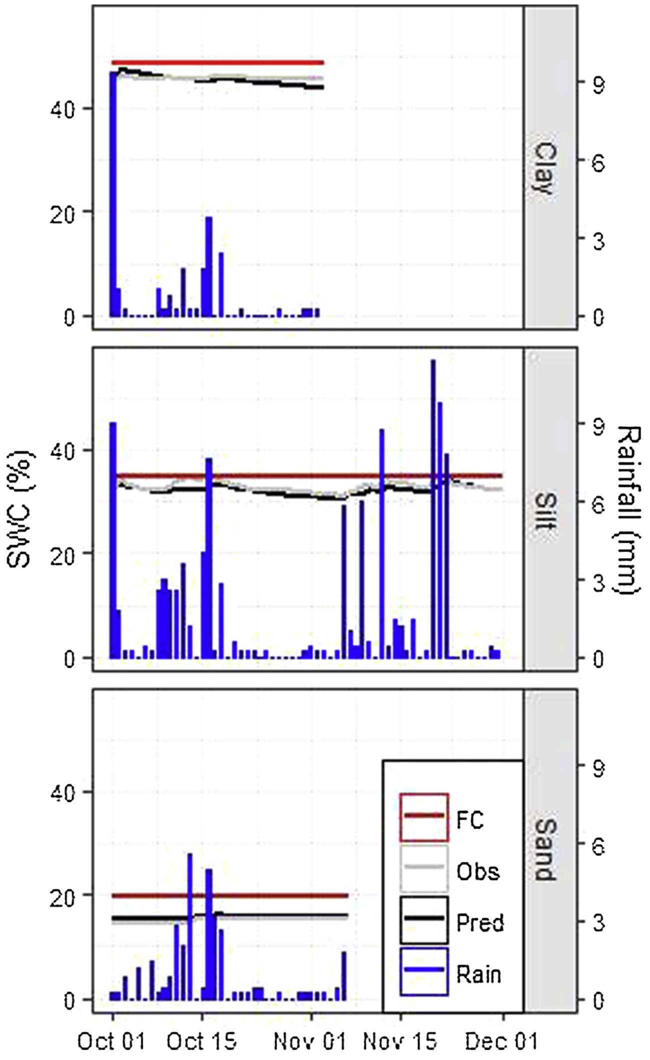


Fig. 4. Comparison between observed (Obs) and predicted (Pred) soil water contents, derived from the field tensiometers and the WASIM model, respectively, field capacity (FC) and rainfall (Rain) at the three field sites (Moulton silty; Ramsey clay; Eagle Sand).

Fig. 4 indicates the WaSim model predicted reasonably well the average soil water content in the upper soil layers measured by the tensiometers in the field. The RMSE for the set of days simulated was 0.91%, 0.96% and 0.52% for Ramsey, Moulton and Eagle. In the silty site (Moulton) there seems to be a slightly greater lag in the topsoil *SWC* response to rainfall compared with the observed data. In both the clayey and the silty soils SWC is close to the topsoil field capacity during the sampling period, whereas it was significantly lower in the sandy soil. It could be expected that the observed *SWC* is closer to field capacity also in the sandy soil. The reason of this difference is found in the measurements taken at 35 cm, which remained at between 7.7 and 8.5%, which is lower than expected from a similar soil from the national soil data base (LandIS, Hallett et al., 2017) which shows the subsoil horizon to have a field capacity of 16.5%. In contrast, measurements at 15 cm ranged from 21.3 to 23.4% and therefore when averaging the moisture contents at the two depths there is a potential underestimation of the soil moisture content from the field data.

3.2. Scenario testing

The DST was developed as a strategic tool for planning regional harvest operations and can also be used for scenario testing of soil trafficability under different soil and weather conditions. The sensitivity of the water balance and the trafficability module to the weather conditions was tested using the Input Rainfall mode of BEETSOIL. We tested scenarios for the whole harvest campaign period (from the 1st of October to the 28th of February). We selected input rainfall based on a long term rainfall series (1975–2016) from Waddington (UK), located in the sugar beet growing area. We selected years that represented maximum (wet), median (average) and minimum (dry) total rainfall values during the period of the field campaign. The total rainfall amounts were 145.9, 245.2 and 435.7 mm, for the dry, median and wet years, respectively. Initial conditions were set either at field capacity or permanent wilting point through the whole soil profile. Sinkage was calculated for a 3-axle sugar beet harvester. Fig. 5 shows the summary of daily predictions of *SWC* at 0–15 cm (SWC_T), *CI* and sinkage for each rainfall scenario (dry, median and wet year), soil type (clay, silt, sand) and starting condition (field capacity or wilting point) for the harvest campaign period.

