AUTHOR QUERY FORM

ELSEVIER	**Journal: TER** **Article Number: 515**	**Please e-mail or fax your responses and any corrections to:** **E-mail: corrections.essd@elsevier.sps.co.in** **Fax: +31 2048 52799**

Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list. Note: if you opt to annotate the file with software other than Adobe Reader then please also highlight the appropriate place in the PDF file. To ensure fast publication of your paper please return your corrections within 48 hours.

For correction or revision of any artwork, please consult http://www.elsevier.com/artworkinstructions.

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof. Click on the 'Q' link to go to the location in the proof.

Location in article	**Query / Remark: click on the Q link to go** **Please insert your reply or correction at the corresponding line in the proof**
Q1	Please confirm that given names and surnames have been identified correctly.
Q2	Please check whether telephone number is okay as typeset.
Q3	The author name 'Reece' does not match with Ref. [87] as per the list. Kindly check.
Q4	Please check whether first names and surnames in all the references are okay as typeset.
Q5	Please check whether the typeset of Ref. [81] is okay.
Q6	The author name 'Gholkar' does not match with Ref. [31] as per the list. Kindly check.
	Please check this box if you have no corrections to make to the PDF file ☐

Thank you for your assistance.

Highlights

▶ Rice cultivations, tractive performance and soil management are reviewed. ▶ Soil, tractive performance and energy data are given for Bangkok Clay soil. ▶ Machinery use can adversely affect hardpan depth. ▶ Issues of climate change are related to soil management and tractor operations. ▶ Mechanization and SRI bring opportunities for more sustainable and precise management.

Available online at www.sciencedirect.com
SciVerse ScienceDirect
Journal of Terramechanics xxx (2012) xxx–xxx
Journal of Terramechanics
www.elsevier.com/locate/jterra

A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production

Alex Keen[a,*], Nigel Hall[b], Peeyush Soni[c], Madhav D. Gholkar[c], Simon Cooper[b], Jannatul Ferdous[c]

[a] *49 Vineyard Drive, Newport, Shropshire TF10 7DF, UK*
[b] *Harper Adams University College, Newport, Shropshire TF10 8NB, UK*
[c] *Asian Institute of Technology, Pathumthani, Thailand*

Abstract

This paper reviews the cultivation practices and tractive performance using wheeled tractors, and how these interact with soil management, in lowland intensive rice production. The paper explores the issues of long term sustainable soil use, the energy inputs required, environmental impact and changes in approach to agronomy and links these to the tractor operations carried out as part of rice production. The paddy soil environment demonstrates very significant changes in soil properties with depth, in particular soil density, penetrometer resistance, soil structure and pore interconnectivity, water content and movement, and soil biology. This is related to the management of the soil hard pan in relation to machinery operations and machinery use. One of the issues appears to be that the hard pan can be deeper than required with consequently unnecessarily high energy inputs. The tractive performance of wheeled tractors on different surface conditions is considered with respect to tractive efficiency and maintenance of a soil hard pan that has the required characteristics for sustainable production. Alternatives to conventional tyres, cage wheels and tracks, are considered. The cultivation operations are evaluated in relation to soil management, crop requirements and energy use. Variation in hard pan characteristics may be disadvantageous and provides opportunities for precision operations.

Keywords: Tractive performance; Soil management; Energy use; Rice production; Sustainability and precision operations

Contents

---

* Corresponding author. Tel.: +44 1952 403024.
E-mail addresses: alexkeen@blueyonder.co.uk (A. Keen), nwhall@harper-adams.ac.uk (N. Hall), soni@ait.asia (P. Soni).

0022-4898/$36.00 © 2012 Published by Elsevier Ltd. on behalf of ISTVS.
http://dx.doi.org/10.1016/j.jterra.2012.08.001

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

Nomenclature

δ	tyre deflection (m)	H	wheel or track thrust (kN)
φ	internal angle of friction (°)	i	wheel slip
τ	shear stress (kPa)	K	soil deformation modulus (m)
$\tau_{\max}$	maximum shear stress (kPa)	L	tyre-soil contact length (m)
A	tyre-soil contact area (m^2)	M	mobility number
b	tyre width (m)	mc	moisture content (%)
c	soil cohesion (kPa)	s	wheel slip
CI	cone index (kPa)	V	forward speed (m/s)
d	tyre diameter (m)	W	dynamic load acting on tyre (kN)
db	dry basis moisture content (%)	2WD	two wheel drive
h	section height of tyre (m)	4WD	four wheel drive

1. Introduction

Rice can be grown in a wide range of locations and climates, but 90% of the world's rice (more than 700 million tons in 2009) is produced in south, southeast, and east Asia, where rice is the staple food of more than 3 billion people [1] and is grown in more than a hundred countries with a total harvested area of nearly 160 million hectares. Asian paddy (80%) is grown under wetland conditions [2]. There are primarily four ecosystems where rice is grown: irrigated, rain fed lowland, upland, and flood-prone. Irrigated rice accounts for about half of the world's harvested rice area and contributes 75% of global rice production [1]. Where water is available for most of the year, farmers can grow rice all year long and can grow two or even three crops per year. Rice is extremely sensitive to water shortage and to ensure sufficient water, most rice farmers aim to maintain flooded conditions in their fields. This is especially true for lowland rice. Rice is unique because it can grow in wet environments that other crops cannot survive in. Such wet environments are abundant across Asia where rice is grown. The use and availability of water is an important consideration of increasing significance. Bouman et al. [3] have estimated that irrigated rice receives 34–43% of the world's total irrigation water and with irrigation accounting for about 70% of the world's developed freshwater resources, irrigated rice receives a share of 24–30%. Chapagain and Hoekstra [4] give the global water footprint of rice production as 784 km^3/year with an average of 1325 m^3/t. This is divided between 48% green, 44% blue, and 8% grey water where irrigation water withdrawn from ground or surface water is termed blue water, rainwater is termed green water and polluted water related to the use of nitrogen fertilisers in rice production is termed grey water. Chapagain and Hoekstra [4] also point out that the virtual water flows related to international rice trade are 31 km^3/year. Thailand, Vietnam and India are the major exporters of rice in the world and therefore export of the order of 1325 m^3 of water per tonne of rice exported.

The aim of this paper is to review the cultivation practices and tractive performance using wheeled tractors, and how these interact with soil management, in lowland intensive rice production. The paper explores the issues of long term sustainable soil use, the energy inputs required, environmental impact and changes in approach to agronomy and links these to the tractor operations carried out as part of rice production.

2. Lowland intensive rice cultivations

A detailed description of land preparation for rice is given at [5] and general information about rice production is available at [1]. As this paper is primarily concerned with lowland intensive rice production on clay soil using irrigation, description and discussion are limited to this operating condition. The aim of land preparation is to place the soil in the best physical condition for plant establishment and crop growth, to ensure that the soil surface is left level and to condition the soil to conserve water. Soil must be

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

tilled to a depth so plants can develop a root system which will physically support the plant and also allow the extraction of sufficient moisture and nutrients so yield potentials can be realised, soil disturbance should be sufficient to control weeds, tillage must leave the soil surface level. Primary cultivation, ploughs or rotavators, also incorporates previous crop residues, as soil is often at 100% saturation this may be predominantly a smearing action. Level fields improve water use efficiency and help to control crop weeds. The field also needs a drainage system that will allow the rapid removal of excess water.

High water loss during land preparation is caused by water flowing through cracks in the soil. Seepage and percolation flows from rice fields are major pathways of water loss. Thorough puddling, the breaking down of soil structure, results in a desirable compacted plough pan that reduces percolation rates throughout the crop growing period. Puddling is carried out for weed control and to reduce soil permeability and perculation losses, and it eases field levelling and transplanting [3]. The standing water in flooded paddy fields is also an important part of weed control. Land preparation covers a range of soil disturbances from zero-tillage, which minimises soil disturbance, through to a totally 'puddled' soil. Puddling is the most common method adopted for wetland paddy field preparation in south and south east Asia. Puddling leads to soil compaction, increases the bulk density and soil penetration resistance in sub-soils which ultimately decreases their permeability and reduces the water losses [6]. Performing puddling operations year after year in the same field for rice production creates a strong hardpan beneath the puddling depth. The hardpan created restricts the water losses and

(a) Primary cultivation with a two disc plough –flooding started when cultivation started

(b) Peg tooth harrow (left), puddling with a peg tooth harrow (right)

(c) Puddlingin deeper water (left) and soil levelling (right)

Fig. 1. Rice cultivations with a two wheel tractor – these are usually fitted with cage wheels.

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

provides the favourable environment for paddy. Generally, in rice fields the adequate depth of the puddling operation is 10–15 cm [7,8].

Tillage requirements will vary according to the cropping system used. For lowland rice, fields are puddled in part to destroy structure and develop a hard pan to reduce water loss through deep percolation, but such a loss of structure and the formation of a physical barrier are totally undesirable in an upland situation. Primary cultivation can start immediately after the crop harvest or at the beginning of the next wet season. When there is sufficient power available some soil types are ploughed dry. Primary tillage, to a depth of 10–15 cm, is the first working after the last harvest and normally the most aggressive tillage operation. It is normally undertaken when the soil is wet enough to allow the field to be ploughed and strong enough to give reasonable levels of traction. Chains, strakes, tyre tracks (half-tracks), ballasting, cage wheels, dual wheels are mainly used as traction aids to achieve the maximum traction on a given terrain. Previous studies have revealed that cage wheels are the best suited traction aids for wetland conditions [9]. Mouldboard ploughs are commonly used with animal draught [5]. With two-wheel tractors both mouldboard and disc ploughs are used. Discs are usually preferred as they can take less power and can handle obstacles more easily. When traction is a problem, cage wheels are often fitted to the tractor. Four-wheel tractors often use mounted three disc, seven disc and offset multi-disc ploughs. Mouldboard ploughs are not commonly used with four wheel tractors. Rotavators are used for primary tillage and secondary tillage. The smearing action of rotavators aids the creation of a hard pan. Peg tooth harrows are used for puddling if rotavators are not available [5]. Fig. 1 shows some of these cultivation operations on Bangkok clay soil with the type of two wheel tractor commonly found in lowland rice production.

3. Bangkok clay soil

Bangkok clay soil is found in the Central Thailand region where irrigated lowland rice is cultivated and is the main soil used at the Asian Institute of Technology (AIT) for research into traction, rice cultivations and related science and technology. This section describes the main characteristics, structure [10] and mechanical properties of Bangkok Clay soil.

