# The effects of coal seam gas infrastructure development on arable land

**Project 5: Without a trace (Final report).**
**08 May 2015**

GISERA, GPO Box 2583, Brisbane QLD 4001, Australia

Gas Industry Social & Environmental Research Alliance

# Document control

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The Gas Industry Social and Environmental Research Alliance (GISERA) undertake publicly-reported research that addresses the socio-economic and environmental impacts of Australia's natural gas industries. GISERA was co-founded by CSIRO and Australia Pacific LNG in July 2011. In March 2014, QGC joined GISERA in recognition that the challenges being addressed through GISERA are relevant to the entire CSG-LNG industry, and that there are benefits from such collaborative research. For further information please visit: www.gisera.org.au.

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# Executive summary


Coal seam gas (CSG) is commercially extracted in several countries throughout the world. The production of CSG in Australia is set to increase driven by increasing global demand for energy and in response to the transition to a lower carbon economy through greater use of gas for electricity generation. In Queensland, the CSG industry provides approximately 90% of the gas supplies and 15% of the gas required for electricity. Despite of many economic benefits being delivered by the CSG industry, concerns have been raised over the potential environmental impacts associated with its production as well as potential long-term effects on agricultural productivity.

The work reported in this document was conducted to: (1) assess the extent of damage to agricultural soil caused by the various elements of CSG development, and (2) estimate the likely impact of soil compaction, caused during the establishment of CSG infrastructure, on crop productivity. The study was conducted using a paired-sites approach by comparing measurements conducted on a range of selected soil parameters in areas around and including well-head sites with measurements in neighbouring agricultural fields. These spatial areas are referred to as 'lease' and 'field' areas, respectively. Measurements were used to guide parameterisation and application of the Agricultural Production Simulation (APSIM) model to assess the likely effects of changed soil conditions on crop productivity. To achieve this, the APSIM model was used to simulate wheat (*Triticum aestivum* L.) yields for 115 years on grey Vertosols in the Darling Downs region of Queensland. Simulations were conducted with soil properties representing: (1) field area conditions not affected by CSG activities, (2) lease area conditions in which soil had been impacted by CSG activities, and (3) lease area conditions where soils had been rehabilitated. Results showed that soil compaction within lease areas was approximately 10% higher compared with fields ($P<0.05$). The modelling work suggested that near-surface soil compaction (depth range: 0-300 mm) in areas affected by CSG activities can lead to significant losses in crop productivity. The simulation analyses predicted a 50% reduction in median wheat yields compared with simulated results in neighbouring agricultural fields. For the bottom and top deciles, predicted relative yields were up to 60% and 32% lower, respectively.

Practical solutions to alleviation and management of such compaction are presented and discussed. Soil cultivation of the top 300 to 350 mm will ensure sufficient water storage in most years thereby reducing the risk of crop failure. Progressive soil loosening techniques for alleviation of deeper compaction were reviewed however their cost-effectiveness requires further investigation. The feasibility of adopting controlled traffic should be considered to minimise additional compaction caused by standard farming operations in field areas. The examination of soil chemical properties indicated that these were affected to a limited extent by the establishment of CSG infrastructure. However, a general requirement is for careful manipulation of sodium-rich subsoil, and avoidance of soil mixing and layer inversion. The dataset acquired and the simulation results derived from this study can be used to help policy makers, land managers and the CSG industry to assess measures relating to improved soil management practices within highly-productive arable land in Queensland. Cost-benefit analyses of soil management practices for reinstatement are required.

# 1. Introduction

Methane from coal seams, commonly referred to as coal seam gas (CSG), is commercially extracted in several countries throughout the world, including the USA, Canada and Australia (Meng et al., 2014). CSG is produced either biogenically or thermogenically, that is, by means of microbial conversion of coal into carbon dioxide ($CO_2$) followed by reduction to methane ($CH_4$) or by chemical de-volatilisation during the coalification process, which releases $CH_4$, respectively (Moore, 2012). The gas is retained in coal by means of adsorption onto the coal surface and trapped by water in the aquifer, and can be extracted by dropping the pressure in the seam and capturing the gas whilst removing the water (Shen et al., 2011; Hamawand et al., 2013). The extraction of CSG results in relatively large quantities of co-produced water, whose recycling to agriculture poses a challenge to the CSG industry due to its chemical composition (Clarke, 1996; Van Voast, 2003; Hamawand et al., 2013; Meng et al., 2014). The production of gas in Australia is set to increase significantly in response to the transition to a lower carbon economy through greater use of gas for electricity generation, as well as the increasing global demand for energy. Estimates (e.g., Lyster, 2012) suggest that global demand for gas will double between 2010 and 2035. In Australia, annual gas production increased from approximately 0.3 PJ in 2004 to 150 PJ in 2013 (DNRM, 2014a) and it could reach 1700 PJ per year as CSG infrastructure is further developed in response to the growing global demand (Klohn Crippen Berger Ltd., 2012). Presently, in Queensland, the CSG industry provides approximately 90% of the gas supplies and 15% of the gas required for electricity generation (GISERA, 2014).

Despite the significant economic benefits being delivered by the CSG and liquid natural gas (LNG) industries, concerns have been raised over the potential environmental impacts caused by this activity (Huth et al., 2014). The establishment of CSG infrastructure in Queensland has seen the development of an extensive network of access tracks, pipelines and wells (Fleming and Measham, 2014), which require the use of heavy machinery during the construction and operational phases. Several studies (e.g., Ponce-Reyes et al., 2014; Vacher et al., 2014) have indicated that long-term agricultural productivity may be affected by CSG development through threats to surface and groundwater resources, impacts to highly-productive agricultural land, and potential effects on the soil resource with associated impacts on the wider environment. These concerns have led to policies, which aim to protect agricultural land by avoiding development or mitigating impacts (Owens, 2012; Swayne, 2012). For example, in Queensland, strategic cropping areas (SCA) are defined as land areas of regional interest and are protected under the Regional Planning Interests Act 2014 (DNRM, 2014b). The land within SCA is, or is likely to be, highly suitable for cropping because of a combination of soil quality , water availability, climate and landscape features (DNRM, 2014b). Existing legislation requires that development on such land that temporarily diminishes its productivity will restore the condition of the land at the end of the development (DNRM, 2014b). Disturbance caused during the establishment and removal of gas infrastructure results in changes in physical, chemical and biological properties of soils, which require the implementation of effective rehabilitation measures to restore their productive capacity. It is envisaged that a balanced coexistence between mining and agriculture is achievable; however, this requires careful planning and management (Walton et al., 2013; Huth et al., 2014).

The environmental footprint of CSG development on agricultural land is regarded to be significantly greater than the proportionally small area devoted to the well-head infrastructure and the surrounding lease area during the development phase (Antille et al., 2014). For example, access roads, installation of pipeline networks, laydown yards, and vehicle mustering points represent additional areas of potential significant impact to agricultural land (Kowaljow and Rostagno, 2008; Olson and Doherty, 2012; Shi et al., 2014). The environmental impact may be higher at the catchment- or regional-scales with increasing density and network connectivity of geographically isolated gas fields. Therefore, designs for CSG infrastructure need to account for the risk of soil disturbance and seek to minimise damage where it is unavoidable (Antille et al., 2014). The extent and nature of damage to the soil resource caused by the various elements of CSG development in Australia are not well documented. Despite this, methods for land reclamation and restoration exist but their suitability and effectiveness in the context of the local CSG industry have yet to be quantitatively assessed.

The Gas Industry, Social and Environmental Research Alliance (GISERA, www.gisera.org.au) was created in 2011 to provide independent scientific research into the socio-economic and environmental impacts of the gas industry. The research undertaken by GISERA draws from an evidence-based understanding of regional processes and issues relating to five topics: (1) Surface and groundwater, (2) Biodiversity, (3) Agricultural land management, (4) Marine environment, and (5) Socio-economic impacts. The work reported in this document was conducted under the agricultural land management theme to extend the knowledge-base of environmental impacts and management associated with development of CSG infrastructure, and to assist the industry meeting the expectations of stakeholders and the wider farming community. This work will also inform land managers and the CSG industry on ways to improve current operations and protect the soil resource. Therefore, the objectives of this research were to:

(1) Assess the damage to agricultural soils associated with development of CSG infrastructure,

(2) Model the likely impact of soil compaction on crop productivity, and

(3) Acquire a background dataset, which may be used to advise policy makers and the CSG industry on measures relating to improved soil management practices within highly-productive arable land in Queensland.

The work was conducted on case-study farms and focuses on the characterisation of key soil quality indicators, which included assessment of selected soil physical and chemical properties in affected and non-affected areas using a paired-sites approach. Measurements within affected areas around and including well-head sites (referred to as 'lease areas') were compared with measurements conducted in neighbouring agricultural fields (referred to as 'field areas'). These data were subsequently used to guide parameterisation and application of the Agricultural Production Simulator (APSIM) model (Keating et al., 2003; Holzworth et al., 2014), which was used to assess the likely impact of soil compaction on crop productivity.

## 1.1 Regional description

Long-term rainfall and evapotranspiration transects for the study area based on data for the period 1910-2000 are shown in Figure 1 (Huth et al., 2014). Within the study area, rainfall decreases in the eastern-western direction and has an annual average of 670 mm. Approximately 70% of the annual rainfall occurs between October and March. Temperature records for the same period show that the mean (annual) maximum and minimum temperatures are 27.1°C (range: 33.1°C in January to 19.8°C in June) and 12.1°C (range: 19.5°C in January to 4.8°C in August), respectively (Bureau of Meteorology, 2014).

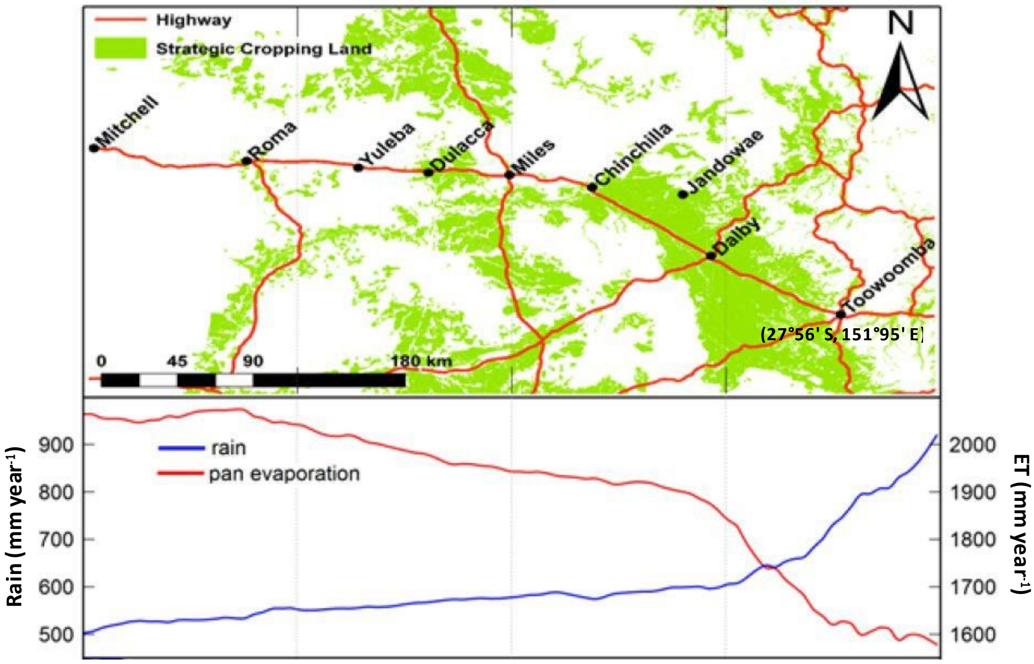



**Figure 1.** Rainfall and evapotranspiration (ET) transects produced with long-term (1910 -2000 ) meteorological records of the study area (after Huth et al., 2014).

## 1.2 Coal seam gas infrastructure development

The majority of current and planned future developments in the CSG industry in eastern Australia are located within the Surat and Bowen Basins (Queensland) (Figure 2) comprising an area of approximately 300,000 km$^2$ and 60,000 km$^2$, respectively (Clarke, 2013). The land is predominantly used for agriculture, including broad-acre cropping both irrigated and dryland, and grazing, and is categorised as classes 2 (production from relatively natural environments), 3 (production from dryland agriculture and plantations) and 4 (production from irrigated agriculture and plantations) based on the Australia land-use and management (ALUM) classification version 7 (DAFF, 2010). Existing wells in southern Queensland are shown in Figure 3. The number of wells established annually has increased from approximately 10 prior to 1995 to about 1400 in 2013 (DNRM, 2014a).

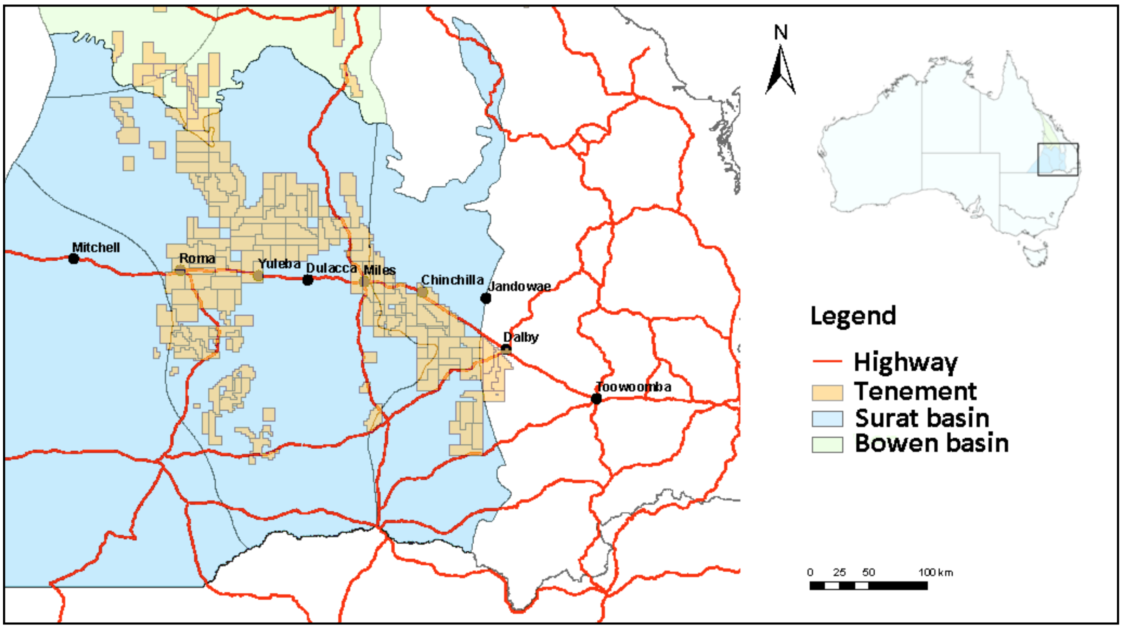
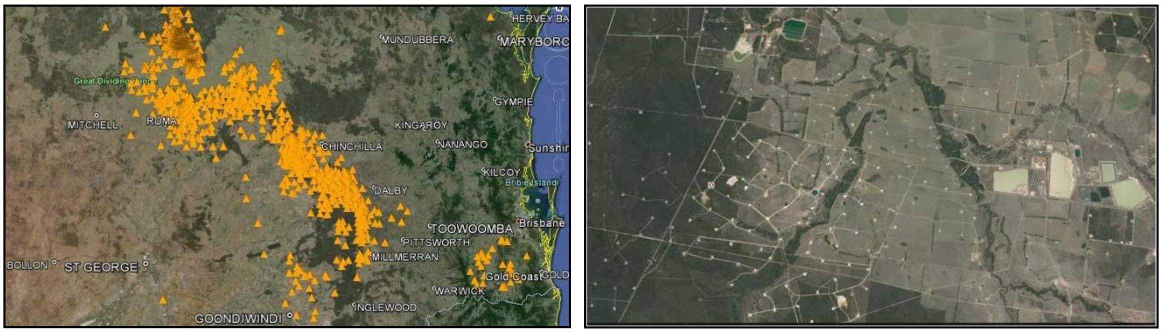



**Figure 2.** Map of the study region showing the current extent of the coal seam gas tenements for which petroleum leases have been granted.