The differences of *SWC* between rainfall scenarios within the same site and starting condition were not significant. If the initial condition was *FC*, *SWC* remained close to this value over the campaign even in the dry year (145.9 mm rain during the campaign), when rainfall was already much higher than potential evapotranspiration (77.2 mm over the same period). When initial condition was *PWP*, SWC_T increased relatively quickly to *FC* depending on precipitation and then remained stable. The variation of SWC_T was higher in the sandy field, which reflects its higher drainage capacity associated to this texture.

In general, for *FC* as initial condition (which is the most likely scenario at the start of the campaign), average *CI* was lowest in the clayey soil, intermediate in the sandy soil and highest in the silty soil. The high values of *CI* in the silty soil may be related to recent agricultural practices and prior compaction, as suggested by the high ρ (Table 3), since silty soils are more prone to compaction (Horn et al., 1995). For *PWP* as initial condition, results were very conditioned by the first days of the simulation, where *CI* was extremely high, due to the shape of the calibration *SWC* - *CI* (c.f. Fig. 3).

The values of *SWC* and the resulting *CI* estimated during the three campaigns (wet, median and dry) have a direct effect on the trafficability of the soils. Modelled *SWC* was compared with the *SWC* values required to support 1, 2, 5, 10, 25 and 50 passes by a 3-axle harvester and a tractor and trailer combination in the 3 different soil types (Table 8). The SWC thresholds were the lowest in the sandy soil, medium in the silty soil and the highest in the clayey soil. Only the *SWC* needed to support 50 passes of the tractor + trailer combination for the clayey and sandy soils are below the topsoil field capacity of the site. There is not a clear rule relating trafficability limit and field capacity. Earl (1997) established trafficability limits for different soil types at determined soil moisture deficits from field capacity. Dexter and Bird (2001) found that the upper limit for tillage could be more than 2% below or almost 7% above *FC* in silty clay loam soils with different management.

The proportion of days within the campaign period when the *CI* values are not able to support the number of passes (i.e. the soil is not trafficable) is shown in Fig. 6. This is used to assess the likelihood of trafficability using different rainfall conditions during the campaign.

The high *CI* values of the silty soil mean it would not have significant trafficability problems even in the wet year starting at *FC*. The only limitation would be in the high pass situation with the tractor and trailer when 28% of the days would not be trafficable. This high-traffic scenario would be equivalent to the access point of the field. As expected, the clayey soil showed the most significant limitations to traffic when starting at *FC*, by both the harvester and the tractor and trailer. Even in the dry scenario there would be limited ability of the soil to support 25 and 50 passes for both vehicle combinations. This could be a problem for the areas trafficked by the tractor and trailer, that commonly have multiple passes. In the clayey soil the average (median) rainfall scenario was also problematic for the harvester, since the soil could not support 5 passes over the same area on 13% of the days. In the wet scenario, for 5% of the days the field is not able to support even one pass by any of the vehicles. The sandy soil showed an intermediate situation and especially the operability of the tractor and trailer combination would be limited in the median and wet years.