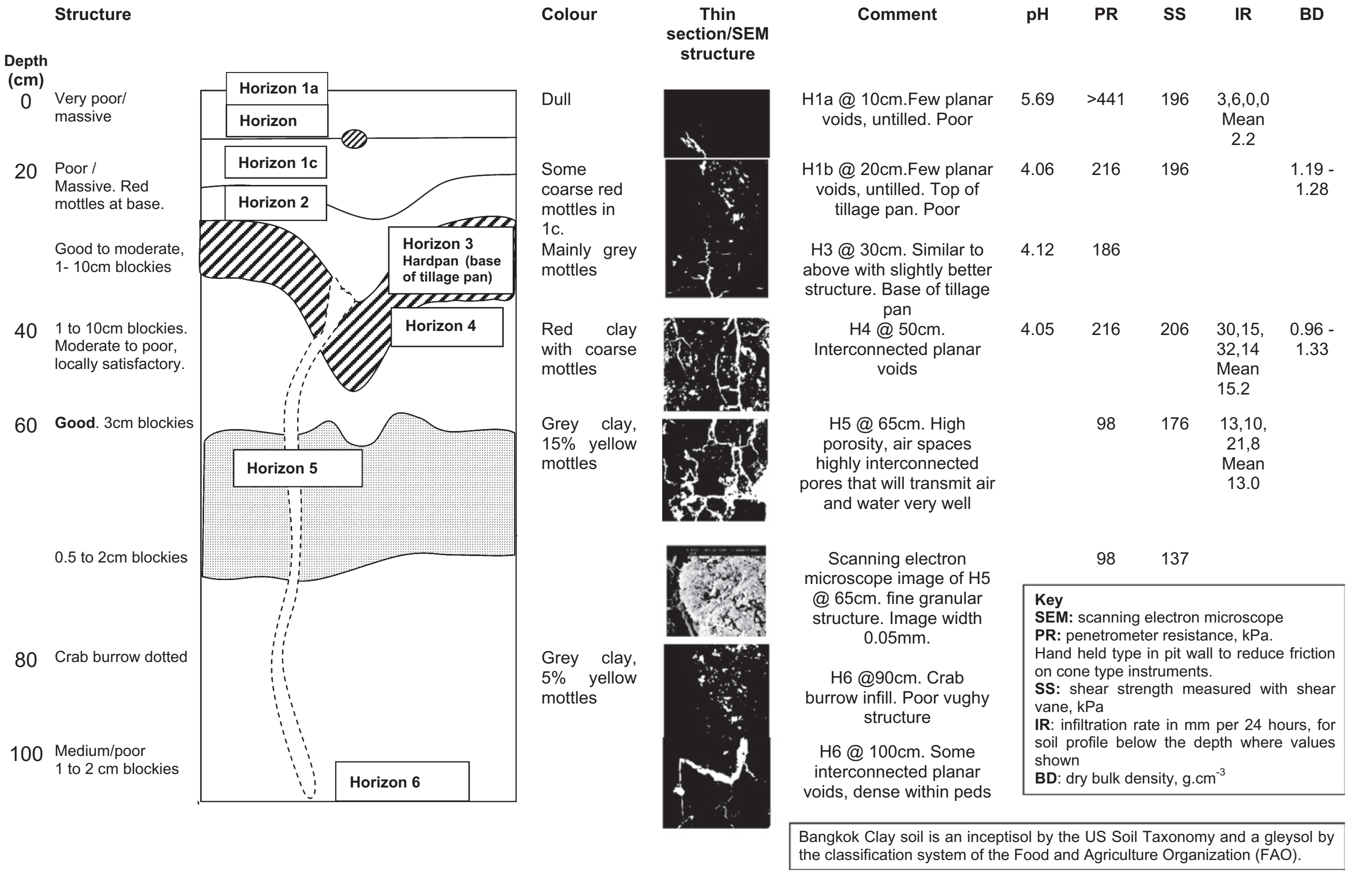
The soil at the AIT trials area, usually referred to as ‘Bangkok clay’, is an inceptisol by the US Soil Taxonomy and a gleysol by the classification system of the Food and Agriculture Organization (FAO) and it occupies a large tract of land in the Bangkok hinterland. The soil is clay to depth, at least 1 m, typically clay is 47–63%, silt 27–38% and sand 5–18% [11]. The sand content generates some frictional soil behaviour although the distribution of sand is not uniform as after puddling, some settling of the sand grains occurs into zones with more or less sand. Fig. 2 shows the horizonation and other parameters measured in this project, bulk density, penetrometer cone index, shear stress data and infiltration rate. Fig. 3 shows a soil profile pit in Bangkok clay at the Asian Institute of Technology to a depth of 1 m corresponding to Fig. 2. The general characteristics are shown in Table 1. These properties are typical of a soil of a clay texture. The clay mineralogy with its low smectite content suggests that shrink swell behaviour and cracking is not as strong a process as in some other soils. Field and laboratory observations show that topsoil shrinkage produces a few large cracks (e.g. 1–2 cm wide and 20 cm apart) rather than a lot of small cracks. Subsoil horizons can demonstrate many small structural units where structure is good, suggesting that severe compaction may take a considerable period of time to repair.

The soil demonstrates redoximorphic features, especially in the zone 20–60 cm. The soil also demonstrates some acid sulphate properties with sodium compounds in solution at depth. The zone of apparent soil structural formation is below the topsoil (horizon 3) with weaker formations in the topsoil (higher horizons) due to puddling and compaction. The notable feature of this soil was the variability in structure and drainage with depth in a relatively uniformly textured soil. The soil profile was analysed when the field was in a fallow period and the structural qualities were the reverse of a normal soil in that the worst structure was the topsoil and this generally improved with depth, reflecting the effect of compaction and puddling. The topsoil was divided into three layers, the top two being dense and dull coloured. Limestone has been applied due to soil acidity but poorly mixed in to 10 cm. The third topsoil layer has a prominent coarse red mottle and demonstrates ‘tonguing’ as shown in Fig. 2. This tonguing may be a zone of preferred water movement into lower horizons. And this layer is the ‘hard pan’ or plough sole. The uppermost layer in the subsoil is a grey layer with some red mottles (23–33 cm). This is probably a zone of water transmission with a distinct anaerobic character and has a moderately good structure. It resembles a slightly bleached layer described in other soils [12] and it gives way to a very coarse red mottled layer especially adjacent to the topsoil tongues (33–45 cm depth). The very prominent red mottles are associated with rapid moisture changes as percolation water moves from the paddy and leaches into deeper layers.

Horizon 4 is very distinctive in having a good soil structure [12–15]. It has yellow mottles which show slow changes in water content. At the time of observations, the water table was at 1 m depth, but presumably this can move upwards freely due to the good structure. Thin sections and scanning electron microscopy of undisturbed soil materials were used to describe soil structure at a range of scales from field observations to microstructure. Infiltration rate was measured in the field and the results shown in Fig. 2. These techniques are in general agreement with each other as illustrated.

Bulk density and penetrometer resistance values are shown. The bulk density results proved not to be very

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001



Depth (cm)	Structure	Colour	Thin section/SEM structure	Comment	pH	PR	SS	IR	BD
0	Very poor/ massive	Dull		H1a @ 10cm.Few planar voids, untilled. Poor	5.69	>441	196	3,6,0,0 Mean 2.2	
20	Poor / Massive. Red mottles at base.	Some coarse red mottles in 1c.		H1b @ 20cm.Few planar voids, untilled. Top of tillage pan. Poor	4.06	216	196		1.19 - 1.28
	Good to moderate, 1- 10cm blockies	Mainly grey mottles		H3 @ 30cm. Similar to above with slightly better structure. Base of tillage pan	4.12	186			
40	1 to 10cm blockies. Moderate to poor, locally satisfactory.	Red clay with coarse mottles		H4 @ 50cm. Interconnected planar voids	4.05	216	206	30,15, 32,14 Mean 15.2	0.96 - 1.33
60	**Good**. 3cm blockies	Grey clay, 15% yellow mottles		H5 @ 65cm. High porosity, air spaces highly interconnected pores that will transmit air and water very well		98	176	13,10, 21,8 Mean 13.0	
	0.5 to 2cm blockies			Scanning electron microscope image of H5 @ 65cm. fine granular structure. Image width 0.05mm.		98	137		
80	Crab burrow dotted	Grey clay, 5% yellow mottles		H6 @90cm. Crab burrow infill. Poor vughy structure					
100	Medium/poor 1 to 2 cm blockies			H6 @ 100cm. Some interconnected planar voids, dense within peds					

Key
SEM: scanning electron microscope
PR: penetrometer resistance, kPa. Hand held type in pit wall to reduce friction on cone type instruments.
SS: shear strength measured with shear vane, kPa
IR: infiltration rate in mm per 24 hours, for soil profile below the depth where values shown
BD: dry bulk density, g.cm^{-3}

Bangkok Clay soil is an inceptisol by the US Soil Taxonomy and a gleysol by the classification system of the Food and Agriculture Organization (FAO).

Fig. 2. A soil profile and associated data for Bangkok clay soil at the Asian Institute of Technology field trials area, after fallow, Hall, Cooper and Leigh [10].

informative, probably because of the clay texture in which large numbers of micropores will exist in a clay even if the clay particles are in the closest packing achieved in normal situations. Burrowing crabs and toads were not very numerous but evidence of their activities was visible. They create channels that can penetrate to a depth of a metre and, until they infill, can transport water from poorly structured surface layers to better structured subsoil volumes. The structure of infill material was the same as the surrounding soil or of poor structure. This is interpreted as showing that these burrows have little influence on soil performance once they are infilled or truncated by paddy operations.

3.1. Depth of hard pan

The above profile observations are very important as to how the farmer plans and implements his cultivation program. As already stated the soil hardpan is usually expected to be at a depth of 15–20 cm, but there is concern that tractors and cultivation practice is having the effect in some situations of increasing the depth at where the hardpan is now found. Kuether [13] reported a four year study of the long term effects of mechanized tillage on the capacity of nearly continuously flooded paddy soils to support the machines used and the increased mobility problems with double compared to single cropping on heavy clay soil. The three mechanized systems were a 50 hp four wheel tractor with extendable cage wheels and a fully mounted rototiller, a 10 hp two wheel walking tractor with a power take off driven rototiller and a 7 hp two wheel tractor with a mouldboard plough and comb harrow. A water buffalo pulled mouldboard plough and comb harrow were used as a control comparison. A cone index of 246 kPa was considered a soft soil condition and a cone index of 492 kPa was considered firm (i.e. the depth of the hardpan). The four wheel tractor affected the depth most at which these resistances were encountered and increased; by the sixth cropping tractor bogging became a problem. The results confirmed farm reports of deepening of the hard pan with the use of wheeled tractors and the problems of bogging with the hardpan at 30 cm or greater depth. The problem was less associated with two wheel lighter tractors. Keuther [13] produced the values shown in Table 2. These results show that larger machines produce compaction at greater depths within the soil. This is evident after one crop and increased up to the eight crops measurement. This is particularly noticeable for the severe compaction threshold, 492 kPa. Compaction will determine the water percolation rate and there has been a lot of discussion about the ideal

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

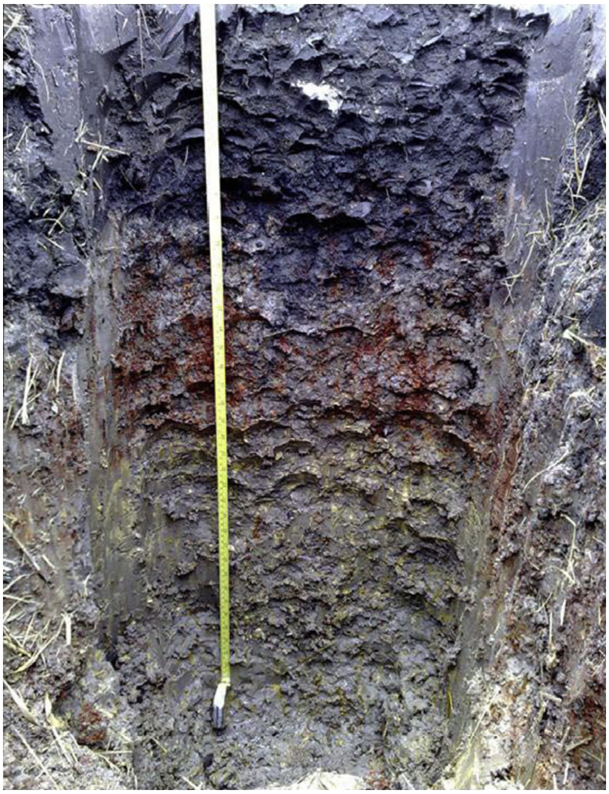


Fig. 3. Soil profile pit in Bangkok clay at the AIT to a depth of 1 m corresponding to Fig. 2.