**(a)** **(b)**

**Figure 3. (a)** Coal seam gas wells (▲) in the Surat Basin in southern Queensland (after DNRM, 2014c ), and **(b)** aerial view of the network of access tracks, pipelines and wells near Chinchilla, Queensland.

## 1.3 Soil resource

The dominant soil types within the Surat and Bowen Basins are Vertosols and Sodosols, and to lesser extent Rudosols, Chromosols, and Kandosols (Isbell, 2002). Localised variability within some soil types can be high (e.g., development of Gilgai in Vertosols), and degradation or susceptibility to degradation in Sodosol and Chromosol soils (Finck, 1961; Silburn et al., 2011). For a detailed description of these soil types and their susceptibility to erosion, the reader is referred to McKenzie et al. (2004). Direct impacts from CSG-related activity can be broadly divided into those affecting the soil's physical, chemical and biological properties. Changes in soil properties often result in additional secondary processes that compound the impact and lead to land sustainability and degradation concerns, particularly in relation to surface and subsurface hydrology, and elevated erosion risk (Vacher et al., 2014). In this respect, traffic-induced soil compaction is recognised as a constituent of soil physical degradation that accelerates erosion processes (Haigh and Sansom, 1999; Rickson, 2014) and loss of soil organic carbon (SOC) (Lal, 2003). Protection of soil health and the need to ensure that essential soil functions are maintained are discussed in several reviews (e.g., Karlen et al., 2003; Kibblewhite et al., 2008).

In the context of CSG, the most common range of direct effects of this activity on the soil resource is: (1) Soil surface disturbance, (2) Soil compaction, and (3) Soil mixing and layer inversion (Vacher et al., 2014). Surface disturbance from removal of vegetative cover during the construction phase exposes the soil, which increases its susceptibility to erosion (Loch, 2000; Silburn et al., 2011). Soil compaction results from vehicular traffic, which causes reduction in hydraulic conductivity and therefore infiltration (Hamza and Anderson, 2005). The effects of compaction are often persistent without intervention (Alakukku, 1999). Some clay soils with shrink-swell properties, for example, are self-restructuring and may recover from the effect of field traffic to a greater extent than typically sandy and silty soils, which do not re-structure naturally following cycles of wetting-drying (Pollard and Webster 1978; Radford et al., 2007; McHugh et al., 2009). Soil mixing and inversion occurs when soil materials are not segregated during excavation, stock-pilling or re-spreading (Vacher et al., 2014). For Vertosols with sodic subsoil and Sodosols, placement of sodium-rich material that is prone to dispersion on the upper part of the profile during backfilling can enhance crusting and erosion (Hardie et al., 2007). This study focuses on the assessment of key soil parameters, which enabled the extent of impact from CSG infrastructure development to be quantified and to produce estimates of potential crop productivity loss associated with those impacts.

# 2. Materials and methods

## 2.1 Description of sites

The sites investigated are listed in Table 1. The impacts on the soil resource associated with CSG activities occur during the following stages: (1) Exploration, (2) Installation of wells, (3) Production, and (4) Decommissioning. These impacts are commonly observed in the following spatial areas: (1) Well lease area, (2) Access tracks, (3) Pipeline right-of-way, and (4) Production areas (Figure 4). The lease area is the designated area of land within which the well is drilled and typically occupies between 0.6 and 1 ha. Access tracks refer to temporary roads (width: 5 to 10 m), which are constructed between the lease area and gazetted roads or existing tracks in the farm. The use of access tracks is mainly during the exploration and development phases when they are subjected to frequent traffic by heavy equipment. Gathering lines refer to the area where pipelines have been installed to transport gas and water from individual wells, and includes a width each side of the pipeline, as negotiated with the landholder right-of-way (construction: 15 to 25 m wide). Production areas include sites devoted to buildings, water storage and vehicle mustering points, and typically occupy between 0.5 and 20 ha per site.

This study was conducted using a paired-sites approach by comparing a range of selected soil parameters in areas affected by CSG activities on already established sites with neighbouring agricultural fields. The fields surrounding lease areas are considered to be the controls and representative of the situation prior to CSG development. In order to comply with health and safety regulations, and related requirements on-site, measurements were only conducted within lease areas with limited investigations conducted on access tracks. Sampling conditions were not always optimal due to requirement to work around the operational needs of gas companies.

(a)

(b)

**Figure 4.** Overview of areas affected by development of CSG infrastructure: (**a**) Established well within the lease area, and (**b**) Pipeline right-of-way during the construction phase.

**Table 1.** Location of case-study sites with the corresponding soil types. Soil order and suborder are based on the Australian Soil Classification (Isbell, 2002 ).

| Site | Soil order | Soil suborder | Texture | Latitude | Longitude | Installation |
|---|---|---|---|---|---|---|
| Gilbert Gully 6 | Vertosol | Grey | Clay | 27˚35'59" S | 150˚54'50" E | 14 Dec 2009 |
| Gilbert Gully 7 | Vertosol | Grey | Clay | 27˚36'16" S | 150˚54'14" E | 6 Feb 2010 |
| Talinga 120 | Vertosol | Grey | Clay | 26˚46'59" S | 150˚21'24" E | 7 Sept 2011 |
| Talinga 127 | Vertosol | Grey | Clay | 26˚46'44" S | 150˚21'53" E | 2 Sept 2011 |

## 2.2 Measurements and analyses

Electromagnetic induction (EM) measurements were conducted to provide a general characterisation of sites (Triantafilis and Lesch, 2005) using a Geonics EM-38 instrument in vertical mode, and carried at a height of 200 mm above the soil surface. The data were digitally recorded from transects spaced at approximately 3 m apart, georeferenced, and reported as apparent electrical conductivity (ECa, mS $m^{-1}$).

Soil bulk density (SBD) was determined at regular depth increments of 100 mm (depth range: 0 to 700 mm) by taking soil cores (diameter: 50 mm) using a soil corer mounted on a hydraulic rig. Measurements were taken five times (n=5) within lease areas and three times (n=3) in the surrounding fields. The field-moist soil was oven-dried at 105±2˚C for 72 hours, and SBD determined based on Blake and Hartge (1986). Differences in soil moisture content in samples from field and lease areas were within ±2% on average. Therefore, comparisons of SBD values observed in these two spatial areas were conducted without correction for moisture content (Rao et al., 1978). The coated clod method (Brasher et al., 1966) was used in situations where the soil exhibited large cracks, which made it difficult to provide reliable estimations of bulk density with samples taken with the hydraulic soil corer. Total porosity of soil was derived from density properties based on Equation (1) (McKenzie et al., 2002) using a nominal particle density of 2.65 g cm$^{-3}$, which was considered to be appropriate for the range of soil types investigated (Hurlbut and Klein, 1977).

$$\eta = 1 - \frac{\rho_b}{\rho_p} \quad \textbf{(1)}$$

where: $\eta$ is total porosity (%), and $\rho_b$ and $\rho_p$ are bulk density and particle density (g cm$^{3}$), respectively.

Cone penetrometer resistance was measured by pushing a cone (125 mm$^2$ base area, 30° apex angle) into the soil to a depth of 575 mm, and digitally recording the force at 25 mm depth increments based on ASAE (1999). Measurements were taken from the lease areas and the surrounding fields. The data presented are reported in kPa and represent the average of twenty readings (n=20). Surface water infiltration was measured using the double-ring infiltrometer method (ASTM, 2009). Infiltration rates were subsequently obtained by differentiating Kostiakov's equation (Equation 2) with respect to time to describe the relationship between the rate of infiltration and time (Equation 3). Measurements were replicated three times (n=3).

$$F_t = a\, t^n \quad \textbf{(2)}$$

$$I_t = a \quad n\, t^{n-1} \quad \textbf{(3)}$$

where: $F_t$ is cumulative infiltration (mm) at time $t$ (h), $a$ and $n$ are constants, and $I_t$ is instantaneous infiltration rate (mm h$^{-1}$) at time $t$ (h).

Saturated hydraulic conductivity (Ks) was determined using small cores (diameter: 50 mm) and by applying a positive head until a constant rate was reached (Klute, 1965). Measurements of Ks were conducted at Gilbert Gully 7 and Talinga 120 only. Soil textural analyses were conducted using the pipette method (British Standard, 2001) for regular depth increments of 200 mm (depth range: 0 to 800 mm), and measurements replicated three times (n=3). The Emerson class test (Emerson, 1967) was performed to provide an indication of soil stability to resist slaking and dispersion (depth range: 0 to 200 mm) based on Standards Australia (1980), and measurements replicated three times (n=3). The modified Proctor test (Proctor, 1933 in Terzaghi and Peck, 1967) was performed to determine soil moisture-soil density relationships for the range of sites investigated. These data were subsequently used to obtain a measure of compaction encountered in the field and in areas affected by CSG activity relative to the maximum dry density. Soil samples for the Proctor test (n=10) were randomly taken from the upper layer of the profile (depth range: 0 to 200 mm), and measurements conducted on one bulked-sample per site.

Soil chemical analyses were conducted using standard laboratory techniques. The following analyses were conducted: soil organic matter (SOM) by loss-on-ignition (British Standard, 2000), soil pH (1:5 soil/water suspension) and electrical conductivity of soil (EC, 1:5 soil/water extract) (Rayment and Lyons 2011). Extractable cations (except Ca) were determined based on MAFF (1986) as follows: Mg (Method No.: 40), K (Method No.: 63), and Na (Method No.: 67). Extractable Ca was determined based on British Standard (2007). Determination of exchangeable cations (Ca, Mg, K, and Na) and cation exchange capacity of soil (CEC) were based on MAFF (1986, Method No.: 16), and Bascomb (1964), respectively. Exchangeable sodium percentage (ESP) is calculated as the ratio of Na to the sum of exchangeable cations (Ca, Mg, Na, K) (Hazelton and Murphy, 2013). For SOM analyses were conducted for the 0 to 200 mm depth layer. Soil pH, EC, cations (extractable and exchangeable), and CEC were determined to a depth of 800 mm at regular depth intervals of 200 mm. The cations ratio of soil structural stability (CROSS) was determined using Equation (4) to quantify the combined effects of Na and K on clay dispersion, and the combined flocculation power of Ca and Mg (Rengasamy and Marchuk, 2011). This approach was preferred to the sodium adsorption ratio (SAR) (Richards, 1954) because it accounts for the relative activity of K as a dispersive clay agent (Rengasamy and Marchuk, 2011).

$$CROSS = \frac{(Na + 0.56K)}{\left[\frac{(Ca + 0.6Mg)}{2}\right]^{0.5}} \tag{4}$$

where: the concentrations of $Na^{+}$, $K^{+}$, $Ca^{2+}$ and $Mg^{2+}$ are expressed in $mmol_c\ L^{-1}$.

## 2.3 Modelling of crop performance

The use of a process modelling approach was chosen to quantify the likely impact of soil compaction upon crop growth. The APSIM modelling framework (Keating et al., 2003; Holzworth et al., 2014) has been developed to simulate biophysical processes in farming systems and has previously been used to estimate the possible impact on grain yield of wheat for varying levels of soil compaction by livestock (Bell et al., 2011). A similar approach to that of Bell et al. (2011) was followed with a few modifications:

(1) Use of the SWIM3 soil water model (Huth et al., 2012) to capture the impact of soil compaction on soil water dynamics, and

(2) Use of an existing model (Dexter, 1987; Whalley et al., 1995) for plant root growth to determine the impact of soil water potential and soil strength on root front advances through the soil profile.

When compacted, soil undergoes changes in pore size and pore size distribution, which affect hydraulic conductivity and water retention (Vomocil and Flocker, 1961). A simple conceptual model was employed to describe these changes. A set of soil properties for a grey Vertosol was chosen from the APSoil database (Dalgliesh and Foale, 1998) to represent the state of the soil before compaction due to CSG-related activity. These soil properties have been used in previous field and simulation studies (e.g., Huth et al., 2002; Huth and Poulton, 2007) and they are representative of the soils at the field sites studied in this work. The database includes specification of SBD, saturation water content (SAT), drained upper limit (DUL) and lower limit (LL, 1500 kPa) water contents. A series of simple adjustments were made to this soil parameter set to account for the impacts of compaction. Based on results from this study, it was also assumed that SBD would increase by approximately 0.1 g $cm^{3}$ as observed at the Talinga sites.

The impact of compaction was assumed to decrease progressively below this depth, which was considered to be a fair assumption based on earlier studies (e.g., Ansorge and Godwin, 2007; Antille et al., 2013). This level of compaction is similar to that described by Connolly et al. (2001) for Vertosols with approximately 50% clay content. Therefore, the soil hydraulic properties were used from the APSoil dataset (Dalgliesh and Foale, 1998) to parameterise the model, and these were adjusted using the following assumptions based upon information from this work and the data of Connolly et al. (2001), as follows:

(1) Saturation water content is approximated by total soil porosity as affected by changes in soil bulk density,

(2) Compaction would have negligible impact on pores holding water at a potential of 1500 kPa (Connolly et al., 2001). The data from our study show little difference in gravimetric water content of dry soils between lease areas and neighbouring fields. Therefore, the increase in volumetric water content at this potential, shown by Connolly et al. (2001), due to compaction is simply captured through the increased bulk density,

(3) The effect of compaction on water content for a given potential decreases progressively for the near-linear section of the water retention curve between 1 kPa and 1500 kPa (see Figure 6 in Connolly et al., 1997). Therefore, the increase in volumetric water content at 10 kPa should be approximately one third of that at 1500 kPa. This suggests a steadily increasing impact of compaction with increasing pore size, and

(4) Measurements of Ks within this study showed a significant decrease due to compaction, which is consistent with earlier work (e.g., Shafiq et al., 1994; Arvidsson, 2001). However, standard errors were large due to the soil water conditions under which the measurements were conducted. Therefore, representative values of Ks were taken from Connolly et al. (2001) who provided parameter ranges for macropores and micropores for clay soils after various cropping histories.