Most of the studies regarding soil trafficability in agriculture are focused on tillage operations and often related to workability too, so comparisons must be taken with caution. Edwards et al. (2016) studied trafficability for tillage operations, in clay loam – sandy loam soils, establishing the threshold at 50Kpa at 50 cm deep. They found soils were trafficable 100% of the days of the autumn season (1 Sep–31 Dec) if minimum tillage was applied, and the percentage decreased to 13–16 % if the field was conventionally tilled. Earl (1997) calculated trafficable days for tillage according to soil moisture deficit values and determined that 54% of days in the autumn season soils were not trafficable. The differences in methodology, soil type and machinery involved made it difficult to directly compare these results to our simulations. For example, a vehicle pass triggering a pressure of 60 kPa at 50 cm deep, but without causing topsoil disturbance, would result in “non-trafficable” using the Edwards et al. (2016) method and “trafficable” using the BEETSOIL model. The Edwards et al (2016) model uses a trafficability threshold of 50 kPa at depths > 50 cm when the field is at or close to field capacity to avoid subsoil structural damage. The BEETSOIL model does not take into account any threshold for potential soil structural damage and therefore fields can still be indicated as trafficable for harvest vehicles. The original application of the trafficability module in BEETSOIL was for military applications where the primary aim was to indicate whether the terrain was passable irrespective of any soil structural damage incurred. Therefore applying the BEETSOIL methodology solely for trafficability assessments may also result in subsoil compaction.

4. Summary and conclusions

This study presents the structure of BEETSOIL, a prototype decision support tool to aid sugar beet harvest planning with regards to soil conditions. The DST incorporates a number of well tested models and calibrations developed specifically for this study. The soil water balance module predicted the soil water content reasonably well during the harvest campaign for the three field sites. This model is the core of the DST and is key to the performance of the rest of the predictive modules of trafficability. This provides confidence that running the model in forecast mode can produce realistic indications of short (weekly) and longer term (monthly) assessments of sugar beet harvest suitability based on soil conditions. The model can also be used for scenario testing on the efficacy of harvest under different soil and climatic conditions when assessing new areas for growing beet. This has an immediate application because since the abolition of the sugar quotas by the EU in 2017 growers have the opportunity to increase production

