Soil quality effects on regeneration of annual *Medicago* pastures in the Swartland of South Africa

Pieter A Swanepoel* and Flackson Tshuma

*Department of Agronomy, Stellenbosch University, Stellenbosch, South Africa

*Corresponding author, email: pieterswanepoel@sun.ac.za

**Abstract**

Annual medic (*Medicago* spp.) pastures are widely used as the forage component of crop rotation systems in the Mediterranean region of South Africa. Reliable establishment of medics can be challenging. This may be related to poor soil quality, an inherent problem of soils in the region often aggravated by poor management. The aim of this study was to determine the underlying soil quality factors that result in classifying soils as having low, medium and high medic pasture production potential. The study was carried out on two farms that have followed crop/pasture rotation systems for the past 20 years. Two growing seasons (2015 and 2016) were evaluated on areas within fields that were identified to have poor, medium and high production potential. Soil samples were taken to evaluate soil quality and to determine the medic seed density in soil. Above-ground seed production and herbage production were monitored during the growing season. The low productivity soils had the lowest below- and above-ground seed density, medic seedlings establishment and medic herbage yield. Soil sodicity was one of the main factors decreasing pasture productivity. In a production system where medics need to regenerate effectively following good seed production, sodic soil may be especially detrimental.

**Keywords:** annual medics, *Medicago polymorpha*, *Medicago truncatula*, sodic soil, sodium

**Introduction**

Annual medic (*Medicago* spp.) pasture systems, also referred to as ley crop or farming systems, were first developed in southern Australia. Annual medics are successfully used as a forage component in rain-fed crop/pasture production systems in the Mediterranean climate zones of North Africa, the Middle East and South Africa (Kotze et al. 1998; Porqueddu et al. 2016). In South Africa, annual medics (*Medicago truncatula* and *M. polymorpha*) are often used in rotation with cash crops such as wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), canola (*Brassica napus*) and oats (*Avena sativa*) (Swanepoel et al. 2016). The incorporation of a leguminous forage crop improves the overall productivity of the system, forage quality and livestock production (Chatterton and Chatterton 1984). The pasture phase in the cropping system also improves overall farm profitability, if managed appropriately (Knot 2015). However, despite this important role played by annual medics in the economic sustainability of crop rotation systems in the winter rainfall region of South Africa, there is a paucity of information on the pasture phase in these systems.

Annual medics are popular in the Swartland region of South Africa for various reasons. The Swartland region of South Africa has a strong Mediterranean-type climate that only allows rain-fed pasture and pasture production during the cool winter months, and annual medics are able to complete their life cycle and produce sufficient seed within the growing season. Annual medics have hard seeds and therefore high dormancy, which allows for pasture regeneration with a cropping phase between each pasture phase. Therefore, no establishment costs are undertaken during the pasture phase.

Management of the cropping system must be sound to ensure proper regeneration. One reason for poor regeneration of medics has been attributed to the depth of tillage when establishing wheat in the cropping phase, whereby a deep disc plough (50–250 mm) drastically reduces the percentage of medic seeds that regenerate in the following pasture phase (Kotzé et al. 1998). Currently, most farmers have converted to minimum-tillage systems where medic seeds tend to be buried effectively to allow germination and establishment of medics in subsequent seasons. Grazing management also influences regeneration, as sheep primarily feed on medic pods during summer. Grazing should be managed in such a way that enough pods remain after summer to ensure sufficient seed is incorporated into the soil during the planting operation of the following season’s cash crop.

In addition to tillage practices and grazing management, poor soil quality also affects persistence of annual medic pastures. Soil quality is the ability of the soil to function (Karlen et al. 1997), and in this case, the capacity of the soil to provide medics with a suitable physical, chemical and biological environment to support high productivity. Important soil quality factors that decrease pasture productivity in Mediterranean regions are low organic carbon (C) content and microbial activity, poor distribution of nutrients, soil salinity, sodicity and soil compaction (Swanepoel et al. 2015a, 2016).
The conversion from conventional tillage to conservation agriculture practices by the majority of farmers in the Swartland since the 1990s has generally improved the soil C content across the region (Swanepoel et al. 2016). Cooper et al. (2014) showed that cropping systems that included medics as the forage component had the highest organic C content, and that soil surface disturbance and root density had a significant impact on organic C content, particularly in the top 100 mm of soil. Ensuring a high productivity of the medic phase therefore not only improves forage availability, but can also increase the performance of the subsequent cropping phase through improving soil quality.