Saturated hydraulic conductivity values for soils prior to damage by CSG-related activities were chosen to represent more than 50 years of cultivation, and included a macropore component and a developing plough pan at the 300-600 mm depth interval. After compaction, the contribution from macropores would be reduced, hence, Ks values were estimated to reflect the micropore values given in Connolly et al. (2001), and the relative change in SBD assumed for a given depth. Soil parameter sets derived to represent soils before compaction by CSG-related activities, after compaction, and after remediation (cultivation to 300 mm) are shown in Table 2. The rehabilitated soil profile uses the field data to 300 mm depth and lease areas' properties for below that depth.

An example showing the impact of these parameter changes on the water retention and hydraulic conductivity for surface soils calculated within the SWIM3 model (Huth et al., 2012) are shown in Figure 5. The model of Dexter (1987) was used to capture the impact of soil strength on root growth. The model can be written as follows:

$$\frac{R}{R_{max}} = -\frac{\Psi_m}{\Psi_w} + e^{-0.6931\left(\frac{Q_p}{Q_{1/2}}\right)} \quad (5)$$

where: R is root front velocity (mm $d^{-1}$), $R_{max}$ is potential root front velocity (mm $d^{-1}$), $\Psi_m$ is soil matric potential (kPa), $\Psi_w$ is plant wilting point potential (kPa), $Q_p$ is soil penetration resistance (kPa), and $Q_{1/2}$ is the soil penetration resistance (kPa) at which root front velocity is reduced by 50%.

The above model is used within APSIM to account for the effect of soil water content and soil strength on root growth on a daily basis within the simulation. Dexter (1987) suggests representative values for $\Psi_w$ (-1500 kPa) and $Q_{1/2}$ (1300 kPa), $R_{max}$ is specified within the formulation of the APSIM wheat model, and $\Psi_0$ is calculated within the SWIM3 model. Simulation of daily estimates of $Q_p$ are provided by a simple model in which penetration resistance is assumed to vary linearly between a maximum value when the soil water content of a layer is at LL and a value of 100 kPa at DUL.

Measurements of penetration resistance were taken when the fields under study were close to LL. Due to the soil conditions observed at both Talinga sites; there was significant variation in data within- and between-sites (Table 3). Therefore, penetration resistance values for all depths at both sites were pooled to provide estimates of $Q_p$ for dry soil for field or lease areas for a grey Vertosol. The impact of these soil conditions on crop production will vary with seasonal growing conditions. Therefore, a long-term simulation was produced to capture the likely seasonal variability for the study region. Weather data for Chinchilla was obtained for the years 1900 to 2014 from the SILO climate database (Jeffrey et al., 2001). APSIM was used to simulate wheat production for this weather record using the soil properties described above. The wheat model within APSIM has been broadly tested across Australia and internationally in a range of experimental (Holzworth et al., 2011; Zhang et al., 2012) and farm (Hochman et al., 2009; Carberry et al., 2013) conditions. Standard agronomic management was specified in the model using the APSIM manager model (Moore et al., 2014).

The sowing rule specified that wheat (*Triticum aestivum* L. *c.v.* Hartog) was to be sown at a population of 100 plants per $m^2$ when the day of year was within 120 and 190, the plant available water stored over the preceding fallow exceeded 100 mm, and when 25 mm of rainfall had occurred over the preceding week. Note that the sowing of all soil conditions was based upon the water content within the field simulation because a farmer would sow all portions of any field (including lease areas) at the same time. Therefore, sowing opportunities within the lease areas would be based upon the prevailing soil water conditions of the wider crop field. Fertiliser was applied at sowing (100 kg $ha^{-1}$ of N) to remove nitrogen (N) as a constraint to production.

**Table 2.** Soil bulk density (SBD), lower limit (LL), drained upper limit (DUL), saturation (SAT) and saturated hydraulic conductivity (Ks) used in the simulations for field conditions, the lease area, and for the lease area after rehabilitation. For field conditions, hydraulic properties SBD, LL, DUL, and SAT were taken from the APSoil dataset (Dalgliesh and Foale, 1998), and Ks from Connolly et al. (2001). Data for the lease areas were adjusted based on field conditions as explained in the text. Data for rehabilitated areas use the same data as field conditions to 300 mm depth and lease areas' properties for below that depth. SBD is soil bulk density at drained upper limit (DUL).

| Depth range (mm) | SBD (g cm$^{-3}$) | LL (m$^3$ m$^{-3}$) | DUL (m$^3$ m$^{-3}$) | SAT (m$^3$ m$^{-3}$) | Ks (mm d$^{-1}$) |
|---|---|---|---|---|---|
| | | | Field conditions | | |
| 0-150 | 1.39 | 0.220 | 0.400 | 0.475 | 48 |
| 150-300 | 1.35 | 0.210 | 0.410 | 0.491 | 24 |
| 300-600 | 1.35 | 0.220 | 0.410 | 0.491 | 6 |
| 600-900 | 1.43 | 0.240 | 0.380 | 0.460 | 12 |
| 900-1200 | 1.44 | 0.260 | 0.380 | 0.457 | 12 |
| 1200-1500 | 1.45 | 0.260 | 0.370 | 0.453 | 12 |
| 1500-1800 | 1.45 | 0.260 | 0.370 | 0.453 | 12 |
| | | | Lease area | | |
| 0-150 | 1.49 | 0.236 | 0.405 | 0.438 | 6 |
| 150-300 | 1.45 | 0.226 | 0.415 | 0.453 | 6 |
| 300-600 | 1.45 | 0.236 | 0.415 | 0.453 | 4 |
| 600-900 | 1.51 | 0.253 | 0.384 | 0.430 | 6 |
| 900-1200 | 1.50 | 0.271 | 0.384 | 0.434 | 8 |
| 1200-1500 | 1.47 | 0.264 | 0.371 | 0.445 | 12 |
| 1500-1800 | 1.47 | 0.264 | 0.371 | 0.445 | 12 |
| | | | Lease area after rehabilitation | | |
| 0-150 | 1.39 | 0.220 | 0.400 | 0.475 | 48 |
| 150-300 | 1.35 | 0.210 | 0.410 | 0.491 | 24 |
| 300-600 | 1.45 | 0.236 | 0.415 | 0.453 | 4 |
| 600-900 | 1.51 | 0.253 | 0.384 | 0.430 | 6 |
| 900-1200 | 1.50 | 0.271 | 0.384 | 0.434 | 8 |
| 1200-1500 | 1.47 | 0.264 | 0.371 | 0.445 | 12 |
| 1500-1800 | 1.47 | 0.264 | 0.371 | 0.445 | 12 |

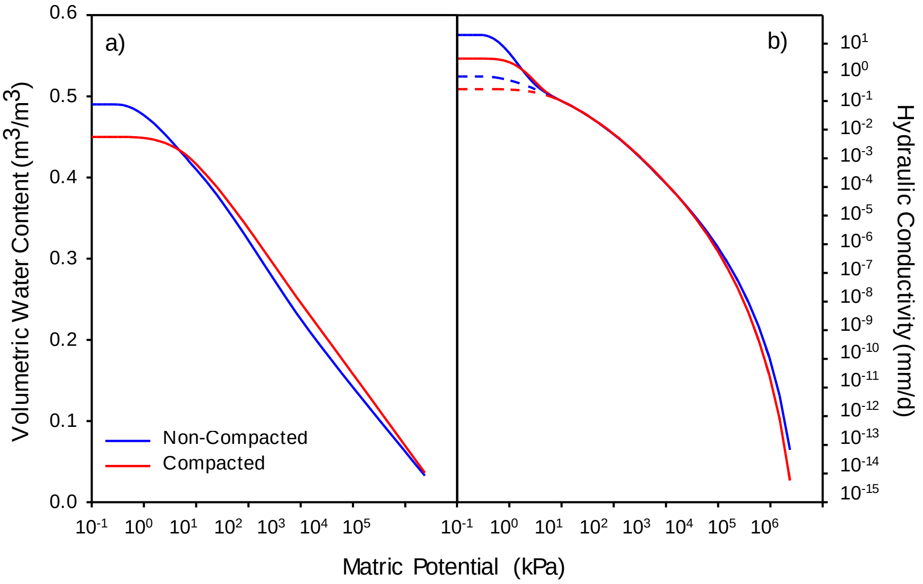



**Figure 5.** An example of the impact of parameter changes on: **(a)** water retention, and **(b)** hydraulic conductivity calculated by the SWIM3 model for a surface soil (depth range: 0-100 mm) used in this study. Note the reduced contribution of larger pores on water retention near saturation in (a), and in the relative difference between total hydraulic conductivity (solid lines) and micropore conductivity (dotted lines) in (b).

## 2.4 Statistical analyses

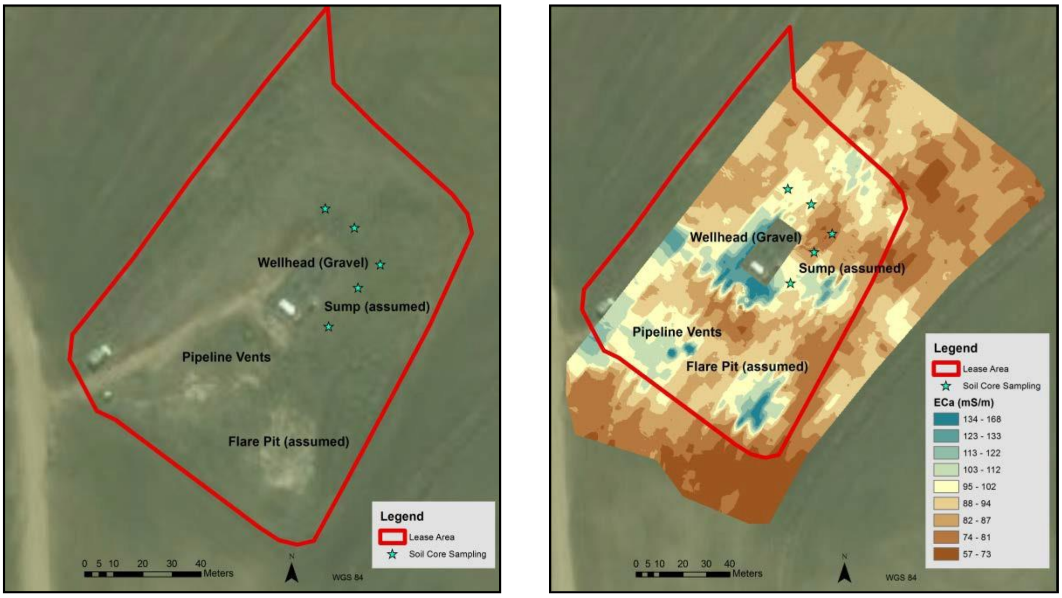
Statistical analyses were undertaken using GenStat Release 16$^{th}$ Edition (VSN International, 2013), and involved analysis of variance (ANOVA) and the least significant differences (LSD) to compare the means with a probability level of 5%. The analyses conducted were graphically verified by means of residual plots. Normalization of the data was not required except for saturated hydraulic conductivity data, which were Ln-transformed and subsequently subjected to statistical analysis.

# 3. Results

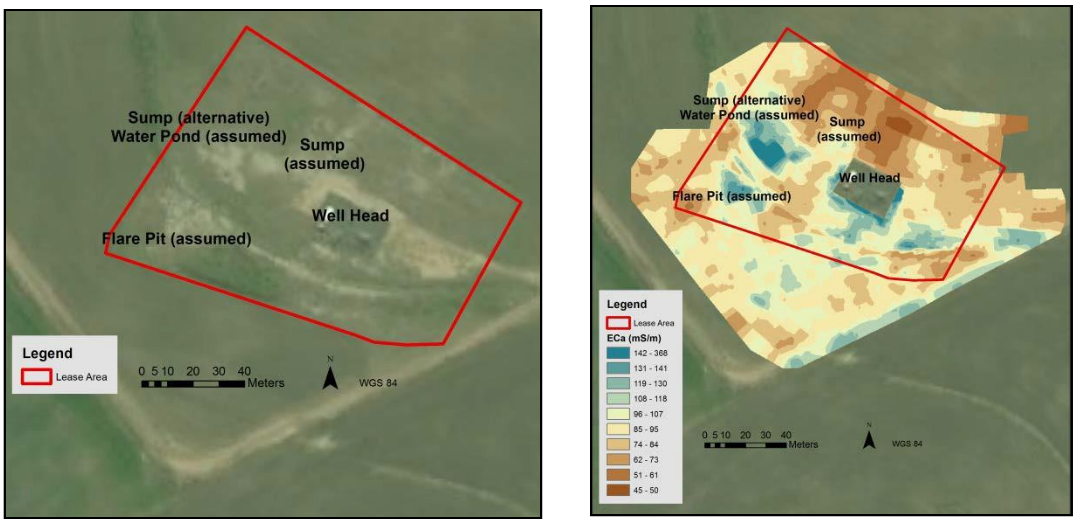
## 3.1 Spatial characterisation

Aerial images from Google Earth and EM-38 surveys produced on the case-study sites (Table 1) are shown in Figure 6. The aerial images show the sites shortly after drilling operations were completed, which enabled depicting features associated with soil disturbance during installation of wells. For example, the levee bank on the western border of Gilbert Gully 6, and the flare pits in Talinga 120 and 127, respectively. For all sites, the apparent electrical conductivity (ECa) within the lease areas, as determined by means of EM-38 image analysis, showed a significantly greater variability compared with the soil outside the lease area used as a control. In Talinga 120 and 127, features on the EM-38 images are less evident than in Gilbert Gully 6 and 7. This is possibly due to differences in soil types and soil conditions during the actual construction of wells, including levelling off the ground. In the proximity of well-head areas, ECa showed relatively high values (typically, >100 mS m$^{-1}$), which are in agreement with features observed on the aerial images and reflect the extent of disturbance on the sites. Due to the relatively high clay content of the soils (≥50%, w w$^{-1}$), differences in soil moisture content would have a significant influence on the ECa readings (Corwin and Lesch, 2005; Costa et al., 2014). This would explain the relatively higher values of ECa encountered in those areas where soil properties had been adversely affected during CSG establishment. Such changes in soil properties resulted in poor crop establishment (based on visual assessment of the sites), and therefore slightly higher moisture content accumulated in the soil profile within those affected areas. The relatively high ECa values (≥100 mS m$^{-1}$) observed within former sump areas are possibly due to salt accumulation from the wells, which also explains poor crop establishment hence reduced water uptake and slightly wetter soil profile in those areas. Such observations were possible due to the dry soil conditions (moisture content ≤25%, w w$^{-1}$) observed in all sites at the time that the surveys were conducted.