Table 1
General soil properties of Bangkok clay soil at the Asian Institute of Technology, after Shrestha [11], as percentages by mass.

Organic carbon	3.8–5.2%
Organic matter	5–6%
Lower plastic limit	22–32%
Sticking point	34%
Liquid limit	48%
Plasticity index	16–25%
Cation exchange capacity	27–33 m.e.100 g^{-1} (0.27–0.33 MolC g^{-1})
Clay mineralogy	
Dominantly chlorite	25%
Illite	20%
Kaolinite	15%
Smectite	10%
Others minerals	25%

Moisture contents in top soils was 27.1–61.5% by mass or 34.9–59.4% by volume.

percolation rate (IRRI, 1978; cited in [16]). Allowing for evapotranspiration, the ideal percolation is stated in the above reference to be 11–21 mm per day in the root zone. The measured values in Fig. 2 show that the topsoil values are very much lower than required and that deeper layers are about right, or perhaps higher than needed for maximum yield. In order to optimise the system, the farmer needs the right depth of plough layer (15–20 cm) and the right density and structural qualities of the hard pan that carries the traffic over years of sustainable agricultural production [17].

The farm manager at the Pathum Thani Rice Research Institute [18] reported a similar problem of increased depth of the hardpan with the use of tractors. The longer soil drying time when the paddy is drained before harvest reduces the harvester axle loads that the fields can support; this reduced the use of tank harvesters, which were getting stuck, and required the use of filling sacks on the harvesters to reduce the axle weights. Fig. 4a shows where a tracked harvester has broken through the surface to sink onto its belly and become stuck. Fig. 4b shows a heavier tanker harvester and Fig. 4c a lighter bagging harvester that has to be used because of the reduced mobility problem. Fig. 4d and e shows tractors working with rotavators on different soil and hardpan conditions.

Kanoksak et al. [19] tested the performance of riding (315 kg) and walking type (75 kg) rice transplanters in Thai soil conditions at Kasetsart University with the hardpan at 15 cm and 17.5 cm depth under two different field conditions [20]. The first field condition was produced using a rotavator attached to a 22 kW four wheel drive (4WD) tractor for primary cultivation and two passes for puddling. The second conventional field condition was produced using a plough for primary cultivation and puddling was carried out using two passes with a rake, both were pulled by a two wheel walking tractor. Transplanting performance was measured by the number of missing, floating, buried and damaged hills. Kanoksak et al. [21] stated that particularly in conventional paddy fields with Bangkok clay soil the hardpan formed due to puddling is observed at 15–20 cm. They found that the riding type transplanter gave a better performance in the fields with the hardpan at 15 cm compared to 17.5 cm while the two row walking type transplanter showed no significant difference in both field conditions.

3.2. Bangkok clay soil mechanical properties

During wetting and drying soil cone index values and other mechanical properties can vary considerably. Fig. 5

Table 2
Mean soil depths to penetrometer resistance values of 246 kPa (moderate compaction) and 492 kPa (severe compaction) after tillage with different ways of trafficing the soil, adapted from Keuther [13].

	4WD	Tractor	10 hp	Tiller	7hp	Tiller	Water	Buffalo
Resistance (kPa)	246	492	246	492	246	492	246	492
Depth after one crop (cm)	20.7	23.9	9.9	23.6	11.9	16.1	11.0	15.1
Depth after eight crops (cm)	22.5	37.7	27.9	31.1	17.1	22.4	18.4	22.2

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

(a) Ruts from a stuck harvester

(b) A heavier tanker harvester on a firm plastic soil

(c) A lighter bagging harvester on the same soil as (a)

(d) Primary cultivation with a rotavator but little wheel sinkage

(e) Primary cultivation with a rotavator but softer soil and a deeper hardpan

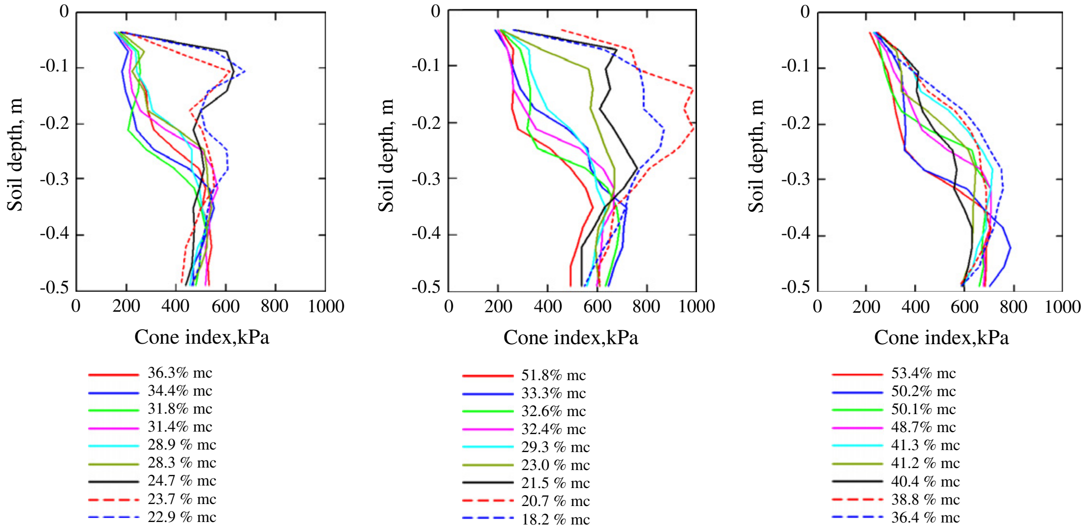
(f) A heavy tracked vehicle with a rotavator in soft soil paddy filling with water

Fig. 4. Varied field conditions and the effects of a deep hardpan.

shows how the cone index varies with soil moisture over the first five weeks of a growing cycle. The data is from Shrestha [11] and includes cone index profiles down to 0.5 m with a range of soil moisture from 18% to 53% dry basis (db). Three sets of data were collected on three separate dates. Individual measurements range from 200 kPa to 1000 kPa. Generally, where the soil moisture content is greater than the plastic limit, and less than the liquid limit, the hardpan can be identified with a cone index of 400–600 kPa at a depth of 0.25 m to 0.3 m with the plough layer having a cone index of 200–400 kPa.

Kanoksak and Gee-Clough [22] measured the soil properties in 49 wet paddy fields throughout the growing season in the Central and Northern regions of Thailand. The average cone index values over the range of 0-21 cm before first ploughing, before puddling and levelling, before transplanting, during mid-growing season and at harvest were measured as 420 kPa, 245 kPa, 311 kPa, 240 kPa and 385 kPa respectively. The average hardpan depth was at 21 cm. Farmers carried out ploughing with field conditions ranging from moist, to wet to flooded; the soil strength in the top 0–14 cm dropped considerably after ploughing, while in the layer from 21 to 31.5 cm it only decreased slightly. The average soil cohesion before first ploughing was measured to be 11 kPa with a soil internal angle of friction of 13°. At harvesting the average soil cohesion was 15 kPa with a soil internal angle of friction of 15°. The soil specific weight decreased after ploughing and puddling from 17.7 kN/m^3 and was a minimum at transplanting. The soil adhesion to steel and soil adhesion to rubber in

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001



(a) at the start of the cycle

(b) after four weeks from the start

(c) after five weeks from the start

Fig. 5. Penetration resistance at different depths during a drying cycle in the field for Bangkok clay, data from Shrestha [11].

wet and flooded conditions approached zero but at harvest they averaged 3.6 kPa and 6 kPa respectively.

Fig. 6 shows soil mechanical properties data collated by Shinde [23] from measurements recorded at the AIT over the last three and a half decades by authors carrying out experimental work on Bangkok Clay. Regression equations are given for cone index, cohesion, internal angle of friction, adhesion and soil-metal friction, with soil moisture content having an effect on these soil properties. The values of cone index, cohesion and internal angle of friction decrease with increasing moisture content. Adhesion and soil-metal friction values increase and then decrease as soil moisture content increases over the range 17–64% dry basis (db). Although a clay soil, the level of sand content in Bangkok clay provides significant internal angle of friction compared to the cohesion. The adhesion and soil-metal friction values are required in implement force prediction.

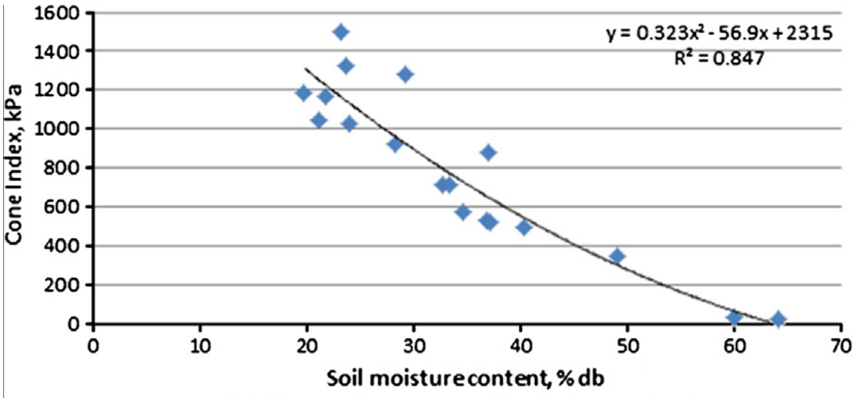
4. Tractive performance

4.1. Traction force prediction models

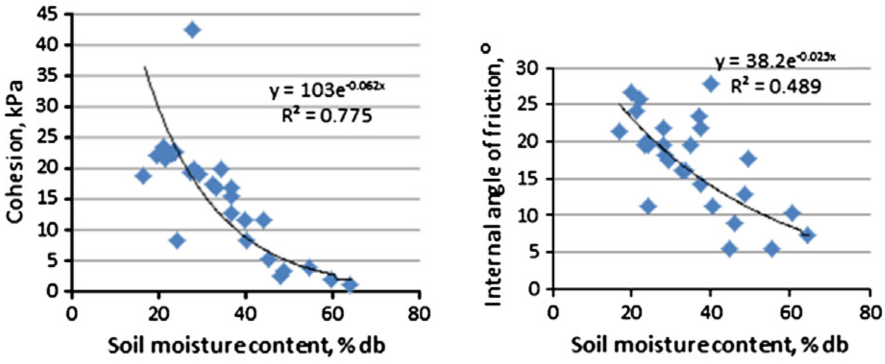
There are a large number of journal papers and books analysing traction including reviews and analysis by Bekker [24–26], Dwyer [27], Reece [28], Wismer and Luth [29], Wismer [30], Plackett [31], Alcock [32], Wong [33,34], Zoz and Grisso [35] and Maclaurin [36]. There are broadly two main approaches to modelling and predicting the tractive performance of an off-road pneumatic-tyred wheel as described by Dwyer [27]. In the first approach the equations use the Coulomb properties of cohesion and internal angle of friction as a measure of soil shear strength. The second approach uses the penetrometer cone index as a measure of soil strength and dimensional analysis and empirical data to determine the prediction equations and can be considered as a semi-empirical approach. There are also equations and definitions derived from empirical data that are concerned more with go/no go mobility [36]. Newer techniques such as finite element analysis and discrete element analysis have also been found useful and have considerable application and potential. Prediction equations have been developed primarily for military, agricultural, forestry and construction vehicle use.