Growth and regeneration of annual medics is known to be severely limited by soil salinity and sodicity (Muir et al. 2001; Hajkowicz and Young 2005), which are common limitations in Mediterranean climate zones. A decline in river water quality in the Swartland over the past three decades indicates that soil salinity and sodicity are increasing across the region (Görgens and de Clercq 2005). Soil salinity in dryland regions results from the mobilisation of salts to the soil surface through seasonal water table rise (Bennett et al. 2009), and land-use change is the most important driver of dryland salinity (Hajkowicz and Young 2005). In the Swartland, it is thought to be caused by the clearance of the deep-rooted natural vegetation (coastal renosterveld), which is then replaced by shallow-rooted annual crops. Soils are classified as saline when the electrical conductivity (EC) exceeds 40 dS m\(^{-1}\).

Sodicity (when soil has excessive sodium (Na) associated with the negatively charged clay particles) affects plant production through degrading the soil structure, which results in a decreased water infiltration rate along with increased surface crusting, waterlogging and erodibility (Levy and van der Watt 1988). The dominant soil forms in the Swartland region are characterised mostly by illite, but also kaolinite clay minerals, which are both susceptible to sodicity (Levy and van der Watt 1988). The most commonly used thresholds to classify soil as sodic are those of the US Salinity Laboratory (Richards 1954), which classifies soil as sodic when the exchangeable sodium percentage (ESP) exceeds 15%. Furthermore, a soil can be classified as saline-sodic when the ESP exceeds 15% and the EC exceeds 40 dS m\(^{-1}\). However, thresholds more suitable for South African conditions are those suggested by Isbell (1996) for Australian soils, in which soils are classified as sodic when the ESP exceeds 6%. This threshold will be used in the current study to classify soil sodicity.

Sodicity poses major problems to agricultural production, not only in South Africa, but also in Western Australia (Clarke et al. 2002). Yet, in South Africa, there are no studies that assess or evaluate the impact of soil sodicity on the regeneration of annual medic pastures. The aim of this study was to determine the underlying soil quality factors that result in classifying soils as having low, medium and high medic pasture production potential.

Materials and methods

Study sites

The study was carried out on two farms in the Swartland area in South Africa during the medic phase of fields under medic/wheat rotations. The first farm, Pringleskraal, is located near Moorreesburg (33°14′58″ S, 18°6′906″ E; 152 m above sea level). The second farm, Langgewens Research Farm of the Western Cape Department of Agriculture, is near Malmesbury (33°29′14″ S, 18°4′138″ E; 187 m above sea level). Pringleskraal and Langgewens are located in moderate and high production potential areas in terms of rainfall with annual rainfall of 386 and 460 mm, respectively. The Swartland receives roughly 80% of its annual rainfall from May to October. Both farms were managed under conservation agriculture principles, including minimum tillage, retention of crop residues on the soil surface, and a crop rotation comprising alternate years of wheat and annual medic. The annual medic phase was grazed by sheep. The stocking rate at Pringleskraal was approximately 4 sheep ha\(^{-1}\) and Langgewens 2–3 sheep ha\(^{-1}\).

Experimental design and treatments

The experimental design for the research was a randomised block design with three treatments, replicated in three fields (as blocks). In each field, the treatments comprised areas of low, medium and high productivity soils. The treatments were selected based on visual assessment of productivity and on farmer experience of low and high producing areas of each field. The medium productivity soils were located between the high and low productivity soils. A treatment plot was located within each of the identified areas of low, medium and high productivity soils, with plot sizes ranging between 100 and 300 m\(^2\).