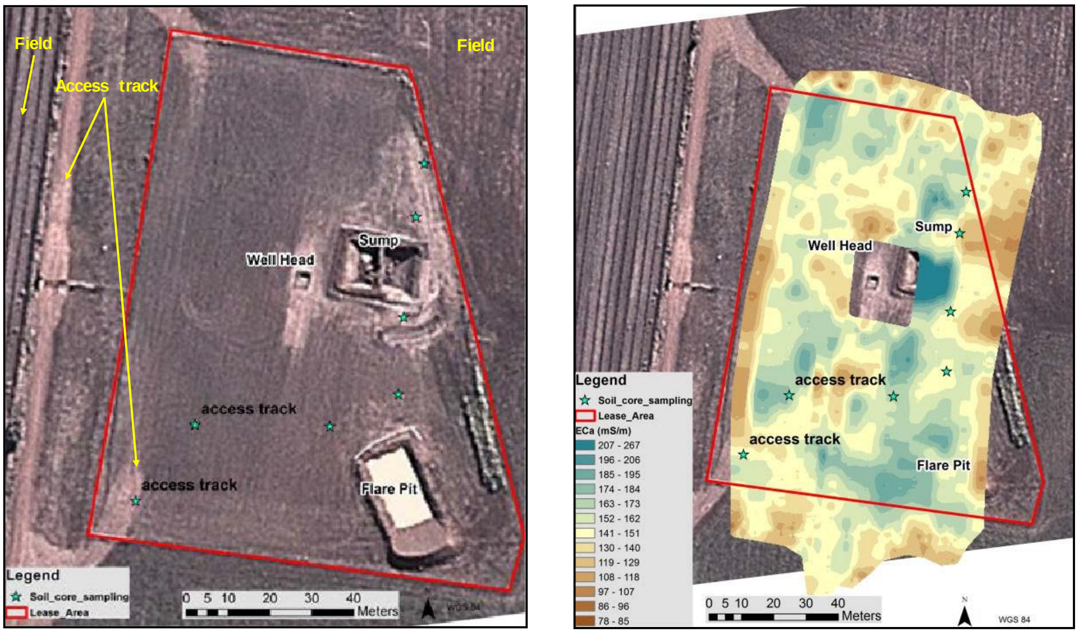
Since layout maps for lease areas were not available at the time of sampling, the EM-38 surveys and feature allocation were based on approximation. The EM-38 surveys were useful to depict and visualise features of the layout plan such as the flare pit, sump and pipelines, and access tracks. Hence, this technology is useful as a rapid assessment tool to identify areas of high impact from gas wells establishment and pipeline construction. The information derived from EM-38 surveys can be used for early diagnosis of impacts and may assist the decision-making as to whether corrective measures need to be undertaken following installation. These measures may be targeted only to affected areas, which will minimise the need for costly rehabilitation practices down the track; for example, when those areas, unable to revegetate properly, have suffered from erosion.


Wellhead (Gravel)
Sump (assumed)
Pipeline Vents
Flare Pit (assumed)
Legend
Lease Area
Soil Core Sampling
0 5 10 20 30 40 Meters
WGS 84
Wellhead (Gravel)
Sump (assumed)
Pipeline Vents
Flare Pit (assumed)
Legend
Lease Area
Soil Core Sampling
ECa (mS/m)
134 - 168
123 - 133
113 - 122
103 - 112
95 - 102
88 - 94
82 - 87
74 - 81
57 - 73
0 5 10 20 30 40 Meters
WGS 84

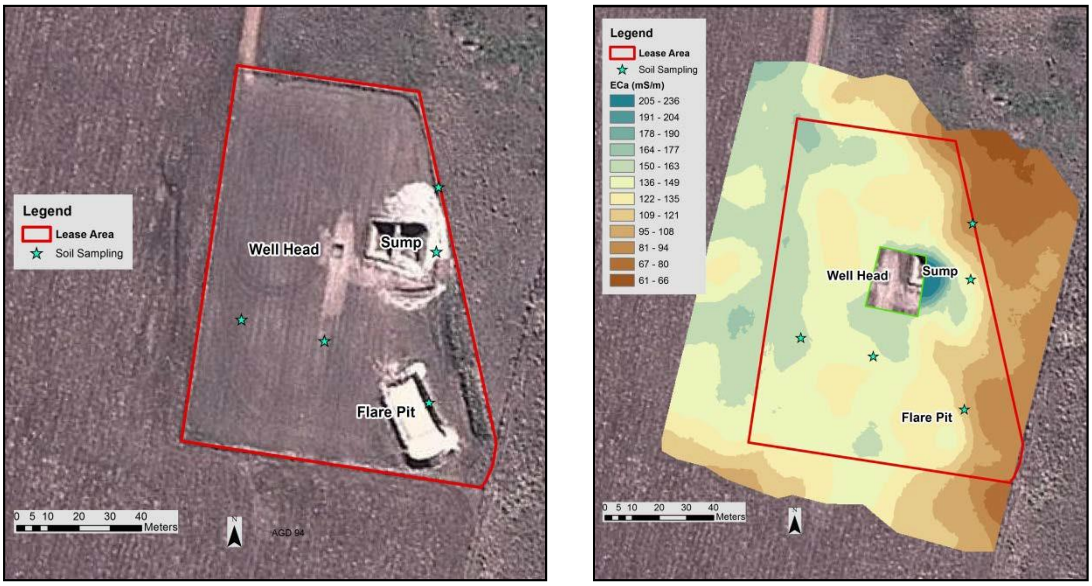
(a)


Sump (alternative)
Water Pond (assumed)
Sump (assumed)
Well Head
Flare Pit (assumed)
Legend
Lease Area
0 5 10 20 30 40 Meters
WGS 84
Sump (alternative)
Water Pond (assumed)
Sump (assumed)
Well Head
Flare Pit (assumed)
Legend
Lease Area
ECa (mS/m)
142 - 368
131 - 141
119 - 130
108 - 118
96 - 107
85 - 95
74 - 84
62 - 73
51 - 61
45 - 50
0 5 10 20 30 40 Meters
WGS 84

(b)




**(c)**

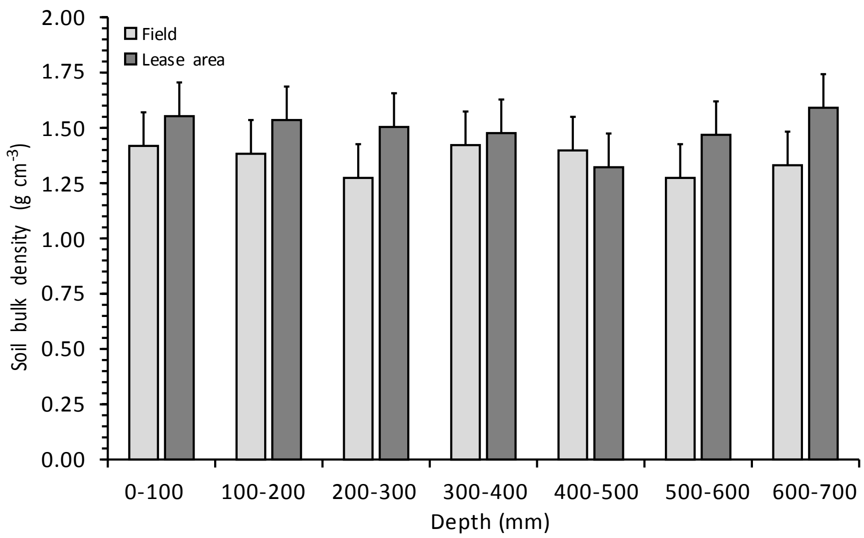



**(d)**

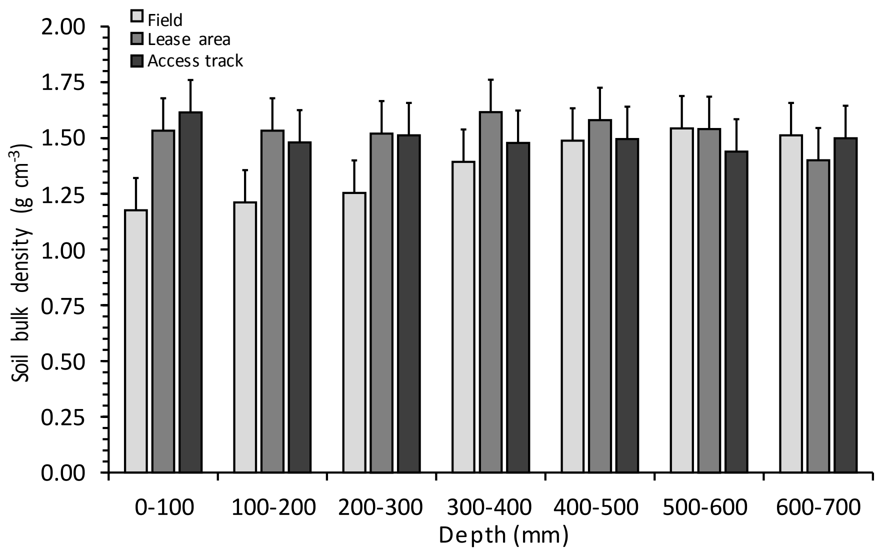
**Figure 6.** Aerial images (left, from Google Earth) and superimposed EM-38 surveys (right) produced on the four case-study sites (Table 1), **(a):** Gilbert Gully 6, **(b):** Gilbert Gully 7, **(c):** Talinga 120, **(d):** Talinga 127. ECa is apparent electrical conductivity (mS $m^{-1}$). Sampling points are indicated with a star.

## 3.2 Soil bulk density and strength

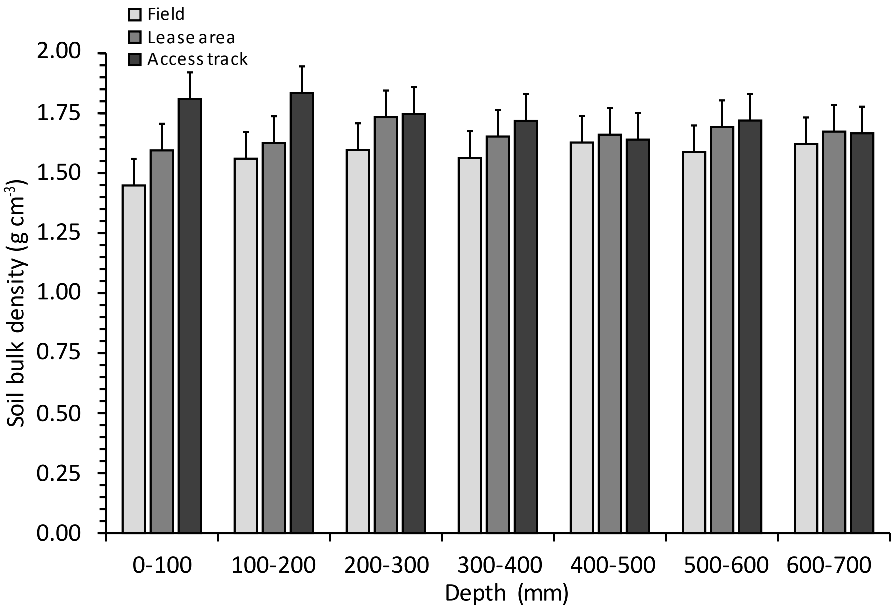
Measurements of soil bulk density (SBD) are shown in Figure 7. All sites exhibited significantly (P-values <0.05) higher SBD in lease areas compared with neighbouring fields, particularly, in the 0 to 400 mm depth range. On average, values of SBD encountered in field areas (range: 1.36 to 1.57 g $cm^{-3}$) were within the range reported in Rao et al. (1978) for Vertosols. Mean SBD values across all lease areas were in the range of 1.49 to 1.66 g cm$^{3}$. The access track at Talinga 120 showed higher ($P<0.05$) SBDs than the field or lease areas. However, this was mainly due to differences recorded in the top 0-200 mm of the soil profile, where the mean SBD was approximately 1.80 g cm$^{-3}$ (standard deviation: 0.03). At greater depths (>200 mm), both the lease area and the access track in Talinga 120 showed, on average, similar ($P>0.05$) values of SBD (range: 1.65 to 1.73 g cm$^{-3}$). Therefore, subsoil compaction within the lease area was comparable to that observed in the access track and significantly higher than the field condition. The relatively high values of SBD observed across all sites with increased soil depth are possibly due to the mechanical behaviour of Vertosols in response to changes in water content (compression caused by overburden weight and effect on matric potential) (Virgo and Munro, 1978). Soil bulk density as determined by means of the coated clod method (depth range: 0 to 200 mm) showed consistent results with those obtained with the hydraulic corer. Lease areas exhibited significantly higher ($P=0.02$) SBDs than field areas; mean values across all sites were 1.57 g cm$^{-3}$ (standard deviation: 0.09) and 1.46 g cm$^{3}$ (standard deviation: 0.05), respectively.



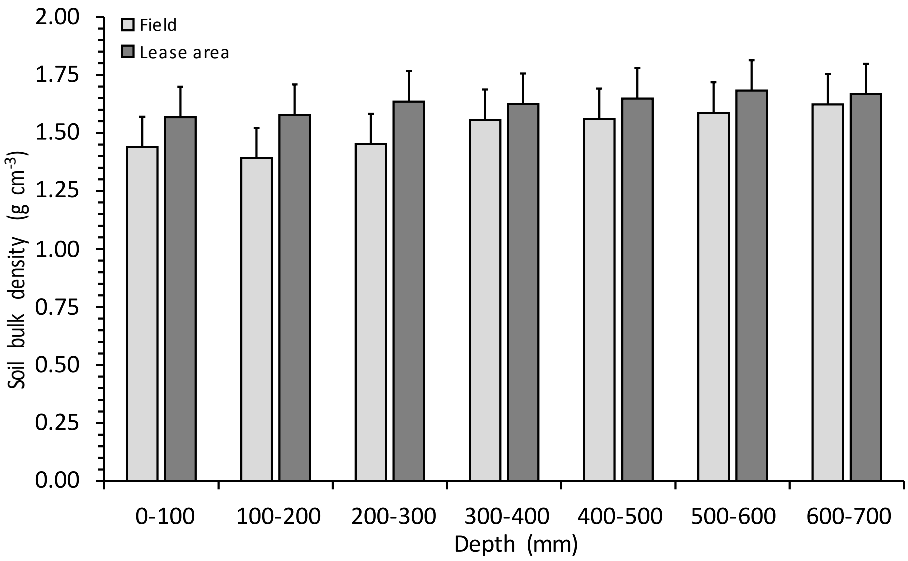

**(a)**




**(b)**




**(c)**




**(d)**

**Figure 7.** Soil bulk density measurements recorded at the four case-study sites (Table 1), **(a):** Gilbert Gully 6, **(b):** Gilbert Gully 7, **(c):** Talinga 120, and **(d):** Talinga 127. Error bars denote LSD values at 5% level. Use P<0.05 (field, lease, access track areas), P>0.05 (depth, except Talinga 127 : P<0 .05 ), and P> 0.05 (depth × areas, exceptGilbert Gully 7: P<0.05).