Traction can be analysed in terms of several forces and terms including wheel thrust (or gross tractive force), wheel rolling resistance, net tractive force (or pull or drawbar pull), and tractive efficiency [27,35]. Table 3 summarises traction equations considered by Gholkar [37] and Ferdous [38] in more recent work investigating traction on soft Bangkok clay. The lack of adequate water control in paddy fields may dictate that vehicles must work in soils that are not only very soft but also very wet [39]. Aggarwal [40] found that the maximum power which a medium power (46 kW) four-wheel two wheel drive tractor could deliver in a flooded field was only about 40% of that which it could deliver when the soil was in its strongest state. Gholkar [37] carried out traction tests with a small 18.7 kW tractor operating in two wheel drive under the three wetland soil states of Bangkok clay in a plastic, sticky and flooded state. The cone index based traction models in Table 3, developed mainly for dry land conditions, were evaluated but none of the model predictions were found to agree with the data from the wetland traction observations. Hence, the new model by Gholkar [37], given in Table 3, was developed for wetland conditions on Bangkok clay. Higher drawbar force, and therefore drawbar power, were found on plastic soil conditions at the same wheelslip compared to sticky soil conditions which in turn had a higher drawbar force

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

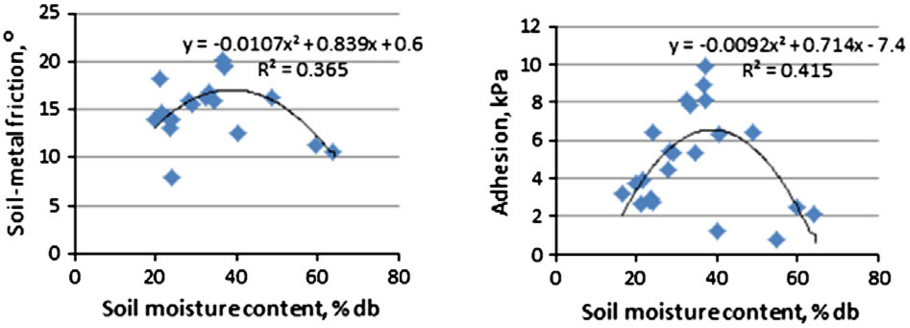


(a) Cone index versus soil moisture content



(b) Cohesion versus soil moisture content

(c) Internal friction versus soil moisture content



(d) Soil-metal friction versus soil moisture content

(e) Adhesion versus soil moisture content

Fig. 6. Bangkok clay soil mechanical properties, data from twelve authors collated by Shinde [23].

and power compared to flooded soil conditions; vehicle slip and surface deterioration due to single passing was increased at the same drawbar pull as soil moisture content increased. Blocking of wheel lugs was found to be more prominent when operating on soil near to the sticky limit. Kanoksak and Gee-Clough [22] carried out field experiments on the tractive performance of a medium range four wheel (two wheel drive) tractor. These were conducted in five different conditions from dry to flooded. It was found that empirical relationships developed for dry land can predict tractor performance quite well up to a soil moisture content of 33% (db) but are unsuitable beyond this value. The first ploughing operation in rice fields is generally carried out after rain in a rain fed area or after the field is flooded by irrigation water. After rain, the wet soil is usually soft enough to be ploughed but farmers always plough fields in flooded conditions because this generates fewer wheel blocking problems [22].

4.2. Modelling soil strength for traction prediction

Cone index is a vertical measure of soil resistance to penetration and does not readily take into account differences in surface condition which may affect horizontal

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

Table 3
Traction prediction equations considered by Gholkar [37] and Ferdous [38] for modelling traction on soft clay.

Author	Surface	Coefficient of rolling resistance	Coefficient of net traction, CT	Mobility number, M
Wismer and Luth [29]	Bias ply agricultural tyres for agri. Soil	$0.04+\frac{1.2}{M}$	$0.75(1-e^{-0.3MS})-\left(0.04+\frac{1.2}{M}\right)$	$\left(\frac{CI\cdot bd}{W}\right)$
Gee-Clough et al. [42]	Agricultural soil	$0.049+\frac{0.287}{M}$	$0.8-\frac{0.92}{M}$ (CT max)	$\left(\frac{CI\cdot bd}{W}\right)\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\frac{1}{1+\frac{b}{2d}}$
Ashmore et al. [43]	Forestry tyres for forestry soil	$-0.1\left(\frac{W}{W_R}\right)+\frac{0.22}{M}+0.2$	$0.47(1-e^{-0.2MS})+0.38\left(\frac{W}{W_R}\right)$	$\left(\frac{CI\cdot bd}{W}\right)$
Brixius [44]	Soil	$\frac{1}{M}+0.04+\frac{0.5S}{\sqrt{M}}$	$[0.88(1-e^{-0.1M})(1-e^{-7.5S})+0.04]-\left[\frac{1}{M}+0.04+\frac{0.05S}{\sqrt{M}}\right]$	$\left(\frac{CI\cdot bd}{W}\right)\left(\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}\right)$
Evans et al. [45]	Grass surface	$\frac{1}{M}+0.04$	$[0.88(1-e^{-0.1M})(1-e^{-4.15S})+0.04]-[\frac{1}{M}+0.04]$	$\left(\frac{CI\cdot bd}{W}\right)\left(\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}\right)$
Gholkar [31]	Soft wet clay paddy field	Not measured	$0.9(1-e^{-0.42MS})(1-e^{-1.1S})$	$\left(\frac{CI\cdot bd}{W}\right)\left(\frac{\delta}{h}\right)^{\frac{1}{2}}\frac{1}{1+\frac{b}{2d}}$
		Gross tractive effort		
Micklethwaite (1944) cited in Reece [28]	Soil	$H_{\max}=A\cdot c+W\cdot\tan(\Phi)$		
Janosi and Hanamoto [41]	Soil	$H=(A\cdot c+W\cdot\tan(\phi))\left[1+\frac{K}{i\cdot L}\cdot\left(e^{-i\frac{L}{K}}-1\right)\right]$		

shear strength. For example, soil drying from the top down with increased cohesion and friction in the surface, or shallow plant roots and plant growth that binds the surface soil and may affect the surface shear strength. Freshly added water to the clay soil surface would also affect the surface condition much more quickly than the plough layer. The soil deformation modulus, K (see Fig. 7), and the length of the contact patch, L, are important in the Janosi and Hanamoto equation [41] as they control the shape of the slip-pull curve with respect to wheel slip. As K becomes smaller the initial gradient becomes steeper and as the contact patch length becomes smaller the curve flattens out. K values are often determined in a laboratory translational or triaxial shear box but can be determined in the field for individual wheels if torque transducers are fitted to the wheels, the wheels can be locked and force and soil deformation are measured as the tractor is pulled a short distance by another tractor. The maximum shear force measured for each wheel is a direct measure of the Micklethwaite term in the Janosi and Hanamoto equation [41].

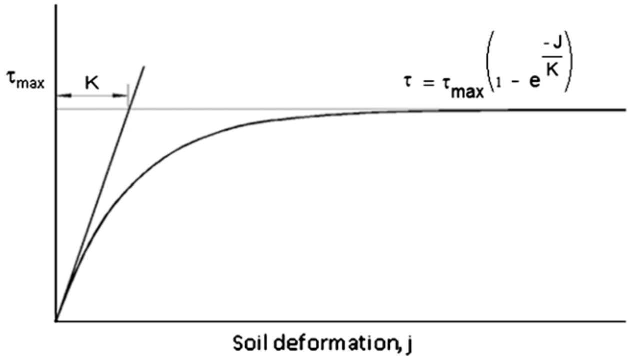
It is proposed that the Janosi and Hanamoto equation, without modification, could be more sensitive to changes in the surface horizontal shear strength than equations using Cone Index. Ferdous [38] has recently investigated the effects of moisture and surface condition of Bangkok clay soil on the tractive performance of a small four wheel drive agricultural tractor fitted with torque transducers in each wheel. Tests were conducted at the agricultural field laboratory of the Agricultural and Systems Engineering department at the Asian Institute of Technology.

Slip-pull traction tests and measurement of the shear force versus soil deformation were made in two wheel and four wheel drive, for a bare surface with no vegetation and a surface with re-growing rice plants with the roots from the previous crop. Three soil conditions were used: a hard plastic condition, a soft plastic condition and a hard dry top soil with wet soft subsoil. The wheel torque sensors also allowed the calculation of net and gross traction and therefore rolling resistance and tractive efficiency. Initial analysis of results has shown that the maximum tractive efficiency was 62% in 4WD on the grass surface on hard soil, and the minimum was 24% for 2WD on the bare surface on soft plastic soil. The grass surface increased the drawbar pull force in both 2WD and 4WD and also for both wet and dry soil conditions. Slightly lower soil deformation modulus was found for the higher inflation pressure front wheels than for the rear wheels.

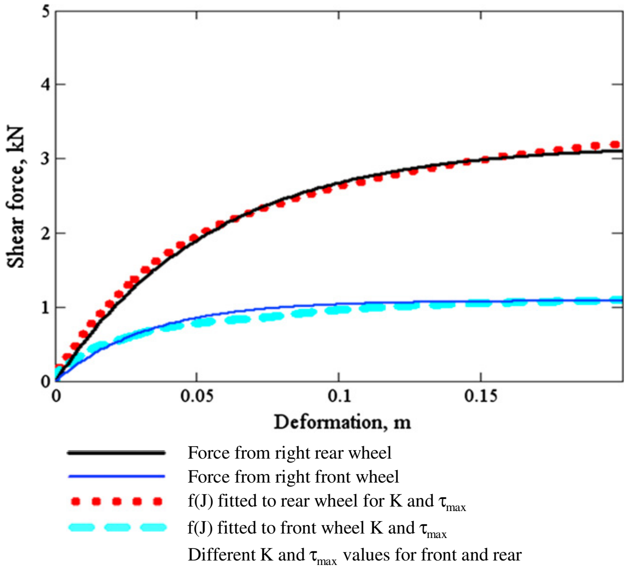
4.3. Drawbar pull and tractive efficiency

Difficulties in modelling traction include variable moisture content in the vertical soil profile, surface condition, wetting and drying, particularly in the surface, measurement, or estimate, of soil mechanical properties, dynamic wheel load as affected by weight transfer and the multi-pass effect of larger rear wheels following smaller front wheels. Tyre surface contact area increases with tyre load and

Q6



(a) Tangent K at J=0 from a soil shear stress-strain curve (Janosi and Hanamoto[41]).