Different sets of three fields were selected on each farm for the two growing seasons (2015 and 2016). The 2015 growing season was a preliminary assessment and therefore samples were only taken at the end of the season (November 2015). For the 2016 season, samples were taken monthly, commencing 30 d after medic seedling emergence in July 2016 until October 2016 to monitor pasture productivity through time.

Sampling procedure

Soil quality analysis

Six soil cores (Ø 45 mm) to a depth of 200 mm were collected per treatment in November 2015, and combined to form a single sample per treatment from which a subsample was collected for standard soil analysis. This procedure was repeated in May and October 2016. The soil analysis included standard procedures of the Non-Affiliated Soil Analysis Work Committee (1990) for EC, pH(KCl), exchangeable calcium (Ca), magnesium (Mg), potassium (K) and Na (citric acid), extractable phosphorus (P; citric acid) and sulphur (S; calcium phosphate), total nitrogen (N; Kjeldahl digestion), organic C (Walkley–Black), copper (Cu; di-ammonium EDTA), zinc (Zn; di-ammonium EDTA), manganese (Mn; di-ammonium EDTA), boron (B; hot water) and a soil particle size analysis (hydrometer method). The ESP and sodium adsorption ratio (SAR) were calculated with Equations 1 and 2, respectively:

\[
\text{ESP (\%)} = \frac{\text{Na}^+}{\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+}}
\]

(1)
level within the borders of a 0.5 m² quadrat placed within to prevent grazing by sheep. Herbage was cut to ground
of medic seedlings in four 0.25 m² quadrats per plot in May
Medic establishment was assessed by counting the number
pods were crushed and seed separated from the chaff as
to determine above-ground seed production. Seed pods
The technique described by Carter et al. (1997) was used
number of above-ground medic seeds per square metre.
All above-ground plant material was collected within a
Above-ground medic seed density
All above-ground plant material was collected within a
0.5 m² quadrat per plot to facilitate the calculation of the number of above-ground medic seeds per square metre.
The technique described by Carter et al. (1997) was used
to determine above-ground seed production. Seed pods
were separated from the herbage samples by hand. Seed
pods were crushed and seed separated from the chaff as
described above.

Medic seedling establishment
Medic establishment was assessed by counting the number
of medic seedlings in four 0.25 m² quadrats per plot in May
2016, prior to grazing.

Medic herbage production
Four exclosure cages (roughly 2 m²) were erected per plot
to prevent grazing by sheep. Herbage was cut to ground
level within the borders of a 0.5 m² quadrat placed within
a randomly selected exclosure cage per plot in July 2016.
Pasture herbage production per plot was monitored by
repeating the cutting process in August, September and
October 2016, each time in a different exclosure cage that
did not previously been grazed or cut. The determined
monthly herbage production therefore represents total
seasonal production to that specific point in time, without
defoliation. Medic herbage samples were oven dried at
70 °C for 48 h to determine the dry matter (DM) herbage
yield per hectare.

Statistical analyses
Statistical analyses were done using Dell™ Statistica™ 13
(Dell Inc. 2015). A two-way analysis of variance (ANOVA)
was used to analyse the soil and seed data at the 5% significance level. Where residuals were not normally
distributed or had heterogeneous variances, the Kruskal–
Wallis and Games–Howell post-hoc tests were performed,
respectively, to confirm the results of the ANOVA. A
repeated-measures ANOVA was used to test for pasture
herbage production through time, for which the fixed effects
were specified as linear time, treatment and their interaction.