For all sites, total porosity ($\eta$) of soil was significantly higher (P-values <0.05) in the field (range: 40.7% to 48.8%) compared with lease areas (range: 37.3% to 44.1%) and access tracks (range: 35.5% to 43.3%), which is consistent with SBD data. Overall, $\eta$ values encountered at Gilbert Gully 6 and 7 were approximately 6.5% higher than those encountered at Talinga 120 and 127, which was observed in all three spatial areas investigated. Proctor test density values were 1.60 (moisture content: 20.5%, w $w^{-1}$) and 1.63 g $cm^3$ (moisture content: 22.5%, w $w^{-1}$) for Gilbert Gully and Talinga, respectively (P>0.05). Therefore, values of SBD encountered in the topsoil (0-200 mm) within-lease areas, relative to those obtained with the Proctor test, were on average 96% (standard deviation: 0.49) and 98% (standard deviation: 1.63) for Gilbert Gully and Talinga, respectively. However, in the field, SBD values recorded at the same depth range were also high (range: 81% to 89%) relative to those of the Proctor test, which suggests background soil compaction associated with standard farm practices. The above results are consistent with values of cone index recorded within-lease and field areas (Table 3). However, across all sites, differences in cone index between these areas appear to be higher than those corresponding to SBD, which is possibly due to increased soil strength in lease areas at low moisture contents (≈14.5%, w w$^{-1}$).

**Table 3.** Mean cone index (n=20, depth range: 0-575 mm) recorded at the four case-study sites (Table 1). MC is moisture content, SE is standard error of means, and LSD is the least significant difference (5% level).

| Parameter | --------- Mean cone index (kPa, depth range: 0-575 mm) --------- | | | | | ------- MC (%, w w$^{-1}$) ------- | |
|---|---|---|---|---|---|---|---|
| Site | Field | Lease area | P-value | LSD (5% level) | SE | Field | Lease area |
| Gilbert 6 | 1591 | 2550 | <0.001 | 217.7 | 78.4 | 14.64 | 14.63 |
| Gilbert 7 | 2123 | 2482 | 0.002 | 228.4 | 82.3 | 15.35 | 14.79 |
| Talinga 120 | 1763 | 3110 | <0.001 | 168.8 | 60.8 | 14.89 | 14.03 |
| Talinga 127 | 1198 | 1757 | <0.001 | 186.6 | 67.2 | 16.48 | 14.57 |

## 3.3 Hydraulic properties

Measurements of surface infiltration rates are shown in Table 4. There were no data collected for Talinga 127 due to the relatively dry soil conditions encountered at the site (excessive cracking), which made it impossible to perform the double-ring infiltrometer test. Therefore, surface infiltration data for Talinga 127 were excluded from the analyses and corresponding results could not be reported. Surface infiltration rates were significantly lower (P-values <0.05) in lease areas compared with measurements conducted in the field at all sites. Therefore, comparison of infiltration responses (Table 4) within-sites will yield significantly different infiltration rates ($I_t$) at any given time ($t$); except for Gilbert Gully 7 for $t$ >5 h, where the equation will yield marginally higher but not statistically different (P>0.05) infiltration rates in the lease area compared with the field. These results are consistent with those corresponding to measurements of saturated hydraulic conductivity (Ks), which reported lower Ks values in lease areas compared with field. In Talinga 120, differences in Ks between lease and field areas were significant (P=0.02); mean values were 0.7 mm h$^{-1}$ (standard deviation: 0.01) and 9.6 mm h$^{-1}$ (standard deviation: 16.5), respectively. In Gilbert Gully 7, differences in Ks between the two study areas were not significant (P=0.08). However, Ks recorded in the field was approximately 20 times higher than that observed in the lease area; mean values were 3.7 mm h$^{-1}$ (standard deviation: 5.2) and 0.2 mm h$^{-1}$ (standard deviation: 0.1), respectively. The variability recorded in Ks measurements, as denoted by the corresponding standard deviation values, helps explain the lack of significant statistical differences in the results.

**Table 4.** Equations describing the relationships between infiltration rate ($I_t$, mm h$^{-1}$) and time ($t$, h) for the case-study sites investigated (Table 1, except Talinga 127). Different (*) denote significantly different (P<0.05) infiltration rates within-sites at any given time, except Gilbert Gully 7 for $t$ >5 h (P>0.05 ).

| Site | Lease area | $R^2$ | Field area | $R^2$ |
|---|---|---|---|---|
| Gilbert Gully 6 | * $I_t = 17.31t^{-0.60}$ | 0.83 | ** $I_t = 35.35t^{-0.64}$ | 0.89 |
| Gilbert Gully 7 | * $I_t = 15.25t^{-0.67}$ | 0.76 | ** $I_t = 32.6t^{-1.15}$ | 0.94 |
| Talinga 120 | * $I_t = 5.08t^{-0.91}$ | 0.90 | ** $I_t = 24.71t^{-0.88}$ | 0.88 |

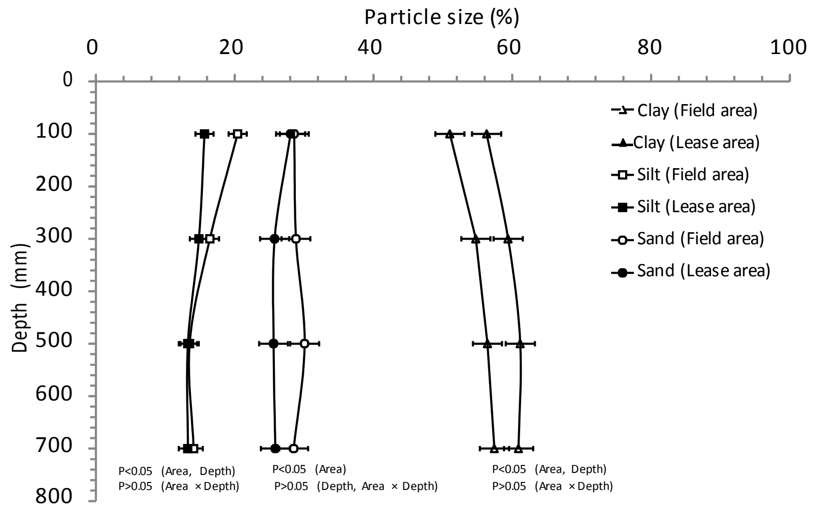
## 3.4 Physico-chemical characteristics

The physico-chemical characterisation of soils at the four case-study sites is summarised in Table 5. Soil textural analyses are shown in Figure 8, and distribution of cations both extractable and exchangeable, and CEC within the soil profile are shown in Figures 9 and 10, respectively. There were no differences (P-values >0.05) in SOM, soil pH and EC of soil in lease areas compared with fields at any site. SOM levels were within the range expected for Vertosols (e.g., Yule and Ritchie, 1980a). The Emerson test data indicated that all soils have relatively low (aggregate) strength to resist slaking and therefore are prone to structural breakdown. However, soil samples from lease areas recorded relatively poorer Emerson scores (i.e., moderate to severe) compared with samples from the fields (i.e., slight to moderate).

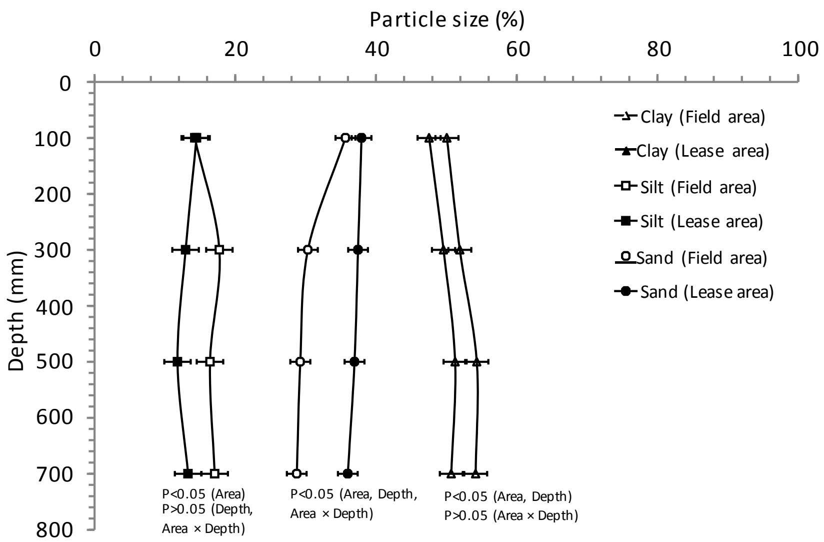
Similarly, all soils within-lease areas showed relatively higher susceptibility to dispersion, with larger number of samples exhibiting dispersion sub-classes 2 and 3 for type 2 and 3 aggregates (Table 5). In lease areas, the inherent susceptibility of soils to slaking and dispersion may have been enhanced by structural damage and mixing caused by vehicular traffic and soil manipulation during the construction phase. Overall, soil textural analyses showed significant differences (P-values <0.05) between field and lease areas for the three particle fractions and this was observed across all sites (Figure 8). In addition, field and lease areas showed consistently different (P-values <0.05) clay contents within the soil profile; except at Talinga 127 where clay distribution with depth in both spatial areas was comparable (P>0.05). These results are possibly associated with soil mixing during the course of the operations. Notice that the sampling points within lease areas were in the proximity of previously highly-disturbed zones such as flare pits and sumps (Figure 6), which helps explain differences in the results encountered for the two spatial areas investigated.

**Table 5.** Physico-chemical characterisation of soils in field and lease areas from the four case-study sites (Table 1). Different letters within-sites and depth ranges indicate that mean values are significantly different at a 95% confidence interval. The standard deviation (SD) is shown as ± the mean value. SOM is soil organic matter, and EC is electrical conductivity of soil. CROSS is cations ratio of soil structural stability. Aggregate stability (Emerson test) is reported as class (sub-class) followed by the number of samples (n) that showed equal rating within the same spatial area.

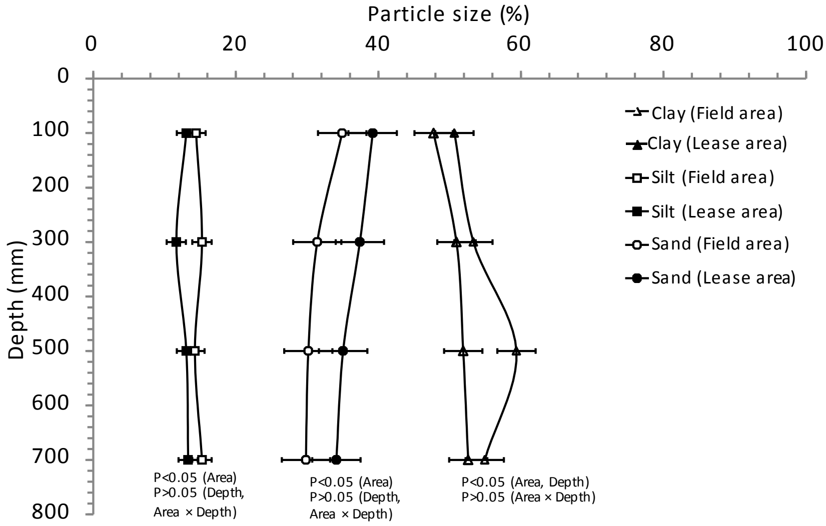
| Site | Depth | Gilbert Gully 6 | | Gilbert Gully 7 | | Talinga 120 | | Talinga 127 | |
|---|---|---|---|---|---|---|---|---|---|
| Parameter | (mm) | Field | Lease area | Field | Lease area | Field | Lease area | Field | Lease area |
| | | (%, w w$^{-1}$) | | | | | | | |
| SOM | 0-200 | 2.44$^{a}$ ±0.2 | 2.49$^{a}$ ±0.5 | 1.35$^{a}$ ±0.2 | 1.32$^{a}$ ±0.1 | 1.49$^{a}$ ±0.2 | 1.56$^{a}$ ±0.1 | 2.13$^{a}$ ±0.1 | 1.68$^{a}$ ±0.4 |
| Soil pH$_{(1:5)}$ | 0-200 | 7.44$^{a}$ ±0.3 | 7.65$^{a}$ ±0.7 | 8.40$^{a}$ ±0.3 | 8.37$^{a}$ ±0.6 | 8.84$^{a}$ ±0.3 | 8.65$^{a}$ ±0.8 | 8.91$^{a}$ ±0.4 | 7.97$^{a}$ ±0.5 |
| | 200-400 | 8.29$^{a}$ ±0.2 | 8.01$^{a}$ ±1.3 | 7.83$^{a}$ ±1.3 | 7.99$^{a}$ ±1.4 | 9.13$^{a}$ ±0.2 | 9.03$^{a}$ ±0.4 | 8.76$^{a}$ ±0.9 | 8.90$^{a}$ ±0.3 |
| | 400-600 | 7.01$^{a}$ ±0.9 | 7.87$^{a}$ ±1.4 | 6.51$^{a}$ ±1.6 | 7.00$^{a}$ ±1.4 | 9.04$^{a}$ ±0.3 | 9.01$^{a}$ ±0.2 | 8.10$^{a}$ ±1.8 | 8.87$^{a}$ ±0.4 |
| | 600-800 | 5.80$^{a}$ ±0.3 | 7.43$^{b}$ ±1.6 | 6.35$^{a}$ ±1.3 | 5.76$^{a}$ ±0.7 | 8.47$^{a}$ ±1.1 | 8.48$^{a}$ ±0.2 | 7.60$^{a}$ ±1.6 | 8.09$^{a}$ ±1.3 |
| | | (dS m$^{-1}$) | | | | | | | |
| EC of soil$_{(1:5)}$ | 0-200 | 0.05$^{a}$ ±0.01 | 0.21$^{a}$ ±0.1 | 0.16$^{a}$ ±0.01 | 0.38$^{b}$ ±0.2 | 0.18$^{a}$ ±0.04 | 0.22$^{a}$ ±0.1 | 0.24$^{a}$ ±0.05 | 0.21$^{a}$ ±0.05 |
| | 200-400 | 0.11$^{a}$ ±0.01 | 0.38$^{b}$ ±0.2 | 0.39$^{a}$ ±0.1 | 0.48$^{a}$ ±0.1 | 0.26$^{a}$ ±0.2 | 0.31$^{a}$ ±0.1 | 0.49$^{a}$ ±0.3 | 0.35$^{a}$ ±0.1 |
| | 400-600 | 0.24$^{a}$ ±0.03 | 0.46$^{b}$ ±0.2 | 0.61$^{a}$ ±0.05 | 0.58$^{a}$ ±0.1 | 0.44$^{a}$ ±0.3 | 0.50$^{a}$ ±0.1 | 0.83$^{a}$ ±0.5 | 0.54$^{b}$ ±0.1 |
| | 600-800 | 0.35$^{a}$ ±0.03 | 0.52$^{a}$ ±0.2 | 0.75$^{a}$ ±0.1 | 0.59$^{b}$ ±0.1 | 0.63$^{a}$ ±0.5 | 0.61$^{a}$ ±0.1 | 0.96$^{a}$ ±0.3 | 0.70$^{a}$ ±0.1 |
| CROSS | 0-200 | 0.36$^{a}$ ±0.66 | 0.63$^{a}$ ±0.52 | 0.75$^{a}$ ±0.71 | 2.24$^{a}$ ±1.16 | 0.03$^{a}$ ±0.09 | 0.05$^{a}$ ±0.01 | 1.35$^{a}$ ±0.69 | 0.87$^{a}$ ±0.12 |
| | 200-400 | 0.61$^{a}$ ±0.12 | 1.38$^{a}$ ±0.82 | 1.44$^{a}$ ±0.44 | 2.62$^{a}$ ±2.01 | 0.08$^{a}$ ±0.05 | 0.09$^{a}$ ±0.02 | 2.25$^{a}$ ±1.04 | 2.38$^{a}$ ±0.97 |
| | 400-600 | 0.87$^{a}$ ±0.34 | 1.26$^{a}$ ±0.88 | 2.23$^{a}$ ±0.80 | 1.94$^{a}$ ±0.36 | 0.12$^{a}$ ±0.07 | 0.14$^{a}$ ±0.03 | 4.82$^{a}$ ±2.89 | 4.68$^{a}$ ±1.82 |
| | 600-800 | 1.38$^{a}$ ±0.53 | 2.21$^{b}$ ±0.35 | 4.97$^{a}$ ±3.02 | 2.14$^{b}$ ±0.31 | 0.16$^{a}$ ±0.08 | 0.18$^{a}$ ±0.03 | 6.22$^{a}$ ±3.33 | 5.09$^{a}$ ±2.87 |
| Emerson test | 0-200 | 3(2), n=2 | 2(2), n=1 | 3(2), n=3 | 3(1), n=1 | 3(1), n=3 | 1, n=1 | 3(1), n=2 | 2(1), n=1 |
| | 0-200 | 3(3), n=1 | 3(3), n=2 | - | 3(3), n=2 | - | 3(3), n=2 | 3(2), n=1 | 2(2), n=1 |
| | 0-200 | - | - | - | - | - | - | - | 3(3), n=1 |