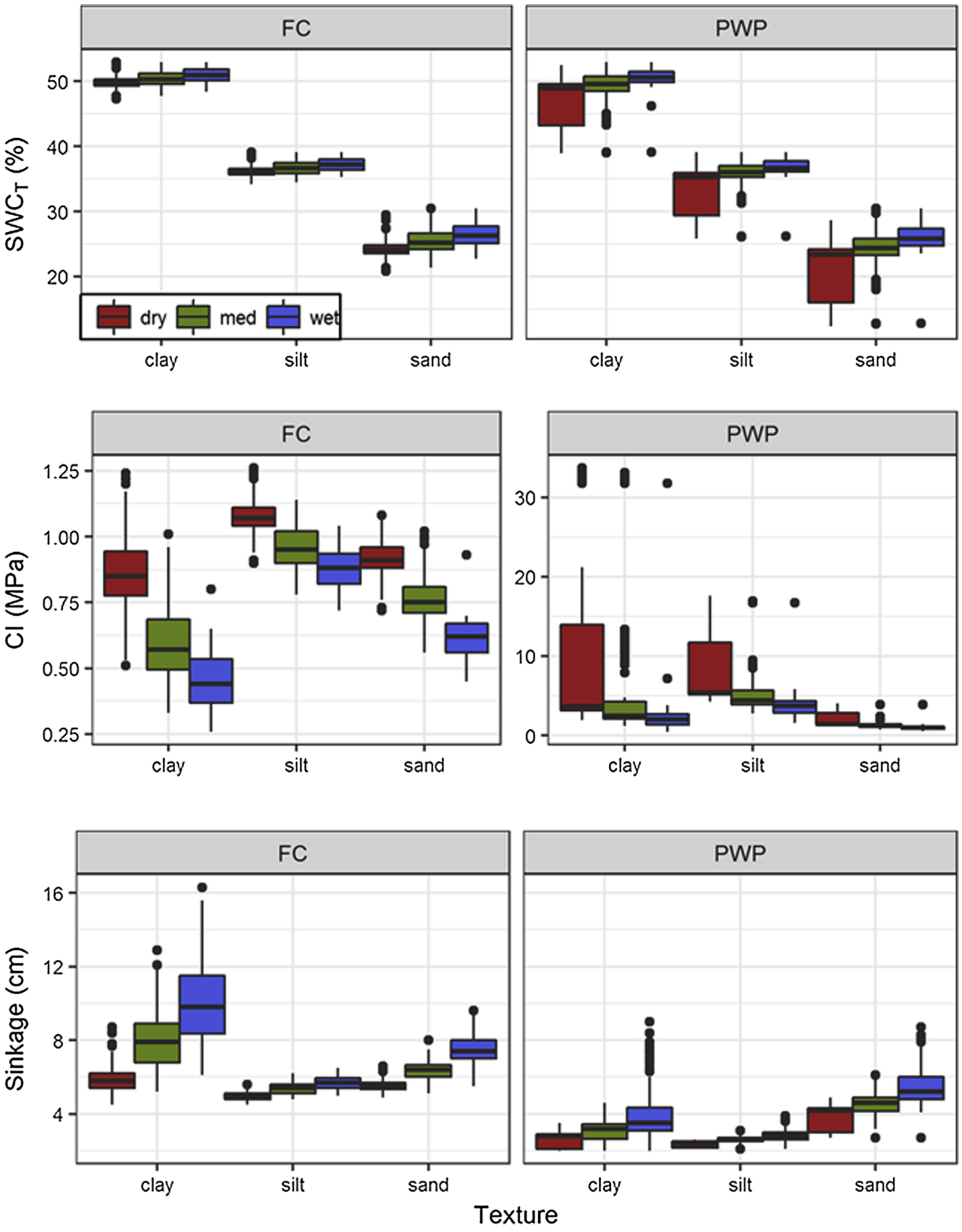


Fig. 5. The boxplots show the daily values over the simulated campaign period (1 October to 28 February) of topsoil soil water content (SWC_T), Cone index (*CI*) and Sinkage for three field sites (represented by different soil type clay, silt and sand). Outcomes are shown for wet, median and dry rainfall amounts over the campaign and starting the simulation at either field capacity (*FC*) or Permanent wilting point (*PWP*). Note the change in the vertical scale.

and are therefore looking to expand the sugar beet growing area in the U.K.

This study is a preliminary step in the operational use of the DST and some of the modules (*e.g.* the equation to predict *SLCH* from *SWC* has not been tested in the UK soils) and outputs (trafficability, sinkage and soil tare) have to be yet validated. We therefore recommend a model validation phase in collaboration with growers and contractors where trafficability, sinkage and soil tare can be quantified by making direct field measurements during harvest operations. Sugar beet (similar to other root crops and late harvested crops) can be harvested in adverse conditions. The effect of harvest in such conditions may be long lasting on the soil (subsoil compaction) and affect the reputation of the crop and reduce the desire to grow it. However, implementing the DST as part of a suite of tools offered to growers for advisory and operational

Table 8
Maximum Soil water content (%) required to support different numbers of passes of the two vehicle configurations on different soil types. *FC*: Field capacity.

n passes	*FC*	Harvester						Tractor + trailer					
		1	2	5	10	25	50	1	2	5	10	25	50
Clay	48.4	51.3	50.8	50.1	49.6	48.9	48.4	51.2	50.7	50.0	49.4	48.8	48.3
Silt	34.7	47.1	45.2	42.8	41.0	38.8	37.3	46.6	44.7	42.3	40.5	38.4	36.9
Sand	22.4	39.1	35.8	31.9	29.1	26.0	23.9	34.6	31.7	28.2	25.8	23.0	21.2