Results and discussion

Soil analyses
The pH (KCl), macro- and micronutrients were within
recommended soil fertility ranges for medic pastures
(data not shown) (Swanepeol et al. 2015b). Soil chemical
indicators that differed (p < 0.05) between treatments for
the 2015 and 2016 seasons are shown in Tables 1 and 2,
respectively. The EC of poor, medium and high produc-
tivity soils was 27, 9.0 and 3.3 dS m⁻², respectively, but
did not differ significantly (p > 0.05) between treatments
(data not shown). As the EC values of these soils were
less than 40 dS m⁻², the soils were not saline. However,
the exchangeable Na content was very high in the low
productivity soils of both farms, indicating high sodicity.
For samples taken in 2015 and 2016 on Pringleskraal the
exchangeable Na content for the low productive soils was
1 194 and 3 661 mg kg⁻¹, respectively, and was higher
(p < 0.05) than the high productivity soils (Table 2). The
ESP and SAR also reflected sodicity problems, particularly
on Pringleskraal. For samples taken in both 2015 and 2016,
the only soil that would be classified as non-sodic using
the thresholds recommended by Isbell (1998) was the high
productivity soil on Langgewens. All other soils surpassed
the 6.0% ESP threshold for sodicity. The ESP values of
the low and medium productivity soils on Pringleskraal and
the low productivity soil on Langgewens indicated strongly
sodic conditions in both years. The SAR values higher than
2.5 also indicate sodicity (Hazelton and Murphy 2007),
values above this threshold were found for the low and
medium productivity soils on Pringleskraal, and the low
productivity soil on Langgewens.

Sodicity is associated with soil surface crustling, low
infiltration rates and erosion. However, rainfall simula-
tion work by Levy and van der Watt (1988) demonstrated
that illitic soils tend to be more susceptible to hard setting
than kaolinitic soils, even though illitic soils are still fairly
stable. Further research evaluating the effects of soil
sodicity on hard setting and infiltrability is recommended,
as this would be particularly important for reclaiming the
soils as the soils in the Swartland region are generally
prone to erode.

For both seasons, the exchangeable S content on
Pringleskraal was higher (p < 0.05) on low productivity
soils. This could be ascribed to gypsum (calcium sulphate)
that was applied by the farmer in an effort to reclaim
salt-affected soils. Gypsum is primarily used on Na-affected
soils as a source of Ca²⁺ ions to displace Na⁺ ions, which
is subsequently leached. The use of gypsum on sodic soils
could also be a reason why there was more Ca in the low
productivity soils at Pringleskraal in 2016. Even though
Ca and Mg concntrations were high, the ratio between

\[
\text{SAR (mmoles L}^{-1})^{0.5} = \frac{\text{Na}^+}{\sqrt{0.5 \times (\text{Ca}^{2+} + \text{Mg}^{2+})}} \tag{2}
\]
these cations were higher than 3 to 1, and we therefore do not expect the Ca or Mg concentrations to have affected plant productivity.

The low and medium productivity soils at Pringleskraal had similar ($p > 0.05$) extractable B content in 2015 (Table 1). The high productivity soils had less ($p < 0.05$) B than the low and medium treatments. The B content was similar in all treatments for both the 2015 and 2016 samples collected from Langgewens (Tables 1 and 2, respectively). Boron is an essential micronutrient for plants and is needed for seed production and germination (Gupta 2007), but is only conductive to plant growth within a narrow range of concentrations (Rashid and Ryan 2004). In general, an extractable amount of less than 0.1 mg kg$^{-1}$ is regarded as inadequate, yet B may become toxic to some field crops when greater than 1 mg kg$^{-1}$ (FSSA 2016). Some crops are known to tolerate B up to 5 mg kg$^{-1}$ (Nable et al. 1997; Rashid and Ryan 2004), while Ozturk et al. (2009) and Howie (2012) suggested that B may only become toxic to annual medics above 15 mg kg$^{-1}$. Phytotoxicity is therefore not expected to have occurred at the concentrations observed in this study. However, knowledge of the B concentration in the plant material is required to definitively confirm phytotoxicity.

Values for pH(KCl) differed between treatments in 2016, but the optimal range for annual medics is 4.8 to 8 (Clark 2014), and all observations fell within that range for both farms. Levels of pH(KCl) are therefore not expected to be a limitation to plant growth in this study.

**Below-ground medic seed density**

Differences in belowground medic seed density were observed between treatments at Pringleskraal in November 2015 and May 2016 (Figures 1 and 2, respectively). In both cases, the low productivity soil treatments were found to have less seeds than the high productivity soil treatments ($p < 0.05$), and this trend also continued into October 2016 (Figure 3), although no significant differences were observed in October 2016 ($p > 0.05$). These differences were likely caused by high soil sodicity leading to crusting of the soil surface. However, B concentrations could also have impacted plant productivity. The B content in the low and medium productivity soils was similar ($p > 0.05$), but was lower ($p < 0.05$) in the high productivity soil (Table 1). Cavalier and Santiago medic cultivars sown on Pringleskraal are sensitive to B, a factor that could have contributed to low seed numbers (Howie 2012).