Particle size (%)
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
Depth (mm)
Clay (Field area)
Clay (Lease area)
Silt (Field area)
Silt (Lease area)
Sand (Field area)
Sand (Lease area)
P<0.05 (Area, Depth)
P>0.05 (Area × Depth)
P<0.05 (Area)
P>0.05 (Depth, Area × Depth)
P<0.05 (Area, Depth)
P>0.05 (Area × Depth)

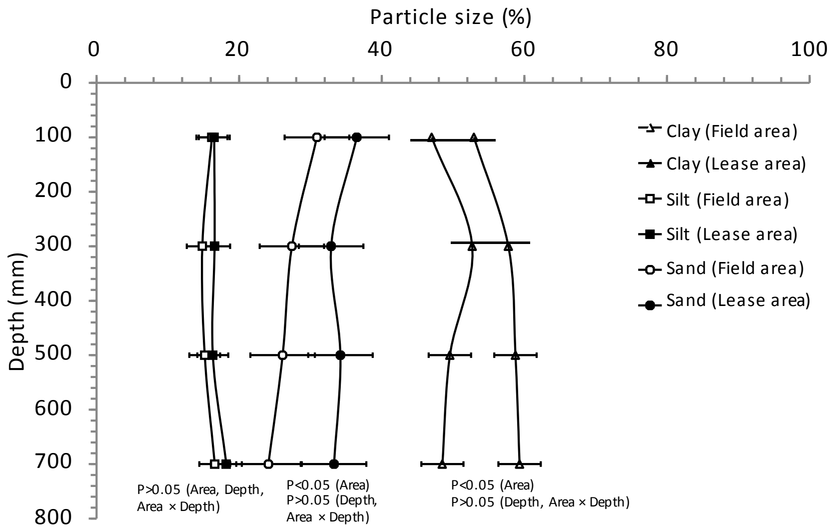
**(a)**


Particle size (%)
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
Depth (mm)
Clay (Field area)
Clay (Lease area)
Silt (Field area)
Silt (Lease area)
Sand (Field area)
Sand (Lease area)
P<0.05 (Area)
P>0.05 (Depth, Area × Depth)
P<0.05 (Area, Depth, Area × Depth)
P<0.05 (Area, Depth)
P>0.05 (Area × Depth)

**(b)**



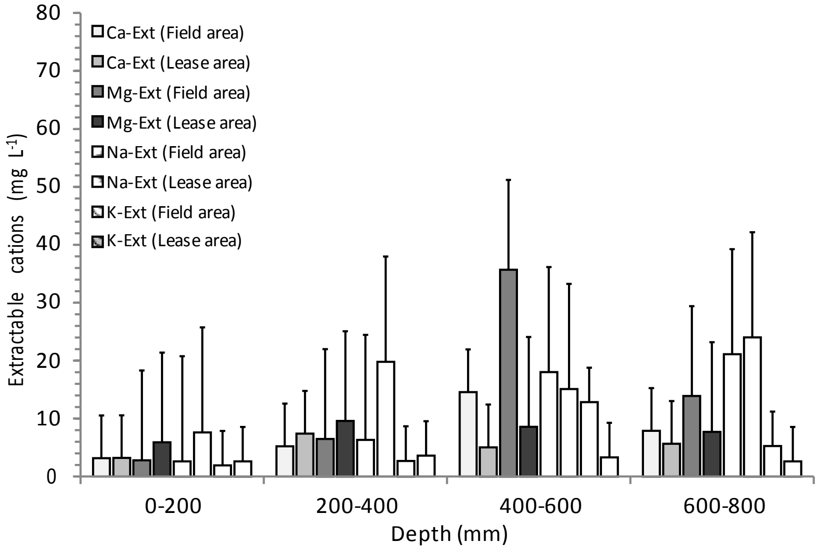

**(c)**




**(d)**

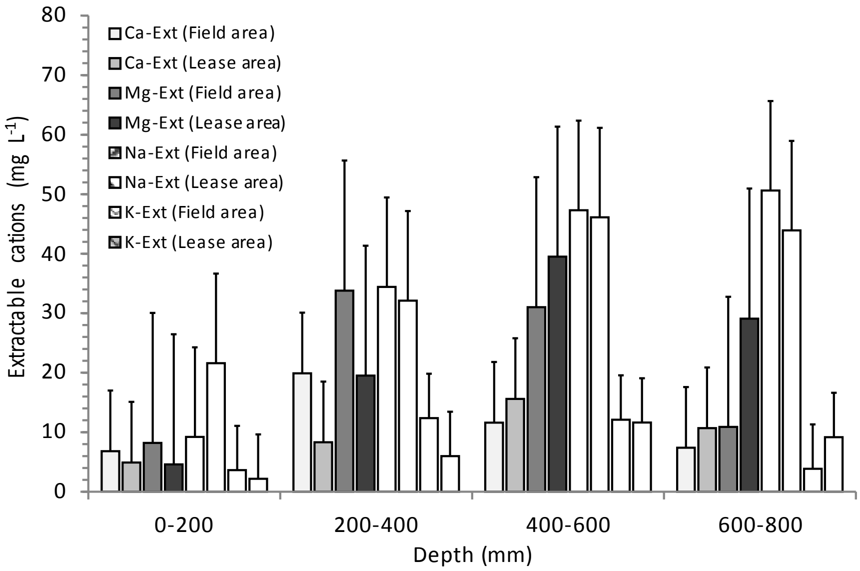
**Figure 8.** Particle size composition in the soil profile determined at the four case-study sites, **(a):** Gilbert Gully 6, **(b):** Gilbert Gully 7, **(c):** Talinga 120, and **(d):** Talinga 127. Error bars denote LSD values at 5% level. Soil fractions are: clay (<2 µm), silt (2 -20 µm), and sand (>20 µm).

Overall, extractable cations recorded in field were comparable (P-values >0.05) to levels observed in lease areas in all sites, except at Talinga 120, which exhibited marginally higher (P-values <0.05) concentrations in samples collected from the lease area (Figure 9). Exchangeable cations recorded in field and lease areas were similar (P-values >0.05) across all sites (Figure 10). Concentrations of Ca and Mg, and their distribution at depth varied relative to the concentration of Na, which was expected.



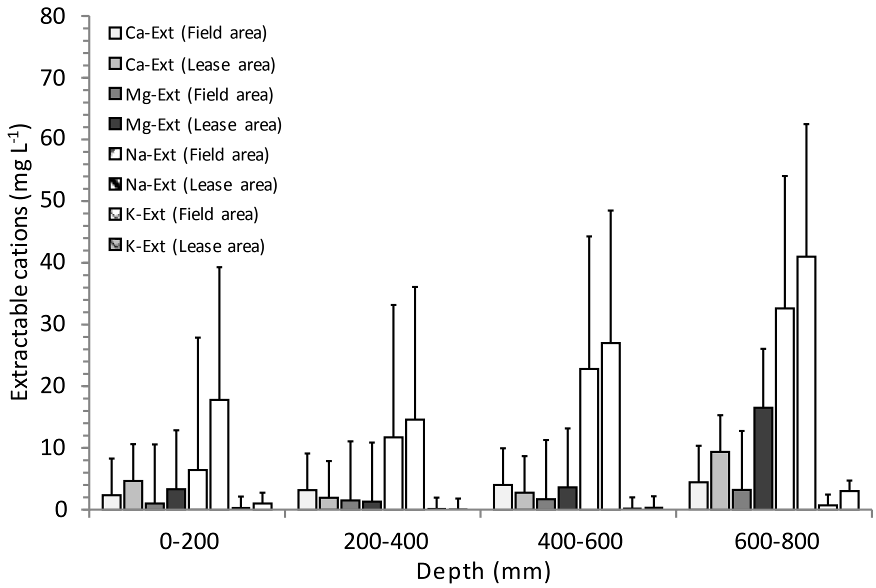
80
70
60
50
40
30
20
10
0
Ca-Ext (Field area)
Ca-Ext (Lease area)
Mg-Ext (Field area)
Mg-Ext (Lease area)
Na-Ext (Field area)
Na-Ext (Lease area)
K-Ext (Field area)
K-Ext (Lease area)
Extractable cations (mg L-1)
0-200
200-400
400-600
600-800
Depth (mm)


**(a)**

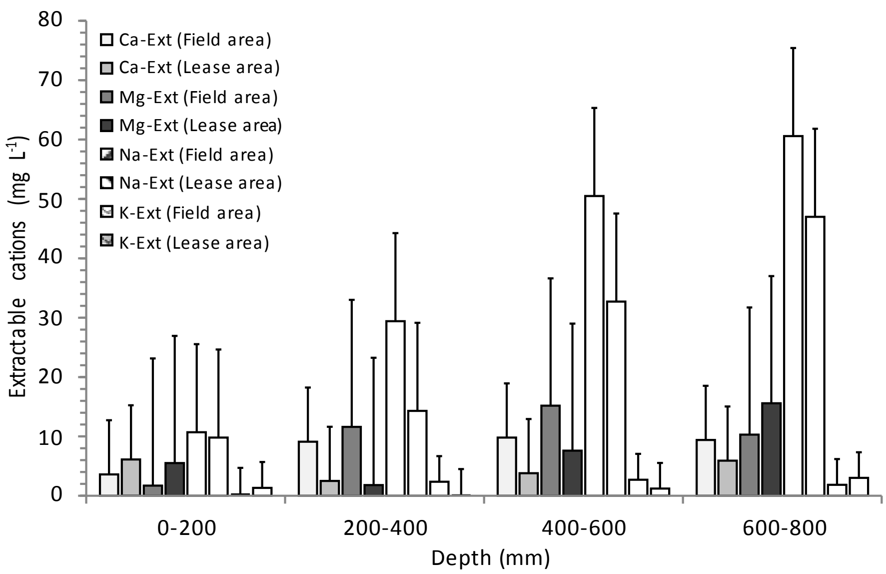


80
70
60
50
40
30
20
10
0
Ca-Ext (Field area)
Ca-Ext (Lease area)
Mg-Ext (Field area)
Mg-Ext (Lease area)
Na-Ext (Field area)
Na-Ext (Lease area)
K-Ext (Field area)
K-Ext (Lease area)
Extractable cations (mg L-1)
0-200
200-400
400-600
600-800
Depth (mm)


**(b)**

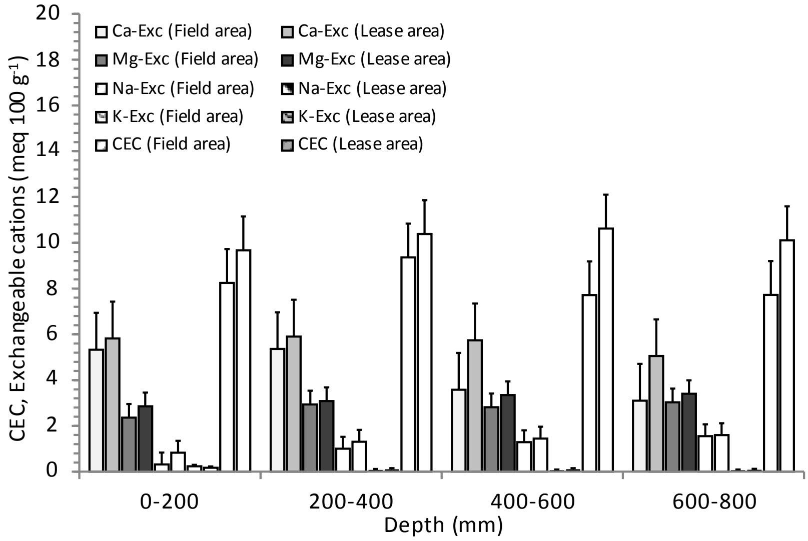



**(c)**



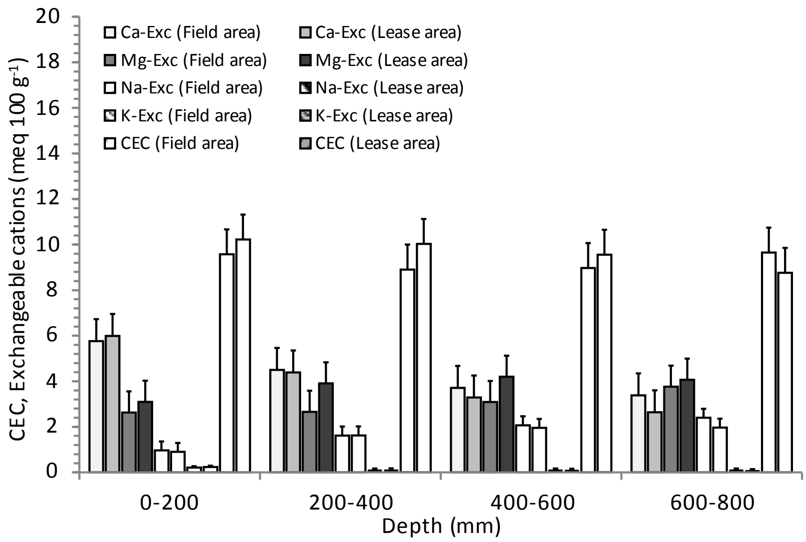

**(d)**

**Figure 9.** Extractable cations in the soil profile determined at the four case-study sites, **(a):** Gilbert Gully 6, **(b):** Gilbert Gully 7, **(c):** Talinga 120, and **(d):** Talinga 127. Error bars denote LSD values at 5% level. Use LSD values to compare the same cation between-spatial areas.