(b) Example of exponential curves fitted to data for front and rear tractor wheels from locked wheel deformation-shear force measurements, from Ferdous [38]

Fig. 7. Determination of soil deformation modulus *K* (from tangent at $J = 0$) from a soil shear stress-strain curve (Janosi and Hanamoto [41]).

dynamic tyre load is affected by weight addition from the implement and weight transfer between the front and rear axles. The magnitude and line of action of the resultant force from the implement affects the dynamic wheel loads. For implements with known force characteristics, estimates of the slip-pull curve and tractive efficiency can be made from the dynamic wheel loads and soil strength. Changes in draught or weight addition will change the dynamic wheel loads and may significantly change the tractive performance. Many of the basic ideas involved with tractive performance have been available for several decades. For example, an analysis of how the dynamic wheel loads can be calculated is given by [46]. Spreadsheets based on the work by Godwin and his colleagues – see [47–49] – for calculating plough, tine and disc forces are available at [50] but are yet to be fully tested in soft soil conditions. For a four wheel drive tractor all the wheel loads are on driven wheels, but the tractive performance of front and rear tyres will be different, as will the performance of tyres on the land and in the furrow during ploughing. On hard soil this difference in wheel performance may be small or negligible, but on soft soil the differences may be significant [51]. Fig. 8 shows the tractive performance of an 18.7 kW 990 kg four wheel drive tractor on Bangkok Clay with two surface conditions without weight transfer, based on data from [38] Maximum tractive efficiency ranges from 57% on a bare drying surface in four wheel drive to 21% on a bare soft plastic surface in two wheel drive. Two wheel drive on the drying surface gave a slightly higher tractive efficiency of 34% compared to a tractive efficiency of 32% for four wheel drive on the soft plastic surface. These are achieved with wheel slips of 21%, 32%, 34% and 45% for highest to lowest tractive efficiencies.

Tractive efficiency is an output from only part of the tractor-implement system. Decisions on choice of engine and transmission (decisions made at tractor purchase), how these are used, what cultivation system is used and the quality of soil tilth produced have important roles in the quantity of fuel used and the overall measure of crop yield per unit of input energy. While the efficiency of a traction device is defined as tractive efficiency, the efficiency of a complete tractor is defined as power delivery efficiency [35]. Power delivery efficiency (PDE) is the ratio of the delivered drawbar power of a tractor to the vehicle input power of the tractor.

Traction and tractor performance is reviewed and analysed by [27,35,52,53], although the earlier references often concentrate on two wheel drive. Zoz and Grisso [35] also consider rubber belt drives. Factors affecting tractive efficiency include tyre type and inflation pressure [54], dynamic wheel load (including ballasting [55]), tyre dimensions, tyre deflection and soil strength. These also affect rolling resistance which in turn also affects tractive efficiency.

Keen et al. [56] have looked at the problem of maximising tractor efficiency in real time. Although draught control and maximum wheel slip control systems are common on agricultural tractors these are still set by the operator working to general guidelines and without quantitative feedback on the real time tractive efficiency. At present there are no commercial automatic control systems on tractors that maximise tractive efficiency. Keen et al. [56] have proposed that real time measurement and control of tractive efficiency during cultivations requires four models:

1. A tractor-linkage kinematic and force model that calculates the current implement vertical and draught forces, their lines of action and the dynamic wheel loads [57].
2. An implement force prediction model that allows estimation of the current soil condition and estimation of the effect of changing operating parameters such as depth, width and speed.

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

3. A traction prediction and evaluation model that determines the current tractive performance – the position on the current slip-pull and tractive efficiency curves.
4. A control model that incorporates the tractor linkage, implement force prediction and traction prediction and evaluation models combined with real time measured data to provide the tractor operator with information to affect changes to maximise the tractive efficiency or a control model that allows full automatic control.

Some performance measurements are difficult to quantify and these will include soil tilth which, until suitable sensors are developed, is judged by the tractor operator. But there are several measures of performance currently used which are easily understood by tractor operators and these include work rate and fuel consumption. Real time measurement and control of tractive efficiency during cultivations should include interpreting tractive efficiency using these measures. The required soil tilth and soil structure should be the first consideration in a cultivation operation. This is likely to mean that implement depth is a defined input parameter. As GPS based control technology, including auto-steer, becomes more readily available through its reduced cost, the environment of a paddy field seems an eminently suitable place to apply it. Economic growth and increasing standards of living in areas where intensive lowland rice production is common may make the uptake of this increasingly proven technology happen.

4.4. Traction aids

A major difference in dryland and wetland cultivations is in the increased difficulty in trafficability and traction due to less favourable soil properties as soil conditions change from hard to hard plastic, soft plastic, sticky and flooded. Problems of tractors fitted with pneumatic tyres in wetland conditions include tractors becoming stuck, breaking through the hardpan and the blocking of tyre treads which takes place particularly in sticky soil conditions. Previous studies have shown that cage wheels are traction aids particularly suited for wetland conditions [9] and these are usually used on small two wheel tractors to replace tyres (see Fig. 1). When cage wheels are fitted to tractors they are usually fitted to drive wheels with a diameter smaller than the tyre diameter (see Fig. 4d and e). The tractive performance is increased by cutting through soft soil in the plough layer and getting better grip and traction on the harder compacted soil in the hardpan [58] and, as evidenced by [14], they can also have the effect of increasing the depth of the hardpan. Tanaka [58] states that on surface conditions where there is no hardpan strong enough to support the vehicle, immobilization may take place. This requires vehicles to operate with less ground contact pressure by using tracks or floats.

The vast majority of cage wheels used in Asian wetland rice cultivation have lugs made from flat metal strips normally inclined at an angle of about 30 degrees to the radial line [59]. When the tractor is moving forward the lugs compress and fail the soil, providing lift and thrust. With the tractor in reverse the lugs act as digging blades and the tractor can quickly become immobilized. Cage wheels have a tendency to completely block at high slip in wet soft soil. Salokhe and Gee-Clough [60] identified three mechanisms by which wet clay soil can accumulate and block cage wheels. Soil-lug adhesion was identified as an important factor leading to blocking.

Salokhe and Gee-Clough [61] investigated the effect of nine different coatings on soil adhesion on cage wheel lugs. The coatings included ceramic tiles, Teflon tape and sheet, chromium plating, lead oxide paint, silicone lubricant oil, gloss paint, varnish and enamel. Enamel was found overall to be the most effective, practical and durable coating to reduce adhesion and to avoid cage wheel blocking. Measured lug pull and lift forces were unaffected and the field performance of a power tiller was improved when the lugs were fitted with bolt on enamel plates. As part of extensive investigations into improving the performance of agricultural vehicles and implements in wet paddy fields, Gee-Clough [59] found that enamel coating reduced the draught of disc and mouldboard ploughs in moist clay soil (Bangkok clay) by between 4% and 22% for a disc plough and between 8% and 23% for a mould board plough. In accelerated wear tests of enamel coated rings it was found that the wear rate of the enamel coating was about the same as mild steel in the same conditions. Soni et al. [62] investigated the effect on ploughing resistance when polyethylene protuberances (base diameter 20–50 mm, protrusion height 0–50 mm) were mounted as embossed arrays on a mouldboard plough working in Bangkok clay soil. When the dimensionless height to diameter ratio was less than 0.5 the biggest reductions in ploughing resistance, up to 36%, were measured in sticky soil.

Detailed experimental and analytical evaluation on cage wheel design and performance has been carried out at the Asian Institute of Technology for several decades and still continues. For example, Salokhe and Gee-clough [63], Salokhe and Gee-clough [64], Salokhe et al. [65], Salokhe et al. [66] and Shinde [23] have investigated factors including wheel slip, lug spacing and angle and moisture content and how single and multiple lugs act on the soil.

Tracks are used on rice harvesters that often work on soil in a plastic condition (see Fig. 4a–c) and, as can be seen in Fig. 4f, can support heavy tractors on flooded soil carrying out primary cultivations. Tracks increase the soil contact area and have two benefits. The increased contact area reduces the soil vertical pressure, and therefore sinkage, and the increased contact area increases the cohesion component in the horizontal shear force developed in traction. This leads to increased gross traction compared to tyres at the same wheel slip and the decrease in rolling resistance, because of less sinkage, also leads to increased net traction and tractive efficiency.

Low cost and local manufacture has helped to make cage wheels the main traction aid on small tractors used

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

in rice cultivations. The use of steel tracks on small tractors has been limited by cost. Recent developments in rubber tracks (belt drives) now allows for the adoption of low cost half-tracks and quad-tracks on small tractors. Dwyer et al. [67] has reported the comparative performance of a rubber tracked tractor and a four wheel drive rubber tyred tractor on a range of surfaces in north European conditions including clay stubble at 41% moisture content (db) and grass on clay loam at 35% moisture content (db). The rubber tracks showed a 10–20% advantage over the rubber tyres. At higher soil moisture contents, rubber tracks may allow for the effective use of tractors operating on soft soil surfaces with little sinkage when carrying out cultivations as opposed to running on the hard pan with tyred wheels and cage wheels. This may lead to better depth control and maintenance of the hardpan but it needs experimental work to investigate the notion properly.

5. Energy use in rice production

Agriculture is essentially an energy conversion process where solar energy is transformed by photosynthesis with the aid of fossil fuel, renewable energy, labour and chemical and organic inputs into food and fibre. Calculating the energy inputs into agricultural operations has been done for several decades [68,69]. There is no quick precise way to account for the energy used indirectly in agricultural production; a very large amount of virtually unobtainable information would be required to detail all the energy inputs to a piece of machinery. The energy used through mechanization to reduce human labour input in crop production may also facilitate the timeliness of key operations such as planting and harvesting, the accuracy and evenness of applying chemicals and the ability to control operations such as cultivations in a way that would not otherwise be possible. Pimentel [70] has shown that replacing the labour required in rice production that uses animal draught can be more than twice that input into the machinery but also considerably less than that in the petroleum fuel used. Ullah [71] surveyed the energy inputs and outputs of small (less than 3.2 ha), medium (3.2 to less than 9.5 ha) and large (9.6 ha or greater) farms producing lowland rice in Central Thailand – see Fig. 9. Total energy inputs per hectare are increased with size class of farm from 14,100 MJ to 19,000 MJ and 22,100 MJ respectively and this represented increased energy inputs of 34% and 56% for the larger classes respectively compared to the smallest farm class. But the output energy per hectare in the rice grain only increased by 15% from smallest farm size class to the middle size farm class with no further increase in energy output from the largest farm size class. The grain energy output to energy input ratio went down from 4.8 to 4.1 and then to 3.5 as the farm size got larger. The tillage energy inputs increased from 1701 MJ/ha to 2370 MJ/ha and then to 2343 MJ/ha as farms got larger. The main other increases in energy input on the larger farms were energy input in irrigation, nitrogen fertilizer and other agri-chemicals. What caused the extra energy inputs into cultivations is not clear and as a percentage of total energy inputs, cultivation input energy was similar at 11–13% across the farms. As Fig. 8 shows, tractive efficiency can vary by more than a factor of two largely due to surface soil strength. The depth of the hardpan, the work done in cultivations and the efficiency of energy conversion through tractive efficiency needs to be measured in the field to investigate this further.