No significant differences were observed in below-ground medic seed density at Langgewens ($p > 0.05$) (Figures 1–3). Soil in the low productivity treatment at Langgewens was found to be sodic, although not to the same extent as the low productivity treatment at Pringleskraal (Table 1). In addition, the Langgewens low productivity treatment had relatively lower levels of B than either the low or medium productivity treatment at Pringleskraal, so it could be that the differences observed at Pringleskraal result from a combination of sodicity and high B concentrations. This result is to be expected given that all soil fertility indicators were equal between treatments.

Langgewens had a relatively lower below-ground seed density than Pringleskraal, which can be attributed to the relatively low stocking rate at Langgewens (approximately 2–3 sheep ha$^{-1}$), and a lack of scarification of the soil. Conversely, Pringleskraal had a stocking rate of approximately 4 sheep ha$^{-1}$ on a continuous grazing system.

---

**Table 1:** Soil fertility indicators for samples ($n = 9$) collected to a depth of 200 mm from two farms in the Swartland during the 2015 season. Values are the mean ± SE. Different superscript letters within each row indicate the treatments (low, medium and high productivity soils) with a significant difference ($P < 0.05$). ESP = exchangeable sodium percentage, SAR = sodium adsorption ratio

| Soil quality indicator | Pringleskraal farm | Langgewens Research Farm |
|------------------------|---------------------|--------------------------|
|                        | Low | Medium | High | Low | Medium | High |
| Sodium (mg kg$^{-1}$)   | 3 661 ± 809.9$^{a}$ | 698 ± 446.1$^{a}$ | 154 ± 48.5$^{b}$ | 345 ± 237.7$^{a}$ | 164 ± 116.5$^{a}$ | 49 ± 3.2$^{a}$ |
| ESP (%)                | 45.1 ± 4.2$^{a}$ | 22.4 ± 10.2$^{a}$ | 9.5 ± 3.4$^{a}$ | 18.2 ± 9.2$^{a}$ | 12.0 ± 7.2$^{a}$ | 4.7 ± 1.5$^{a}$ |
| SAR (mmoles L$^{-1}$)   | 16.6 ± 3.1$^{a}$ | 4.7 ± 2.9$^{a}$ | 1.2 ± 0.4$^{a}$ | 2.9 ± 1.9$^{b}$ | 1.5 ± 1.1$^{a}$ | 0.5 ± 0.1$^{a}$ |
| Sulphur (mg kg$^{-1}$)  | 796.7 ± 207.4$^{a}$ | 129.7 ± 58.0$^{a}$ | 44.4 ± 23.1$^{a}$ | 81.7 ± 39.6$^{b}$ | 39.7 ± 21.4$^{b}$ | 14.0 ± 2.1$^{b}$ |
| Calcium (mg kg$^{-1}$)  | 2 126 ± 303.3$^{a}$ | 1 056 ± 136.1$^{a}$ | 962 ± 128.4$^{a}$ | 714 ± 174.5$^{b}$ | 663 ± 78.4$^{b}$ | 841 ± 281.1$^{b}$ |
| Boron (mg kg$^{-1}$)    | 2.5 ± 0.31$^{a}$ | 1.4 ± 0.20$^{a}$ | 0.7 ± 0.10$^{b}$ | 0.4 ± 0.15$^{a}$ | 0.32 ± 0.06$^{a}$ | 0.28 ± 0.03$^{a}$ |
| Total cations (cmol+, kg$^{-1}$) | 34 ± 5.5$^{a}$ | 12 ± 2.6$^{a}$ | 7.3 ± 0.4$^{b}$ | 6.4 ± 2.0$^{b}$ | 5.7 ± 0.7$^{b}$ | 5.6 ± 1.3$^{a}$ |
| pH(KCl)                | 7.0 ± 0.06$^{a}$ | 6.0 ± 0.1$^{a}$ | 5.9 ± 0.37$^{b}$ | 5.6 ± 0.09$^{bc}$ | 5.3 ± 0.09$^{bc}$ | 5.4 ± 0.22$^{bc}$ |
| Magnesium (mg kg$^{-1}$) | 882 ± 104.7$^{a}$ | 344 ± 107.2$^{a}$ | 171 ± 12.7$^{bc}$ | 98 ± 36.2$^{c}$ | 81.7 ± 12.2$^{c}$ | 92 ± 21.2$^{c}$ |
and included scarification of soil in prior to onset of the growth season. We do not expect the annual medics to be overgrazed, as 4 sheep ha$^{-1}$ corresponds with the area average (Basson et al. 2017).