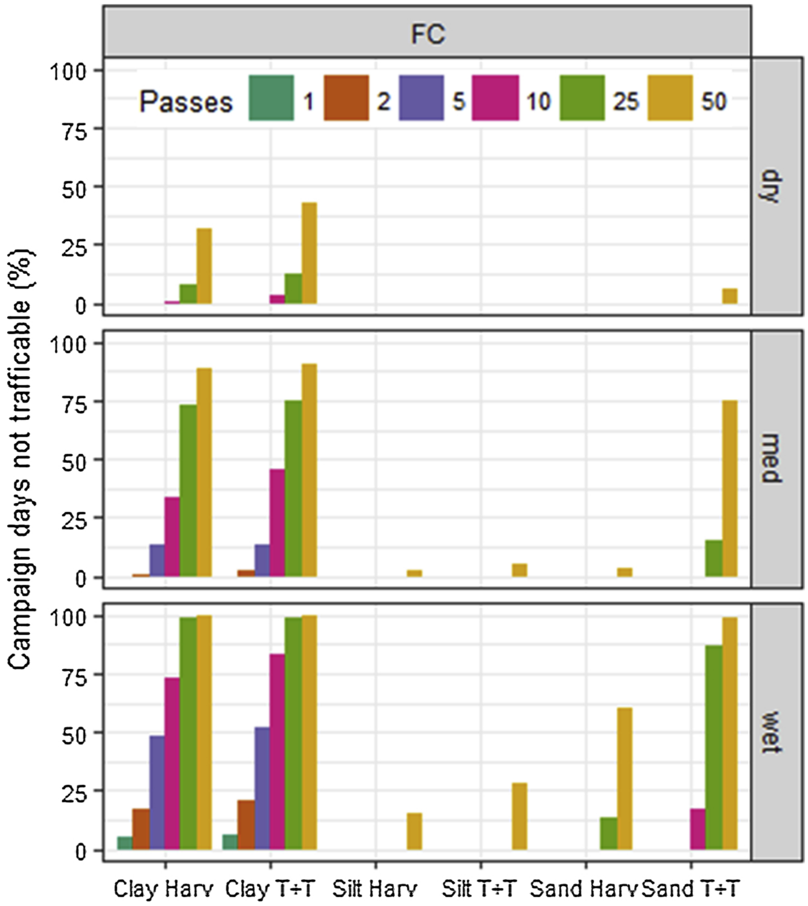


Fig. 6. Proportion of days when the *SWC* value is not able to support 1, 2, 5, 10, 25 and 50 passes of a harvester (Harv) and a tractor + trailer combination (T + T). This is shown for rainfall scenarios for a dry, median and wet campaign, for the three field sites and starting the simulation at field capacity (*FC*).

applications may incentivise growers to contract to grow a sugar beet crop, ensuring sufficient supply to the processing business.

Declarations of interest

None.

Acknowledgements

The authors would like to acknowledge Tim Hess and Thomas Keller for kindly providing a copy of the WaSim and SoilFlex models respectively. We also thank two anonymous reviewers for their comments that improved the manuscript. This work was part of a Knowledge Transfer Partnership supported by Innovate UK and AB Sugar (grant number KTP009858). Information about the data used in this paper can be found at https://doi.org/10.17862/cranfield.rd.8025401.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2019.04.001.

References

Arvidsson, J., Sjöberg, E., van den Akker, J.J.H., 2003. Subsoil compaction by heavy sugar beet harvesters in southern Sweden III. risk assessment using a soil water model. Soil Till. Res. 73, 77–87.

Audsley, E., 1984. Use of weather uncertainty, compaction and timeliness in the selection of optimum machinery for autumn field work – a dynamic programme. J. Agr. Eng. Res. 29, 141–149.

Avery, B.W., Bascomb, C.L., 1982. Soil Survey Laboratory Methods, Soil Survey Technical Monograph No. 6. Rothamsted Experimental Station, Harpenden. U.K.

Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B., Hallet, P.D., 2015. Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil Till. Res. 146, 10–25.

Défossez, P., Richard, G., 2002. Models of soil compaction due to traffic and their evaluation. Soil Till. Res. 67, 41–64.

Dexter, A.R., Bird, N.R.A., 2001. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. Soil Till. Res. 57, 203–212.

Dexter, A.R., Czyz, E.A., Richard, G., Reszkowska, A., 2008. A user-friendly water retention that takes account of the textural and structural pore spaces in soil. Geoderma 143, 243–253.

Earl, R., 1997. Prediction of trafficability and workability from soil moisture deficit. Soil Till. Res. 40, 155–168.

Edwards, G., White, D.R., Munkholm, L.J., Sørensen, C.G., Lamandé, M., 2016. Modelling the readiness of soil for different methods of tillage. Soil Till. Res. 155, 339–350.

Etana, A., Håkansson, I., 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Till. Res. 29, 167–172.

Freitag, D.R., 1966. A dimensional analysis of the performance of pneumatic tires on clay. J. Terramech. 3, 51–68.

Hallett, S.H., Sakrabani, R., Keay, C.A., Hannam, J.A., 2017. Developments in Land Information Systems: case studies in land resource management capabilities and options. Soil Use Man. 33, 514–529.