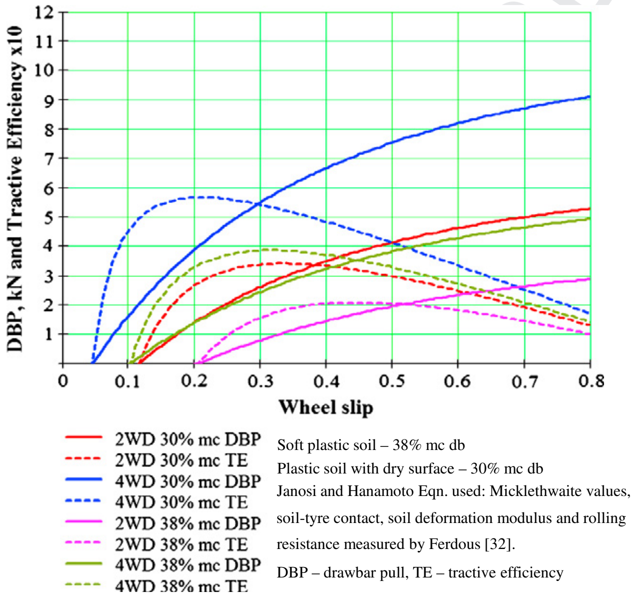


Fig. 8. Tractive performance of an 18.7 kW 990 kg four wheel drive tractor on Bangkok Clay with two surface conditions, based on data from Ferdous [38].

6. Discussion

The terrestrial soils system holds twice as much organic carbon as that in the atmosphere, or two to four times as much as that in the terrestrial biomass [72]. Under agricultural practice such as tillage, fertilisation and irrigation, the agricultural soil carbon pool changes continually. Global

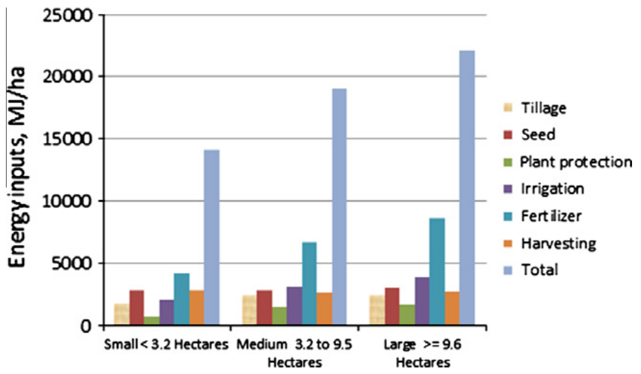


Fig. 9. Energy inputs to three size classes of lowland rice farm in Central Thailand, data from Ullah [71].

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

carbon cycling is recognised to impact the atmospheric concentrations of greenhouse gases and hence global warming [73]. Irrigated rice fields are important sinks of carbon and sources of greenhouse gas emissions [74]. Jaiarree [75] has reported that in 2009, agriculture contributed about 22% of Thailand's total greenhouse gas emissions of which 59% was from rice cultivation and 18% was from agricultural soils. Altering the management of agricultural ecosystems can result in changes in carbon fluxes, including changes in soil organic carbon and associated carbon dioxide emissions. Agricultural crop and animal production systems are important sources and sinks for atmospheric methane. The major methane sources from this sector are ruminant animals and flooded rice fields [76]. Wetland rice has contributed to the increase in atmospheric methane concentration, which has more than doubled during the past 200 years and emissions from flooded rice fields have been estimated at approximately 10% of the total global methane emission [77]. Methane is second in importance as a greenhouse gas and Thailand's Office of Environmental Policy and Planning (OEPP) [78] states that in Thailand in 1994 about 91% of methane emissions were from agriculture and of this approximately 73% were from rice cultivation. Emissions of the greenhouse gas nitrous oxide come from rice fields as a result of nitrification and de-nitrification during periods of alternating drying and wetting although continuous wetlands are a negligible source of nitrous oxide [79].

Pressure on global food production is linked to increased world population, changing diet, climate change and loss of agricultural land. How can cereal yields be maintained and increased in a sustainable way? How can the soil growing medium and environment be managed to maximise crop yields and efficiently use energy, water and chemical inputs to minimise the adverse effects on the environment and on climate change? The interaction between agricultural machines and the soil has a systemic interaction with soil and its environment.

Mishra [80] states that although the primary focus and challenges of the past were mainly to increase food production, the present scenario is quite different. The challenges now are multiple where food production has to be increased by countering other challenges such as global warming, water scarcity, soil fertility degradation, and misuse and over-use of farm chemicals. Kibblewhite et al. [81] have stated that "the major challenge within sustainable soil management is to conserve ecosystem service delivery while optimising agricultural yields. They proposed that soil health is dependent on the maintenance of four major functions: carbon transformations; nutrient cycles; soil structure maintenance; and the regulation of pests and diseases". Their working definition is that 'a healthy agricultural soil is one that is capable of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity'. Bouman et al. [3] state that rice environments provide unique, but as yet poorly understood, ecosystem services such as the regulation of water and the preservation of aquatic and terrestrial biodiversity. Progress in understanding the interactions between management interventions and the capacity of the soil to respond depends on insights into its functioning as an integrated subsystem of the agro-ecosystem. Kibblewhite et al. [81] focus on analysing the extent to which soil can be seen to be responding as a living system to agricultural intervention and the implications of this for sustainable agricultural practices. The systemic interaction between mechanized operations, soil behaviour and water use and conservation is thus becoming of increased relevance and importance within the overall concerns over climate change and environmental good management and sustainability.

An approach that supports this philosophy is the system of rice intensification (SRI), a methodology for increasing the productivity of irrigated rice by changing the management of plants, soil, water and nutrients, leads to healthier soil and plants supported by greater root growth and the nurturing of soil microbial abundance and diversity [82]. Key SRI practice involves careful planting of young seedlings (8–12 days old) singly and with a wide spacing (25 cm or more), keeping the soil moist but well-drained and well-aerated, adding compost or other organic material to the soil as much as possible. Mishra [80] reports work on SRI carried out at the AIT. The benefits of SRI include increased yield (50–100% or more), a reduction in seed requirements (up to 90%) and water savings (50% or more) [82]. Many SRI users also report a reduction in pests, diseases, grain shattering, unfilled grains and lodging. Mishra and Salokhe [83] provide an explanation for root vigour under SRI. In unfertilized seedbeds, seedlings allocate more dry matter to the roots for better nutrient uptake, whereas in soil where nutrients are easily available, shoot growth can take preference over roots. After establishment, seedling growth rate is a function of soil nutrient status. Therefore, SRI seedbed management helped to improve seedling establishment and accelerated seedling growth with more nodal roots and shoot growth. As a climate-smart agricultural methodology, additional environmental benefits stem from the reduction of agricultural chemicals, water use and methane emissions that contribute to global warming. New varieties or the application of chemical inputs is not essential.

As already stated, within world agriculture, irrigated rice production is the largest source of demand for fresh water. Increasing demand from domestic and industrial use puts pressure on the agricultural availability and use of water for crop irrigation. Over time, what began as an adaptation to unfavourable growing conditions became the norm – rice could grow successfully inundated with flood and irrigation water, which also reduced competition from weeds [84]. As Bouman et al. [3] have pointed out, puddling is not a pre-requisite for rice production and some of the highest yielding rice production is carried out

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

in Australia and California where puddling is not carried out. The system of rice intensification (SRI) has great potential as a methodology for reducing water requirements in irrigated rice production. The role and development of mechanized cultivation operation within SRI provides scope for important investigation. For example, how is water infiltration rate best managed within SRI? Is there a need to maintain any form of hard pan? With more aerobic conditions weed control becomes an increased problem and precision mechanical weeding techniques increase in importance. As can be seen from Fig. 9, SRI saving in fertilizer and irrigation water and increases in yield will generate substantial savings in energy inputs per ha.

Although the use of larger, heavier tractors has generally been avoided in wet soft soil cultivation, larger higher power tractors may enable new opportunities for mechanized shallow tillage for improved recycling of crop residues, which usually requires greater machine power [73]. The long-term consequences of minimum tillage for soil organic matter turnover in intensive rice systems compared with a system with ploughing and puddling are unknown. However, new opportunities to manipulate soil organic matter cycling in intensive rice systems, including dry tillage and crop residue incorporation during the fallow period may allow for more accelerated aerobic decomposition of crop residues. Dobermann and Witt [73] discuss the related soil carbon and nitrogen transformations but the depth, type and degree of cultivations, and whether carried out under aerobic or flooded conditions, requires further investigation. The energy, financial, agronomic and environmental costs and benefits are complex to evaluate and systems modelling of the plant-soil biology [85], energy and soil management will be an important tool in developing understanding of alternative approaches. Equilibrium in soil organic matter in rice paddy will be long term, 2–300 years or greater [86] and an important consideration in the long term sustainable management of the soil. Yilmaz et al. [14] demonstrated the effect of years under cultivation (40, 400, 4000 years of intensive use under irrigation) and influences on soil character that cannot be explained by organic matter content, and these could be important depending on the history of land use.

With increasing focus on the use and cost of fuel in agricultural tractors, and the environmental impact of energy use, the conversion of power into drawbar work, a primary purpose of agricultural tractors, is becoming more important, particularly as saving fuel by improving tractive efficiency can also increase work rates and reduce costs. Gholkar found that equations developed for dryland conditions using cone index over predicted tractive performance in wet soft soil and he modified the Brixius constants to use these equations for a small 2WD tractor. The approach of using the Janosi and Hanamoto equation and replacing Micklethwaite's equation to represent maximum wheel thrust with measured maximum shear force from slipping locked wheels looks promising but requires further investigation and analysis of the curve fitting characteristic soil deformation modulus, determination of how representative are the soil parameter values found for Bangkok clay compared to other clays where intensive lowland rice is grown, and further evaluation and modelling of rolling resistance on soft clay soil. Soil deformation modulus is a curve fitting parameter, the inverse of the gradient of a shear-soil deformation plot at zero soil deformation for unit shear force. For a hard compacted soil the value will be small (a few millimetres representing a steep gradient) and for a loose cultivated soil the value will be much higher representing a less steep gradient). Reece [87] and Q3 Godbole et al. [88] have argued the modifying effect of the soil normal stress on soil deformation modulus. Soil deformation modulus is usually measured in a translational (direct shear) box or triaxial shear apparatus. In the first the soil is in a physically confined state and in the second the soil is in a controlled pressure confined state or is unconfined in tests to determine cohesion. The soil-tyre shear area, shape and perimeter length may be different in the field for front and rear tyres and the normal pressures may be different. Further, the pass of the front wheels will modify the soil and surface condition for the pass of the rear wheels. Soil sampling and preparing the test sample for laboratory shear tests may also have an effect on the value of the soil deformation modulus measured. Using locked or slipping wheels in the field to measure the shear force versus soil deformation curve should remove the problem of error introduced through sampling and handling.