**Above-ground medic seed density**

The above-ground medic seed density for Pringleskraal increased ($p < 0.05$) from low to high productivity soils (Figure 4). The low, medium and high treatments at Pringleskraal had 42, 704 and 1 929 seeds m$^{-2}$, respectively. At Langgewens, the high and medium productive soils were similar ($p > 0.05$), and differed ($p < 0.05$) from the low productive soils. The above-ground medic seed density for the low, medium and high productive soils were 693, 1 850 and 2 993 seeds m$^{-2}$, respectively.

The lower seed production could be explained by decreased plant productivity as sodicity increases. An excess amount of Na ions disrupt plant cell functions and water uptake leading to stunted plant growth (Zhu 2001; Nichols et al. 2009), and soil compaction and crusting can affect root formation. As discussed in regard to below-ground seed density, B was also highest in the low and medium productivity treatments at Pringleskraal and the low productivity treatment at Langgewens, and may also have contributed to reduced seed production in these treatments.

**Annual medic seedling establishment**

Patterns of seedling establishment were similar to patterns of below-ground seed density. There was no difference ($p > 0.05$) in the number of medic seedlings that established between the low, medium and high productivity soils at Langgewens (Figure 5). The low, medium and high productivity soils had 147, 353 and 420 seedlings m$^{-2}$, respectively. The number of medic seedlings in the low, medium and high productivity soils at Pringleskraal were 4, 311 and 589 seedlings m$^{-2}$, respectively. The difference between the low and high productivity treatments was significant ($p < 0.05$), although differences between low and medium and between medium and high were not ($p > 0.05$). It is likely that sodicity is the main factor contributing to low seedling numbers, either through reducing the number of seeds that are produced and incorporated into the soil (as indicated by the relative below-ground seed densities), and/or through decreasing the physical quality of the seedbed. High B levels may also contribute to reduced germination and seedling vigour (Martínez-Ballesta et al. 2008; Mohamed et al. 2015).

**Herbage production**

Medic herbage yields were significantly higher ($p < 0.05$) on the medium and high productivity treatments than the low productivity treatment at Pringleskraal from August onwards (Figure 6). The herbage produced on the low productivity treatment was negligible and did not contribute to farm
Swanepoel and Tshuma

On Langgewens, the low productivity treatment produced significantly less herbage than the medium and high treatments in July and August, although there were no significant differences by September and October. Poor herbage production was found on soils where sodicity is problematic. Mitigation strategies to alleviate soil sodicity need to be found, or tolerant crops should be introduced. Evaluation of salt-tolerant grazing crops, particularly legumes such as messina (*Melilotus siculus*), is highly recommended for sodic soils. Messina is a recently domesticated annual pasture legume with a higher salt tolerance than other legumes and also a high tolerance to waterlogging (Nichols et al. 2012). It was recently developed and introduced in Australia and has been used successfully there in crop rotation systems, which are similar to those of the Swartland. Alternatively, any palatable salt-tolerant forage crops, such as the slender wheatgrass (*Elymus trachycaulus*), or the not-so-palatable tall wheatgrass (*Thinopyrum ponticum*) can be used to keep sodic soils in production and maintain soil structure and infiltration by improving the organic matter content. Plants observed on the low productivity soils were mostly salt-tolerant weeds such as Lindley’s saltbush (*Atriplex lindleyi* subsp. *inflata*) and the succulent slender leaf iceplant (*Mesembryanthemum nodiflorum*), indicating that only the very salt-tolerant plants managed to survive on these soils. Gypsum has been used for the purpose of alleviating sodicity on both farms, but has not been found to be effective, particularly on Pringleskraal. Mulching (for example with straw) can be considered as an additional treatment on low productivity soils, as it would prevent soil surface crusting, increase water infiltration and keep soil cool to reduce evaporative water loss. These effects are expected to reduce the translocation of salts from below-ground to the plant root zone. With good rainfall, the salts may then be leached away before they reach the surface.