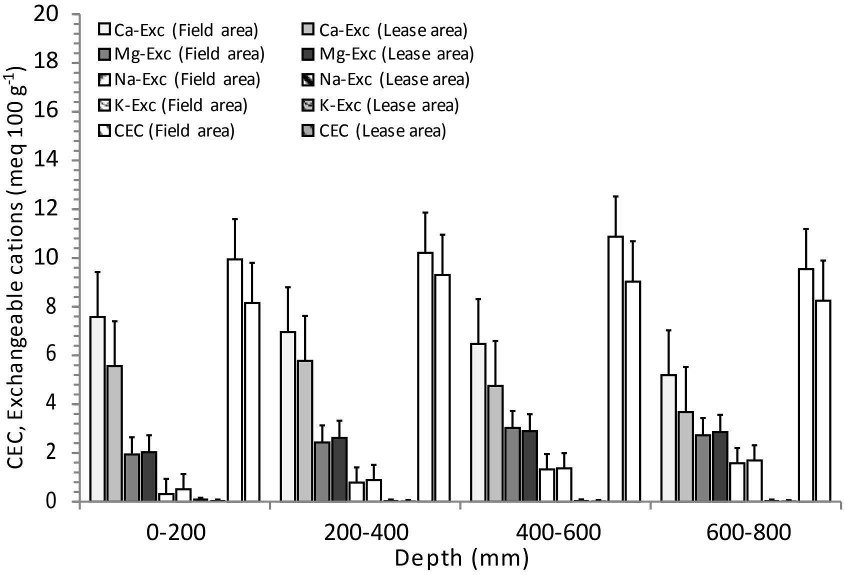
Ca-Exc (Field area)
Ca-Exc (Lease area)
Mg-Exc (Field area)
Mg-Exc (Lease area)
Na-Exc (Field area)
Na-Exc (Lease area)
K-Exc (Field area)
K-Exc (Lease area)
CEC (Field area)
CEC (Lease area)
CEC, Exchangeable cations (meq 100 g-1)
0
2
4
6
8
10
12
14
16
18
20
0-200
200-400
400-600
600-800
Depth (mm)


**(a)**

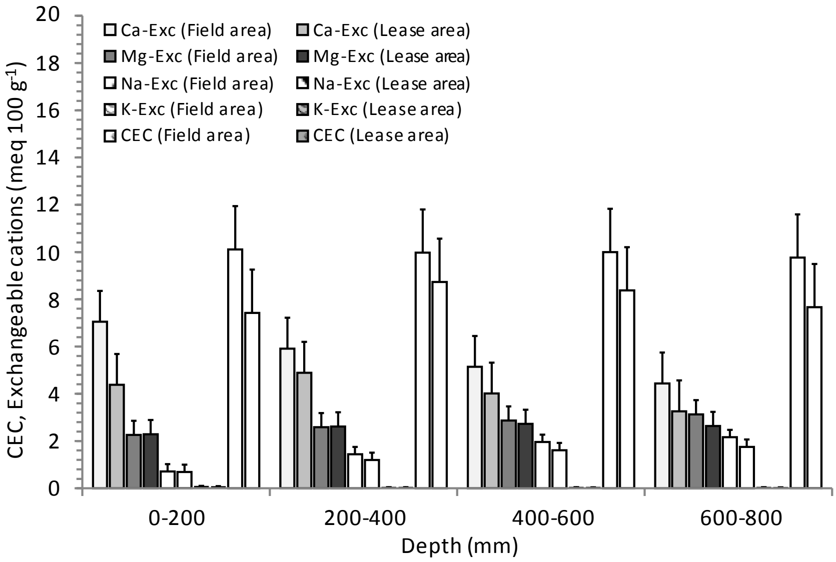


Ca-Exc (Field area)
Ca-Exc (Lease area)
Mg-Exc (Field area)
Mg-Exc (Lease area)
Na-Exc (Field area)
Na-Exc (Lease area)
K-Exc (Field area)
K-Exc (Lease area)
CEC (Field area)
CEC (Lease area)
CEC, Exchangeable cations (meq 100 g-1)
0
2
4
6
8
10
12
14
16
18
20
0-200
200-400
400-600
600-800
Depth (mm)


**(b)**




**(c)**




**(d)**

**Figure 10.** Exchangeable cations in the soil profile determined at the four case-study sites, **(a):** Gilbert Gully 6, **( b):** Gilbert Gully 7, **(c):** Talinga 120, and **( d):** Talinga 127. CEC is cation exchange capac ity of soil. Error bars denote LSD values at 5% level. Use LSD value to compare the same cations between-spatial areas.

Figure 11 shows that in all soils ESP increases with increase in depth ($P<0.05$), which is consistent with values of soil pH reported in Table 5. For Australia, Northcote and Skene (1972) proposed the following sodicity rating based on the soil ESP value: <6% (non-sodic), 6%-14% (marginally sodic to sodic) and >14% (strongly sodic). Based on these categories, all soils may be considered as marginally sodic to sodic in the 0-200 mm depth interval and strongly sodic at greater depths. All sites reported ESP values ≥14% at depths greater than approximately 500 mm. Rengasamy and Olsson (1991) define the critical ESP value in relation to soluble salt levels because the electrolyte concentration in the soil solution offsets the dispersive effect of exchangeable Na.

The critical ESP above which dispersion occurs is dependent on the EC of the soil-water solution and the amount of energy applied to the soil (Hazelton and Murphy, 2013). Dispersion caused by rainfall may be observed in soils with ESP of 3% or lower because of the low EC of rain water coupled with raindrop impact on the soil surface (Hazelton and Murphy, 2013). The topsoil in Gilbert Gully 6 showed higher ESP in the lease area compared with the field, which suggests placement (e.g., layer inversion or mixing) of Na-rich material in the upper part of the soil profile (0-300 mm deep). To a lesser extent, these changes in ESP were also observed in Talinga 120 in the 0-300 mm depth interval. On average across all sites and spatial areas, and based on the range of clay contents encountered in the soils investigated, soil salinity (Table 5) was rated low to medium (EC <0.55 dS $m^{-1}$) for the 0-400 mm depth interval, and medium to high (EC between 0.55 and 1 dS $m^{-1}$) for the 400-800 mm depth interval (Shaw et al., 1987). Overall, soil salinity does not appear to have changed significantly within lease areas since values of EC were comparable to those observed in the surrounding fields (Table 5).

CROSS calculations did not yield significant differences (P>0.05) between different spatial areas. However, at Gilbert Gully 6 and 7, CROSS values were slightly higher in lease areas compared with fields (Table 5). There exists a positive correlation between the percentage of dispersed clay and CROSS (Rengasamy and Marchuk, 2011). Therefore, higher soil dispersion (lower structural stability) may be observed in lease areas compared with fields, which is consistent with the results derived from the Emerson test. There also exists a negative correlation between hydraulic conductivity and CROSS (Rengasamy and Marchuk, 2011), which suggests reduced internal drainage in the lease areas of Gilbert Gully 6 and 7 compared with fields. Given the sodic nature of the subsoil of the sites investigated (Figures 10 and 11), reductions in hydraulic conductivity (impaired drainage) will occur to a greater extent in situations where exchangeable Mg is higher than Ca (Emerson and Smith, 1970).

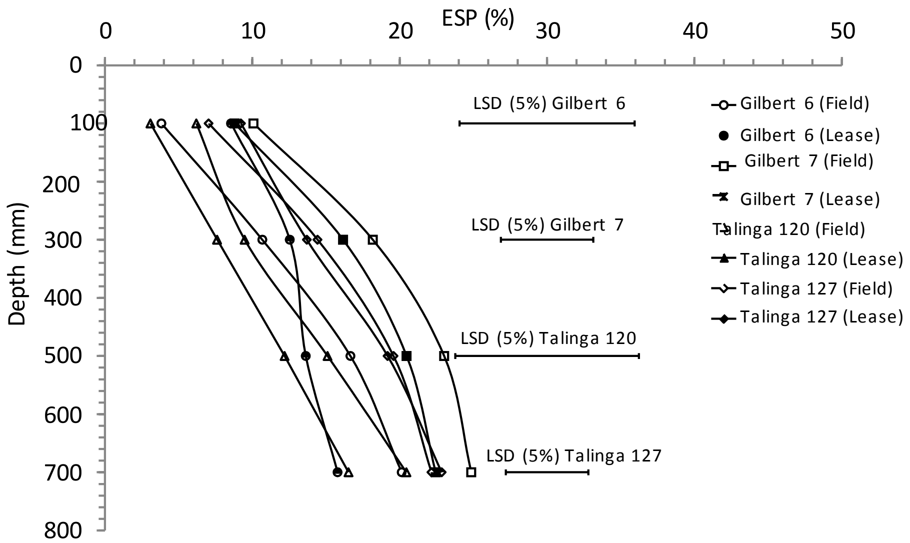



**Figure 11.** Exchangeable Na percentage (ESP) in the soil profile determined at the four case-study sites. Error bars denote LSD values at 5% level. Use P<0.05 (depth), P<0.05 (spatial area, except Gilbert 6 and Talinga 127: P>0.05), and P>0.05 (spatial area × depth).

## 3.5 Modelling of crop performance

Cumulative probabilities of simulated grain yield for 115 years of wheat production on a grey Vertosol at Chinchilla are shown in Figure 12a. Results are presented for the field area (control), inside the lease area after CSG-related compaction, and for a rehabilitated lease area. Median yield was reduced by 53% within the lease area when compared to yields within the surrounding field. Absolute yield reductions were similar across the entire yield distribution and therefore relative losses were higher for lower yielding seasons. Hence, relative yield losses were 32% and 61% for top and bottom deciles. Radford et al. (2007) measured a 43% yield loss for maize in the first year after successive compaction events with a 10 Mg axle load on a grey Vertosol. This level of compaction had resulted in increased penetration resistance to that measured in this report and used in this simulation study. Simulations for rehabilitated soil suggest that cultivation of the surface 300 mm would be adequate to overcome the impacts of soil damage due to compaction in most seasons. Possible reasons for these crop and soil interactions are examined in the following paragraphs.

Yield reductions will be due to reduced water supply, which in turn are determined by changes in soil water infiltration and storage, and the crop's ability to extend a root system to access that water. Such a response to compaction is discussed in several studies (e.g., Barraclough and Weir, 1988; Ramos et al., 2010). Other possible effects on yield not considered in the modelling are impaired germination due to increased soil mechanical strength and subsequent reduction of plant stand (Hadas et al., 1985; Radford et al., 2000). Figure 12b shows that the model predicts a reduction in median rooting depth of approximately 340 mm. This reduction is relatively consistent across seasons; except in wetter seasons during which deeper infiltration of water allows roots to extend to nearly 1800 mm in the soil profile. However, in lease areas roots do not extend past 1200 mm deep because water infiltration is restricted by compaction and soil strength remains high (>2000 kPa) at that depth (Bengough and Mullings, 1990). These responses also agree with those observed in previous studies on grey Vertosols, which showed reduction in rooting depths to approximately 300 mm in soils affected by compaction (Radford et al., 2001).

Simulations for the rehabilitated soil suggest that much of the reduction in rooting depth is due to reduced depth of soil water storage during the preceding fallow (Figure 12b). In these simulations, increased soil strength below the depth of rehabilitation have little impact, suggesting that increased infiltration allows deeper water storage, which then facilitates deeper root growth into the soil profile. The importance of increased infiltration is further demonstrated in Figure 13a. Soil water storage at sowing was significantly lower in simulations for the compacted lease area. Median soil water storage was approximately 100 mm lower under compacted conditions. Radford et al. (2007) observed a similar decrease in sowing soil moisture in the first year after successive compaction events with a 10 Mg axle load on a grey Vertosol. Figure 13b shows that this decrease in soil water content can be accounted for by the increase in annual runoff after compaction (≈110 mm). Rehabilitation allows for improved water infiltration, which facilitates soil water storage and increases rainfall use efficiency, which subsequently translates into increased crop yield.

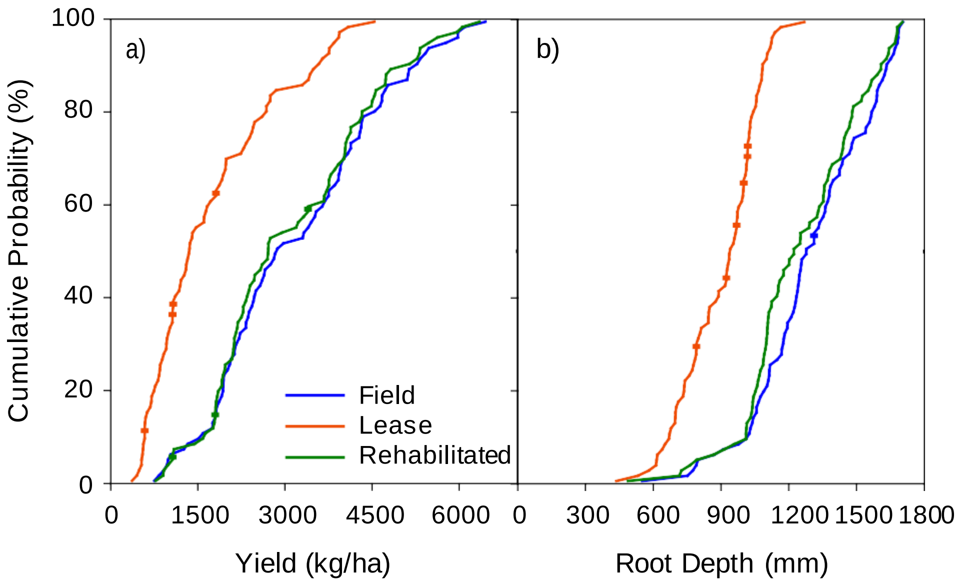



**Figure 12.** Cumulative probability distributions for **(a)** grain yield of wheat, and **(b)** rooting depth for 115 years of simulated wheat production on a grey Vertosol at Chinchilla for normal field conditions, soil after CSG-related compaction, and compacted soil that has been cultivated to a depth of 300 mm.