The Bekker pressure sinkage equation does not include the effects of deformation rate. Sargana et al. [89] carried out plate sinkage tests in saturated, puddled Bangkok clay soil. They developed the Bekker pressure sinkage relationship to include a term that accounts for the rate of sinkage. El-Domiaty and Chancellor [90] carried out triaxial tests to determine the stress-strain characteristics of a saturated clay soil at various rates of strain. Both Sargana *et al.* [89] and El-Domiaty and Chancellor [90] developed equations using theory by Reiner [91] to include strain rate and the plastic viscosity of the soil. This evidence suggests that strain rate should also be considered along with normal pressure when measuring and modelling soil deformation modulus in soft clay soil.

Gee-Clough [39] considers models of rolling resistance in soft wet clay for towed rigid wheels and observes that unlike on sand where bulldozing in front of the wheel takes place there is no bulldozing in soft wet clay but what was observed was that as the wheel width increased, vertical displacement of the soil on each side of the wheel increased and that this behaviour seemed to cause the increase in rolling resistance. There is still no theory currently available for vehicle performance prediction in wetland on soft saturated clay soil.

The Brixius equations predict tractive force and rolling resistance from one soil strength parameter, cone index,

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

and have been adapted to different soil/terrain conditions with changes to the constants and, as Gholkar has shown, they can be adapted to Bangkok clay. The Coulomb approach as used by Janosi and Hanamoto requires shear versus soil deformation tests to determine the Coulomb parameters used in Micklethwaite's equation, or, alternatively, moisture content, a more easily measured parameter could be used with data such as that in Fig. 6. The Coulomb approach has been linked to Bekker's rolling resistance theory by Janosi and Hanamoto [41]. The Bekker rolling resistance theory uses plate sinkage tests to determine a further set of soil parameters and has not been commonly used partly because of the difficult extra soil measurements and parameter determination required. The approach used by Ferdous uses pulled/pushed locked wheels to measure the maximum shear force developed for each wheel to replace the Micklethwaite term in the Janosi and Hanamoto equation, ie. a direct measure of maximum shear force *in situ* in the field which also takes account of the surface condition and how soil drying has affected the soil moisture vertical profile. The direct measure of maximum shear strength, soil moisture content and surface condition, as well as operational and tractor parameters could form part of further investigation in rolling resistance. The rolling resistances used in Fig. 7 were from values measured by Ferdous using torque measurement sensors on each wheel and relating these values to the drawbar pull. The technique requires more investigation and evaluation but provides quick and easy field measurement and the potential for real time traction measurement and evaluation. Real time sensing to measure cone index could also make equations based on this measurement valid to use in real time.

7. Conclusions

Centuries of evolutionary development has produced rice growing systems to suit a range of prevailing soil and environmental conditions and in particular methods that allow the production of a cereal crop in difficult wetland ecosystems. The production systems have evolved complementary with the human labour and animal draught available. The speed of mechanization to replace animal draught with, firstly, two wheel tractors and, now increasingly, four wheel tractors of increasing size, raises a range of issues and considerations that need to be addressed.

One of the key issues in conventional rice production appears to be that in clay soils the hard pan, a defining soil characteristic in rice production, can be deeper than required with consequently increased energy inputs, effects on soil wetting and drying which can affect machine mobility, water use, greenhouse gas emissions and agrichemical use. The long term effects of these interactions on soil sustainability are yet to be fully investigated. The effective design and use of wheeled tractors on different surface conditions needs further investigation, particularly in combination with implements; how traction aids such as cage wheels, rubber tracks, rubber half-tracks and rubber quad tracks improve performance, the efficiency of draught and powered cultivation implements, and the role of implement surface coatings and finishes. These need to be considered with respect to tractive efficiency and maintenance of a soil hard pan that has the required characteristics for sustainable production. Methods that effectively measure soil and surface characteristics in the field should be more reliable models of tractive performance than laboratory data alone. Combining soil-implement models and tractor-implement models with tractive performance models will provide an analytical framework to evaluate part of the cultivation machinery performance. Modelling traction in soft soil with the Janosi and Hanamoto equation and modified Brixius equations requires further investigation, particularly the development of a robust rolling resistance model. Evaluation of the determination of the behaviour of soil deformation modulus under tractor wheels, measured *in situ* and in the laboratory, requires further investigation.

The recent introduction of SRI methods of production has great importance. These include the potential to save large volumes of irrigation water, increase yields, save on inputs including agrichemicals and save energy inputs associated with agrichemicals and irrigation. SRI methods also provide the opportunity to develop mechanization techniques that avoid, or reduce, the problems of wetland tractor operations, and possibly, the need to maintain a hard pan at a shallow depth. The increasing use of more powerful four wheel drive tractors should allow for the higher work rates and labour output required in growing economies. So far, there appears to have been little investigation on how tractors and machines can effectively and sustainably be used in SRI rice production in intensive lowland areas.

With the increasing use of computers and control systems on agricultural tractors the one area where these have not been introduced with any major innovation in recent years is the fundamental operation of agricultural tractors: traction and the tractive efficiency with which draught operations are carried out. Although draught control and maximum wheel slip control systems are common on agricultural tractors these are still set by the operator working to general guidelines and without quantitative feedback on the real time tractive efficiency. At present there are no automatic control systems on tractors that maximise tractive efficiency. The development of instrumentation, particularly soil condition sensors, and tractor computer based technology may open up this area for innovation in the near future. Operations such as primary cultivation, puddling, soil levelling, precise depth control and mechanical weeding in SRI methods will provide opportunities for GPS linked precision operations.

Acknowledgements

The authors would like to thank the British Council for the financial support provided by the PMI2 Research Co-

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

operation programme. The authors would also like to thank the technician support at the Asian Institute of Technology and at Harper Adams, and use of resources at both Institutions.

References

[1] IRRI; 2011. http://irri.org/about-rice/http://irri.org/about-rice/rice-facts [accessed April 2011].

[2] FAOSTAT. Food and Agricultural Organization Annual Report. Rome, Italy: FAO Publications; 2006.

[3] Bouman BAM, Humphreys E, Tuong TP, Barker R. Rice and water. Advances in agronomy, vol. 92. Academic Press; 2007. p. 188–237.

[4] Chapagain AK, Hoekstra AY. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecological Economics 2011;70:749–58.

[5] IRRI. http://irri.org/about-rice/rice-facts/rice-production-and-processing Land preparation; 2011 [accessed April 2011].

[6] Verma AK, Dewangan ML. Efficiency and energy use in puddling of lowland rice grown on Vertisols in Central India. Soil Till Res 2006;90(1–2):100–7.

[7] Rautaray SK, Watts CW, Dexter AR. Puddling effects on soil physical properties. Agric Mech Asia, Africa Latin Am 1997;28(3):37–40.

[8] Salokhe VM, Ramalingam N. Effects of direction of rotation a rotary tiller on properties of a Bangkok clay soil. Soil Till Res 2001;63(1–):65–74.

[9] Salokhe VM, Gee-Clough D. Cage wheel blocking in wet clay soil. J Agric Eng Res 1988;39:277–86.

[10] Hall NW, Cooper SE, Leigh T. Internal report. Harper Adams University College, UK; 2011.

[11] Shrestha S. Study of some physical, chemical and mechanical properties of Bangkok clay soil. Masters thesis no. AE-02-05, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2002.

[12] Hall NW. Soil structure transformations over the growing season – a micromorphological approach. In: Proceedings of the international working meeting on soil micromorphology, Townsville, Australia, Developments in Soil Science 22, Elsevier; 1994. p. 659–667.

[13] Kuether DO. Soil compaction and wetland rice tillage systems. ASAE paper no. 77–1021; 1977.

[14] Yilmaz K, Hall NW, Coşcan PK. Evaluation of soil compaction in the Narli Plain irrigation area, Kahramanmaraş, eastern Turkey. Soil Sci 2003;168(7):516–28.

[15] Hall NW. Micromorphology and complementary assessments of soil structure description and their relationships to the length of time under tillage and calcium carbonate contents. In: Proceedings of the International Working Meeting on Soil Micromorphology, San Antonio, Texas, USA. Developments in Soil Science, Elsevier; 1990. p. 53–60.

[16] Koga K. Introduction to paddy field engineering. Bangkok, Thailand: Asian Institute of Technology; 1992.

[17] Hall NW, Huang Quanzhong, Yilmaz Kadir, Tekin Yucel, Shaw MS, Howard-Smith MJ, et al. Sustainable soil use in the UK. In: Proceedings of the Institute of Agricultural Engineering Conference ‘Sustainability in Engineering Design’ held at Harper Adams University College, 9th of March 2005; published in Landwards, vol. 60, no. 3; 2005. p. 13–21.

[18] Somchai. Personal communication. Pathum Thani Rice Research Institute, Thanya Buri, Thailand; 2009.

Q4 [19] Kanoksak Eam-o-pas, Munthumkarn Vicha, Ounkong Narong, Goto Yoshiaki, Yamauchi Toshio. Performance of a self-propelled riding type rice transplanter. Kasetsart J (Nat Sci Suppl) 1988;22:79–87.

[20] Kanoksak Eam-o-pas, Goto Yoshiaki. Comparative performance of the rice transplanters by Thailand’s field conditions. Kasetsart J (Nat Sci Suppl) 1990;24:64–8.

[21] Kanoksak Eam-o-pas, Munthamkarn Vicha, Ounkong Narong, Goto Yoshiaki; Maeoka Kunihiko, Miyazaki Masahiro, Yoneyama Masahiro. Performance of the rice transplanters by Thai soil condition. AGRIS record, TH2000002591, Kasetsart Univeristy, Bangkok, Thailand; 1990.

[22] Kanoksak Eam-o-pas, Gee-Clough D. Improving the tractive performance of wheeled tractors in wet paddy fields: final report. Research report No. 203, Asian Institute of Technology, Bangkok, Thailand; 1987.

[23] Shinde VS. Modelling tractive performance of cage wheels by dimensional analysis. Masters thesis no. AE-10-03, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2010.

[24] Bekker MG. The theory of land locomotion. Ann Arbor: University of Michigan Press; 1956.

[25] Bekker MG. Off the road locomotion. Ann Arbor: University of Michigan Press; 1960.

[26] Bekker MG. Introduction to terrain vehicle systems. Ann Arbor: University of Michigan Press; 1969.

[27] Dwyer MJ. The tractive performance of wheeled vehicles. J Terramech 1984;21(1):19–34.

[28] Reece AR. Tractor design and tractive performance. Agricultural Engineering Symposium of the I.Agri.E. Paper no. 3/4/E/34; 1967.