Hess, T., Counsell, C., 2000. A water balance simulation for teaching and learning – WaSim. ICID British Section Irrigation and Drainage Research Day. HR Wallingford.

Horn, R., Domżał, H., Słowińska-Jurkiewicz, A., van Ouwerkerk, C., 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Till. Res. 35, 23–36.

Keller, T., Défossez, P., Weisskopf, P., Arvidsson, J., Richard, G., 2007. SoilFlex: a model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. Soil Till. Res. 93, 391–411.

Larminie, J.C., 1988. Standards for the mobility requirements of military vehicles. J. Terramech. 25, 171–189.

Larminie, J.C., 1992. Modifications to the mean maximum pressure system. J. Terramech. 29, 239–255.

Maclaurin, E.B., 1990. The use of mobility numbers to describe the in-field tractive performance of pneumatic tyres. Proc. 10th ISTVS Conf. 177, 186.

Maclaurin, E.B., 1997. The use of mobility numbers to predict the tractive performance of wheeled and tracked vehicles in soft cohesive soils. Proc. 7th Eur. ISTVS Conf. 391, 398.

Raper, R.L., 2005. Agricultural traffic impacts on soil. J. Terramech. 42, 259–280.

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: towards effective design and delivery. J. Agric. Food Syst. Community Dev. 149, 165–174.

Rowland, D., 1975. A review of vehicle design for soft ground operation. Proc. 5th Int. Conf. ISTVS 179, 219.

Rücknagel, J., Hofmann, B., Deumelandt, P., Reinicke, F., Bauhardt, J., Hülsbergen, K.-J., Christen, O., 2015. Indicator based assessment of the soil compaction risk at arable sites using the model REPRO. Ecol. Indic. 52, 341–352.

Ruysschaert, G., Poesen, J., Verstraeten, G., Govers, G., 2005. Interannual variation of soil losses due to sugar beet harvesting in West Europe. Agric., Ecosyst. Environ., Appl. Soil Ecol. 107, 317–329.

Ruysschaert, G., Poesen, J., Wauters, A., Govers, G., Verstraeten, G., 2007. Factors controlling soil loss during sugar beet harvesting at the field plot scale. Eur. J. Soil Sci. 58, 1400–1409.

Saarilahti, M., Anttila, T., 1999. Rut depth model for timber transport on moraine soils. Proc. 9th Int. Conf. ISTVS 29, 37.

Schjønning, P., Lamandé, M., Keller, T., Pedersen, J., Stettler, M., 2012. Rules of thumb for minimizing subsoil compaction. Soil Use Manage. 28, 378–393.

Semenov, M.A., Barrow, E.M., 2002. LARS-WG. A Stochastic Weather Generator for Use in Climate Impact Studies. Version 3.0 User Manual.

Soil Science Society of America, 1996. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI.

Stettler, M., Keller, T., Schjønning, P., Lamandé, M., Lassen, P., Pedersen, J., Weisskopf, P., 2014. Terranimo® – a web-based tool for evaluating soil compaction. Landtechnik 69 (3), 132–138.

Sullivan, P.M., Anderson, A.B., 2000. A Methodology for Estimating Army Training and Testing Area Carrying Capacity (ATTACC) Vehicle Severity Factors and Condition Factors. ERDC TR-00-2 US Army Corps of Engineers ERDC.

Weekly, Farmer's, 2018. UK Sugar Beet Yields Hit Record Levels. (accessed 2 Dec 2018. https://www.fwi.co.uk/arable/sugar-beet/uk-sugar-beet-yields-hit-record-levels.

Zumsteg, R., Puzrin, A.M., 2012. Stickiness and adhesion of conditioned clay pastes. Tunn. Undergr. Sp. Tech. 31, 86–96.

BEETSOIL: a decision support tool for forecasting the impact of soil conditions on sugar beet harvest

Gabarron Galeote, Miguel

2019-04-09

Gabarron Galeote MA, Hannam JA, Mayr T, Jarvis PJ. (2019) BEETSOIL: a decision support tool for forecasting the impact of soil conditions on sugar beet harvest. Soil and Tillage Research, Volume 191, August 2019, pp.131-141

https://doi.org/10.1016/j.still.2019.04.001