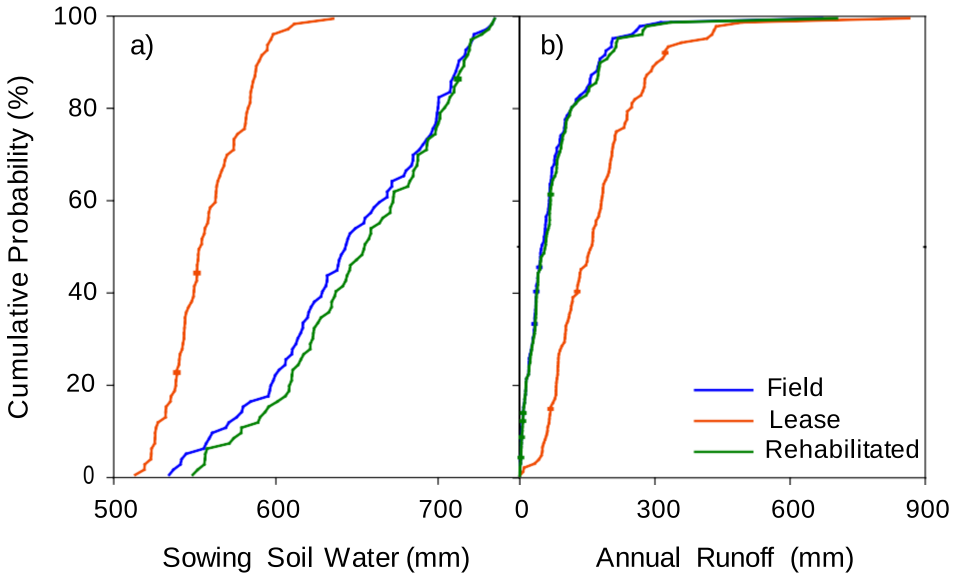



**Figure 13.** Cumulative probability distributions for **(a)** soil water availability at sowing, and **(b)** annual runoff for 115 years of simulated soil water dynamics on a grey Vertosol at Chinchilla for normal field conditions, soil after CSG-related compaction, and compacted soil that has been cultivated to a depth of 300 mm.

# 4. Discussion

Examination of soil chemical properties from the four case-study sites indicates that these were affected to a limited extent by development of CSG infrastructure. However, a general requirement is for careful manipulation of Na-rich subsoil (ESP ≥10% observed at depths ≥300 mm, Figure 11), and avoidance of soil mixing and layer inversion. There is evidence from one site (Talinga 120) showing increased ESP in the lease area compared with measurements conducted in the field. Such a soil disturbance can cause poor crop establishment and consequently enhance runoff and erosion due to reduced ground cover (Silburn, 2011). Infiltration rates observed in field areas were comparable to those measured by Krantz et al. (1978) on Vertosols. Solution of infiltration equations from field areas (Table 3) will yield terminal infiltration rates of similar order to those obtained by Jewitt et al. (1979) in similar soils but higher ($P<0.05$) than in lease areas. In situations where the concentration of Na in soil exceeds that of Ca (e.g., Figure 9c-d), crop nutritional constraints may occur (Naidu and Rengasamy, 1993). Therefore, correction of sodicity is required to improve chemical fertility status and application of N fertiliser will ensure high biomass C, which needs to be returned to the soil to improve SOM and structural stability (Oades, 1984; Naidu and Rengasamy, 1993). The use of nitrate-based fertilisers (e.g., calcium ammonium nitrate) in situations of relatively high soil pH is preferable to ammonium-based fertilisers (e.g., urea) to increase use efficiency (Mengel and Kirkby, 1987). Land application of biosolids or compost are known to be effective in restoring SOC levels and accelerating regenerative processes in similarly disturbed soils such as in reclamation of mine sites (Ussiri and Lal, 2005; Silva et al., 2013; Pedrol et al., 2014). Build-up of SOC increases aggregate stability and soil structural development (Watts and Dexter, 1997; Bronick and Lal, 2005). Legumes (nitrogen-fixing plants) play an important role in restoring soil fertility properties and assisting revegetation of reclaimed land (Ruthrof, 1997).

Simulated impacts of CSG-related activity on soil water dynamics, crop growth and yield were consistent with previous soil compaction studies conducted on grey Vertosols in Queensland (e.g., Radford et al., 2000). Crop yields are likely to be reduced, on average, by approximately 50% immediately after CSG-related compaction within the lease area surrounding a CSG well. Vertosols are well known for their shrink-swell behaviour and to some extent have the ability to repair themselves over time as the soil undergoes a series of wetting and drying cycles (Yule and Ritchie, 1980a-b; Chinn and Pillai, 2008; Dinka et al., 2013). Crop growth facilitates this process via 'biological tillage' as the extraction of water by the crop accelerates soil shrinkage, cracking and opening-up of previously compacted soil (Virgo, 1981; Pillai and McGarry, 1999). Shrinkage is not necessarily affected by severe compaction; however, formation of cracks occurs at increasingly lower rate with increasing soil compaction, which is due to reduced root growth and function under such condition (Batey and McKenzie, 2006; Andersen et al., 2013). In the subsoil, compaction is aggravated by the in-filling of open cracks with topsoil during a dry period; when the soil is re-wetted, the natural swelling compresses the soil between the in-filled cracks thereby increasing compaction (Smart, 1998; Batey and McKenzie, 1999). This behaviour provides a possible explanation to the relatively high values of SBD observed in the subsoil (>300 mm deep), particularly, within lease areas (Figures 7a-d). It also agrees with previous studies, which showed that amelioration of soil compaction can take more than five years on Vertosols (Radford et al., 2007). Similar observations were made in several studies conducted on clay soils although with less shrinking-swelling capacity (e.g., Gameda et al., 1987; Gameda et al., 1994). The return interval for work involving rigs and other heavy CSG equipment is well within this window. Thus, it is likely that without intervention (deep loosening) there are little or no opportunities for soil repair through natural processes during the operational phase of wells.

In land restoration, soil damage due to compaction is often coupled with structural degradation, therefore, rehabilitation is required (Spoor, 2006). Whilst correcting soil compaction problems without significant loss of load-bearing strength would be desirable, in practice it is difficult to attain (Spoor and Foot, 1998). In such situations, general soil loosening with tine implements may be recommended, and where structural degradation has also occurred the soil has to be broken down into smaller units to enable roots to penetrate it and assist regenerative processes (Spoor and Godwin, 1981; Spoor, 2006). If compaction exists at depths greater than about 450 mm, which has been observed within lease areas and access tracks (Figures 7b-c); it is expensive (energy-demanding), and cumbersome, to remove that compaction (Godwin et al., 1984; Spoor et al., 2003; Spoor, 2006; Moitzi et al., 2014). Therefore, the loosening depth should be defined to be equivalent to the root zone depth needed to withstand soil moisture deficits that may occur in the area (Spoor, 2006). In defining this depth, changes in soil moisture content in deeper layers of the soil profile need to be observed because of the compression effect on matric potential (Virgo and Munro, 1978). In agreement with observations reported in other studies (e.g., Radford et al., 2001; Li et al., 2008), APSIM simulations conducted for the sites investigated showed that the main impact of soil compaction is through reduction in hydraulic conductivity and water infiltration, and that restoring the soil to depths between 300 to 350 mm through cultivation may be sufficient to return the lease area to profitable crop production.

Subsoiling needs to be performed below the compacted layer and with the correct moisture conditions to ensure sufficient soil fissuring is created (Spoor, 2006). Care must be exercised to ensure that alleviation of existing compaction does not create deeper compaction, which may be achieved by avoiding traffic loads after loosening tillage operations were completed (Chamen et al., 2003; Spoor et al., 2003). The risk of subsequent soil recompaction is also high in soils with low structural stability and when operations are conducted under wet (i.e., above friable consistency) soil conditions (Spoor and Foot, 1998). Spoor (2006) suggests that during such operations, the movement of structural units should be minimised so that sufficient fissuring is created but without significant loss of load-bearing strength. In situations where deeper soil loosening is needed, the approach developed at Cranfield University Silsoe (United Kingdom) may be applied (Spoor and Foot, 1998). This approach consists of working progressively at depth increments of about 150 mm with multiple passes of the tine implement (e.g., 3 to 5 passes with a subsoiler) but ensuring that the tractor traffics on the same path in subsequent passes. The traffic lane created should remain undisturbed until the desired loosening is achieved on the final pass performed at the maximum depth (e.g., 600 or 700 mm). Loosening of the tractor path is performed in a single pass by fitting the subsoiler with shallower tines leading deeper tines, which work in the wheelway (Spoor and Foot, 1998; Spoor, 2006). Alternatively, shallower leading and deeper following tines may be fitted to the frame of the subsoiler to enable working at, for example, three different depths in a single pass (Spoor, 2006). Optimal arrangement of tines on the subsoiler's frame and practical considerations for working depth are discussed in Spoor and Godwin (1978) and Godwin et al. (1984). Diagnosis of soil compaction and recommended management practices relevant to agricultural soils are also given in the SoilPack Manual (Daniells et al.,1996).

Owing to difficulties often encountered in performing deep tillage operations successfully, amelioration of compaction through the use of plant species capable of penetrating densified soil layers is mentioned in several studies (e.g., Dexter, 1991; Materechera et al., 1992). Biopores created following the decay of roots in compacted layers will facilitate water movement and gaseous exchange in the soil profile, and will enable root growth of subsequent crops (Goss and Watson, 2003). The reader is referred to studies by Materechera et al. (1993), Atwell (1993) and Clark et al. (2003), which deal more specifically with the ability of roots of different crop types (and varieties) to penetrate compacted soil layers. Fertilisation practices, such as localised placement, are reported to influence roots' responses to compaction in winter cereal crops (Pfeifer et al.,2014).

The APSIM simulation analyses were conducted to capture the impact of soil compaction on water dynamics and crop growth. Additional soil damage due to, for example, mixing of soil layers, was not captured in the model. At the field-scale, the presence of infrastructure associated with CSG development such as wells, access tracks and contour banks specially constructed, may aggravate soil compaction issues. This occurs because of additional manoeuvring and turning that are required to cultivate the soil around established infrastructure and within confined spaces. Estimates (authors' own data) suggest that traffic associated with conventional field operations (e.g., seedbed preparation, planting, spraying and harvesting) may increase by up to 10% or greater compared with the situation prior to establishment of CSG-related infrastructure. Consequently, the efficiency of farming operations may be adversely affected, which impacts on timeliness of operations and energy requirements, including the need for tillage repair in areas otherwise not affected by compaction. This observation also explains the relatively high values of SBD encountered in field areas (Figure 7). Therefore, careful planning is required to optimise layout of CSG-related infrastructure, including location of wells and engineering design (dimensions and spacing) of soil erosion control structures such as contour banks and constructed waterways.

In arable land, the establishment of permanent traffic lanes conveniently oriented for surface drainage and logistics can provide an effective means to minimise the area subjected to vehicular traffic during farm operations. In well-designed systems, permanent traffic lanes typically occupy 20% or less of the total cultivated area. Such systems are commonly referred to as controlled traffic farming (CTF). CTF systems require that all farm machinery has the same or modular working and track gauge widths to enable load-bearing wheels to traffic along those consolidated wheelways. Several studies (e.g., Tullberg et al., 2001; Li et al., 2009) have shown that reduced compaction in CTF compared with non-CTF systems significantly reduces runoff and erosion because of improved infiltration and soil structural conditions in the absence of traffic (McHugh et al., 2009). The up/down orientation of tramlines in CTF systems improves the efficiency of field operations due to reduced number of turnings and traffic intensity compared with across-slope orientation in non-CTF systems. Therefore, adoption of CTF may be considered as a practical solution to optimise logistics and minimise adverse effects of traffic compaction in situations where CSG-related infrastructure, such as well-heads and contour banks, interferes with farm operations within a field. Additional agronomic and environmental benefits of CTF are discussed in Antille et al. (2015).

# 5. Conclusions

The main conclusions derived from this research are:

1. Increased soil compaction associated with traffic during establishment of CSG infrastructure has an impact on agricultural productivity. Measurements showed that compaction was approximately 10% higher within lease areas compared with surrounding agricultural fields, which had a negative effect on hydraulic conductivity, surface infiltration rates, and rainfall use efficiency. The modelling study suggested that in average rainfall years, simulated compaction levels within lease areas can result in up to 50% reduction in grain yield compared with yields in the surrounding fields. For the bottom and top deciles, relative grain yields can be up to 60% and 32% lower, respectively. Simulation analyses for rehabilitated soil suggested that removal of compaction through cultivation to a depth of approximately 300 to 350 mm will be effective to ensure sufficient root growth and soil water storage during the preceding fallow, which will reduce the risk of crop failure.

Progressive loosening techniques were reviewed and these may be employed in situations where deeper alleviation of compaction was needed. However, their cost-effectiveness requires further investigation,

2. At the farm- or field-scale, the layout of infrastructure associated with CSG development, including location of lease areas, access tracks and contour banks specially constructed, needs to be designed to:

   (a) Minimise the need for additional manoeuvring of farm machinery when conventional field operations are performed,

   (b) Ensure field operating efficiency (timeliness and energy consumption) is not adversely affected, and

   (c) Avoid secondary effects associated with increased traffic intensity within the field (soil compaction), which reduces water infiltration, increases the risk of erosion and runoff generation, and nutrient transport to water courses. The establishment of permanent traffic lanes correctly oriented to optimise surface drainage and logistics (controlled traffic systems), can assist in reducing the effects of compaction while improving trafficability and timeliness of farm operations,

3. The effects of CSG infrastructure development on soil physico-chemical properties were not significant in most circumstances. However, field investigations showed changes in particle size distribution within the soil profile associated with soil mix ing. Soil structural damage was noticeable because of compaction but at least in one of the sites investigated there was evidence of this problem being exacerbated by the presence of Na within the soil profile. Therefore, inspection of the soil profile prior to disturbance and careful management of Na-rich subsoil is required, including avoidance of soil mixing and layer inversion. In such situations, rapid rehabilitation using standard techniques (e.g., application of gypsum) followed by establishment of suitable cover crops may be recommended to assist in the regeneration of soil structure. Based on reported evidence from land rehabilitation in mine sites, addition of N fertiliser to sustain sufficient biomass production, and soil incorporation of crop residues and organic manures will facilitate regenerative processes,
4. The dataset collected and the modelling approach employed in this study enable crop productivity losses to be predicted, and may be used by land managers and the CSG industry to improve current CSG and soil management practices.

# 6. Further work

1. A critical review of current CSG and soil management practices for reinstatement is required to further assess strategies relating to soil conservation. This work needs to be conducted to:
   (a) Validate risks and quantify risk levels,
   (b) Determine the total effectiveness of all control measures acting upon those risks, and
   (c) Determine costs and benefits of soil management practices,
2. Conduct risk assessment of key land degradation risks in relation to soil management practices during the construction phase, including:

(a) Management of topsoil, and risk of soil mixing and layer inversion, including requirements for soil amelioration, such as correction of sodicity or acidity, and restoration of soil fertility and soil organic carbon,
(b) Determine the cost-effectiveness of measures used for control of soil erosion and runoff. In the context of the CSG industry, these data appear to be limited. This requires the assessment of susceptibility of dominant soil types to erosion processes under CSG development, and
(c) Review of procedures used for field design. This would enable minimal interference of established CSG infrastructure with standard farming operations within a field and will therefore reduce the risk of traffic compaction during such operations,

3. Develop industry best management practices, which are consistent with land-use, soil type, and climatic conditions,
4. Validate the outcomes of the modelling work conducted in this study, which will enable assessment of potential crop productivity loss in a wider spectrum of edapho-climatic conditions.

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