[29] Wismer RD, Luth HJ. Off-road traction prediction for wheeled vehicles. Trans ASAE 1974;17(1):8–10. 14.

[30] Wismer RD. Soil dynamics: a review of theory and application. SAE paper no. 820656. SAE, Warrendale, PA; 1982.

[31] Plackett CW. A review of force prediction methods for off road wheels: review paper. J Agric Eng Res 1985;31:1–29.

[32] Alcock R. Tractor-implement systems. PP44-72. AVI Publishing; 1986 [chapter 5/6]. ISBN 0-87055-522-7.

[33] Wong JY. Terramechanics and off-road vehicles. Amsterdam, the Netherlands: Elsevier Science; 1989.

[34] Wong JY. Theory of ground vehicles. 3rd ed. New York: John Wiley; 2001.

[35] Zoz FM, Grisso RD. Traction and tractor performance. ASAE Distinguished Lecture Series, Tractor Design No. 27; 2003.

[36] Maclaurin EB. Comparing the NRMM (VCI), MMP and VLCI traction models. In: Proceedings of the 9th European conference of the ISTVS, Harper Adams, UK, September 8th to 11th; 2003.

[37] Gholkar MD. Modelling tractive performance of pneumatic tyres under wet land conditions. Masters thesis no. AE-08-05, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2008.

[38] Ferdous J. Effects of surface condition on the tractive performance of small agricultural tractor on Bangkok Clay. Masters thesis no. AE-11-xx, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2011.

[39] Gee-Clough D. The special problems of wetland traction and flotation. J Agric Eng Res 1985;32:279–88.

[40] Aggrawal S. Tractive performance of a two wheel drive tractor in wet soils. Masters thesis no. AE-80-21, Asian Institute of Technology, Bangkok, Thailand; 1980.

[41] Janosi Z, Hanamoto B. The analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils. In: First int. conf. mechanics of soil-vehicle systems, Torino-St. Vincent; 1961.

[42] Gee-Clough D, Mcallister D, Pearson G, Evernden DW. The empirical prediction of tractor-implement performance. J Terramech 1978;15(2):81–94.

[43] Ashmore C, Burt EC, Turner JL. An empirical equation for predicting tractive performance of log-skidder tyres. Trans ASAE 1987;30(5):1231–6.

[44] Brixius WW. Traction prediction equations for bias-ply tires. ASAE paper no. 871622. ASAE, St. Joseph, Mich; 1987.

[45] Evans MD, Clark RL, Manor G. An improved traction model for ballast selection. Trans ASAE 1991;34(3):773–80.

[46] Zoz FM. Predicting tractor field performance. ASAE paper no. 70-118, St. Joseph, MI: ASAE; 1970.

[47] Godwin RJ. A review of the effect of implement geometry on soil failure and implement forces. Soil Till Res 2007;97(H.2):331–40.

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001

[48] Godwin RJ, O'Dogherty MJ, Saunders C, Balafoutis AT. A force prediction model for mouldboard ploughs incorporating the effects of soil characteristic properties, plough geometric factors and ploughing speed. Biosyst Eng 2007;97(1):117–29.

[49] Godwin RJ, O'Dogherty MJ. Integrated soil tillage force prediction models. J Terramech 2007;44(H.2):3–14.

[50] Godwin RJ, Upadhyaya SK. Tillage: Part II, development of comprehensive tillage force prediction spreadsheets, with accompanying cd. Advances in soil dynamics, vol. 3, ASABE; 2009. p. 320–2. ISBN 1-892769-73-5 [chapter 3].

[51] Keen A. Tyres – tyre/soil-performance. In: Harms H, Meier F, editors. Year Book Agricultural Engineering. DLG Verlag; 2009. ISBN 978-3-7690-0728-2 [chapter 3.3].

[52] Gee-Clough D, Pearson G, McAllister M. Ballasting wheeled tractors to achieve maximum power output in frictional-cohesive soils. J Agric Eng Res 1982;27(H.1):1–19.

[53] Gee-Clough D. Selection of tyre sizes for agricultural vehicles. J Agric Eng Res 1980;25(H.3):261–78.

[54] Zoz FM, Turner RJ. Effect of "correct" pressure on tractive efficiency of radial ply tires. ASAE paper no. 94–1051, St. Joseph, MI: ASAE; 1994.

[55] Zoz FM, Wiley JC. A theoretical basis for tractor ballasting recommendations. In: Proc 5th North American ISTVS conference, Sasketoon, SK, Canada; 1995.

[56] Keen A, Ward J, Godwin RJ, Hall NW, Cooper SE. The tractive efficiency of agricultural tractors carrying out cultivations. In: ASABE summer meeting, Reno, Nevada, pm-18 324 096639; 2009.

[57] Keen A, Gholkar MD, Ward J, Salokhe V, Soni P. Force measurement between a tractor and a three point linkage mounted cultivation implement. In: International agricultural engineering conference, Bangkok, Thailand, 7–10 December, 2009, IAEC Ref. 253; 2009.

[58] Tanaka T. Operation in paddy fields: state of the art report. J Terramech 1984;21(2):153–79.

[59] Gee-Clough D. Improving the performance of agricultural vehicles and implements in wet paddy fields: final report. AIT research report no. 256, Asian Institute of Technology, Bangkok, Thailand; 1992.

[60] Salokhe VM, Gee-Clough D. Cage wheel blocking in wet clay soil. J Agric Eng Res 1989;39:277–86.

[61] Salokhe VM, Gee-Clough D. Applications of enamel coating in agriculture. J Terramech 1989;26(3/4):275–86.

[62] Soni P, Salokhe VM, Nakashima H. Modification of a mouldboard plough surface using arrays of polyethylene protuberances. J Terramech 2007;44:411–22.

[63] Salokhe VM, Gee-Clough D. Behaviour of wet clay soil under single cage wheel lugs. J Agric Eng Res 1987;37(4):255–66.

[64] Salokhe VM, Gee-Clough D. Wet clay soil behaviour under multiple cage wheel lugs. J Agric Eng Res 1988;39(1):57–70.

[65] Salokhe VM, Manzoor S, Gee-Clough D. Pull and lift forces acting on single cage wheel lugs. J Terramech 1990;1(1):25–39.

[66] Salokhe VM, Hong TranThi, Gee-Clough D. Effects of low-to-medium slip, lug spacing and moisture content on lug forces. J Terramech 1994;31(6):385–94.

[67] Dwyer MJ, Okello JA, Scarlett AJ. A theoretical and experimental investigation of rubber tracks for agriculture. J Terramech 1993;30(4):285–98.

[68] Leach G. Energy and food production. London: International Institute for the Environment and Development; 1975.

[69] Pimental D. Handbook of energy utilization in agriculture. CRC Press; 1980. ISBN 0-8493-2661-3.

[70] Pimentel D. 2009 Energy inputs in food crop production in developing and developed nations. Energies 2009;2:1–24. http://dx.doi.org/10.3390/en20100001 (http://www.mdpi.com/1996-1073/2/1/1).

[71] Ullah A. A comparative analysis of energy use patterns in small and large scale irrigated rice farming systems: a case study in Ayutthaya province in central region of Thailand. Masters thesis, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2009.

[72] Huang Yao, Sun Wenjuan. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. Chin Sci Bull 2006;51(15):1785–803.

[73] Dobermann A, Witt C. The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems. In: Kirk GJD. Olk DC, editors. Carbon and nitrogen dynamics in flooded soils. Proceedings of the workshop on carbon and nitrogen dynamics in flooded soils, 19–22 April 1999. Los Baños, Philippines. Makati City (Philippines): International Rice Research Institute; 2000. 188 p.

[74] Cox PM, Betts RA, Jones CD, Spall SA, Totterdell J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 2000;408:184–7.

[75] Jaiarree S. Soil management for maximizing carbon sequestration in Thailand. In: Proceedings of the international workshop on evaluation and sustainable management of soil carbon sequestration in Asian countries, September 28–29; 2010. p. 153–166.

[76] Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K, Johnson DE. Mitigating agricultural emissions of methane. Clim Change 1998;40:39–80.

[77] Neue H. Methane emissions from rice fields: wetland rice, a major contribution to global warming. BioScience 1993;43(7):466–73.

[78] OEPP. Thailand's initial national communication under the United Nations Framework Convention on Climate Change. Office of Environmental Policy and Planning, Ministry of Science, Technology and Environment, Thailand; 2000.

[79] EPA (United States Environmental Protection Agency). Methane and nitrous oxide emissions from natural sources. Office of Atmospheric Programs (6207J), 1200 Pennsylvania Ave., NW, Washington, DC 20460; 2010.

[80] Mishra A. Effects of water regimes and plant densities on rice (*Oryza sativa* L.) growth under system of rice intensification (SRI) management. Doctoral dissertation no. AE-08-01, Asian Institute of Technology, Bangkok, Thailand (unpublished); 2008.

[81] Kibblewhite MG, Ritz K, Swift MJ. Soil health in agricultural systems. Philos Trans Roy Soc Lond B Biol Sci 2008;363(1492):685–701 [Published online 2007 September 4. doi: 10.1098/rstb.2007.2178. Copyright © 2007 The Royal Society]. Q5

[82] SRI; 2011. <http://sri.ciifad.cornell.edu/index.htmla>.

[83] Mishra Abha, Salokhe VM. Seedling characteristics and the early growth of transplanted rice under different water regimes. Expl. Agric. 2008; 44: 365–383, Cambridge University Press;.

[84] Uphoff N. The system of rice intensification (SRI) as a methodology for reducing water requirements in irrigated rice production. International dialogue on rice and water: exploring options for food security and sustainable environments, held at IRRI, Los Baños, Philippines, March 7–8; 2006.

[85] Arah JRM, Kirk GJD. Modelling rice plant-mediated methane emission. Nutr Recycl Agroecosyst 2000;58:221–30.

[86] Koelbl A, Kalbitz K, Fiedler S, Braeuer T, Grootes PM, Cao Z, et al. 2000 years of paddy soil development – gain and loss of soil carbon. In: American geophysical union, fall meeting 2010, abstract #B41H-0409; 2010.

[87] Janosi Z, Hanamoto B. The analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils: discussions. In: First int conf mechanics of soil-vehicle systems, Torino-St. Vincent; 1961. p. 727–736.

[88] Godbole R, Alcock R, Hettiaratch D. The prediction of tractive performance on soil surfaces. J Terramech 1993;30(6):443–59.

[89] Sargana MA, Gee-Clough D, Gupta CP. A dynamic equation for the pressure–sinkage relationship in saturated clay soils. J Terramech 1985;22(2):111–20.

[90] El Domiaty AM, Chancellor WJ. Stress–strain characteristics of a saturated clay soil at various rates of strain. Trans Am Soc Agric Eng 1970;20(1):21–5.

[91] Reiner M. Deformation, strain and flow. 3rd ed. London: H. K. Lewis; 1969. p. 115.

Please cite this article in press as: Keen A et al., A review of the tractive performance of wheeled tractors and soil management in lowland intensive rice production, J Terramechanics (2012), http://dx.doi.org/10.1016/j.jterra.2012.08.001