Evaluation of the effects of conservation agriculture on soil sodicity is also recommended, as conservation agriculture practices are now widely adopted in the Swartland. These practices are effective in conserving water, which can increase the likelihood of the water table reaching the soil surface and depositing salts within the root zone. The problem is further exacerbated by the region’s reliance on shallow-rooted crops (Görgens and de Clercq 2005). Exploring possibilities for using deep-rooted crops or restoring areas of natural vegetation within farms could therefore contribute to regulating the water table.

**Conclusion**

This study highlighted the severity of sodicity and its effects on pasture production. The productivity of annual medics in the sodic soils was very poor when compared with the medium and high productivity soils. The low productivity soils had the lowest amount ($p < 0.05$) of
below- and above-ground medic seeds, medic seedlings establishment and medic herbage yield. These effects were especially pronounced on Pringleskraal farm, which was more severely affected by soil sodicity. Given that salinity and sodicity appear to be increasing within the Swartland (Görgens and de Clercq 2005), farm management practices that mitigate soil sodicity will be necessary to sustain the region’s crop and pasture production.

Acknowledgements — The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at are those of the author and are not necessarily to be attributed to the NRF. We thank Prof. TN Kotzé for availing his farm Pringleskraal for the research, together with the Western Cape Department of Agriculture for availing Langgewens Research Farm. Prof. D Nel is thanked for the statistical analyses. Prof. GA Agenbag and Prof. MB Hardy are thanked for their comments to improve the manuscript. Ms Chloe MacLaren is thanked in particular for carefully reading the manuscript and her many insightful comments and substantive linguistic editing.

References

Basson CH, Strauss JA, Hoffmann WH. 2017. A financial analysis of crop-livestock integration in conservation agriculture. Paper presented at the African Combined Congress, 23–26 January 2017, Bela-Bela, South Africa.

Bennett SJ, Barrett-Lennard, Colmer TD. 2009. Salinity and waterlogging as constraints to saltland pasture production: a review. *Agriculture, Ecosystems and Environment* 129: 349–360.

Carter ED, Challis S, Ridgway IR. 1977. The use of heavy solvents for separating seed from soil. In: Wojahn E, Thöns H (eds), *Proceedings of the 13th International Grassland Congress*, Leipzig, 18–27 May 1977. Berlin: Akademie-Verlag, pp 735–738.

Chatterton B, Chatterton L. 1984. Alleviating land degradation and development. *Degradation and Development* 16: 417–433.

Hazelton PA, Murphy BW. 2007. Interpreting soil test results: what do all the numbers mean? Collingwood: CSIRO Publishing.

Howie JH. 2012. Boron tolerance in annual medics (*Medicago spp.*). *Crop and Pasture Science* 63: 886–892.

Isbell RF. 1996. *The Australian soil classification*. Melbourne: CSIRO.

Knott SC. 2015. An analysis of the financial implications of different tillage systems within different crop rotations in the Swartland area of the Western Cape, South Africa. MSc thesis, Stellenbosch University, South Africa.

Knöz TN, Langenhoven WR, Agenbag GA. 1998. The influence of soil tillage on the distribution of medic seeds in the soil, regeneration of medic and wheat yields in a medic wheat rotation. *Field Crop Research* 55: 175–181.

Levy GJ, van der Watt HV. 1988. Effects of clay mineralogy and soil sodicity on soil infiltration rate. *South African Journal of Plant and Soil* 5: 92–96.

Martínez-Ballesta MDC, Bastías E, Carvajal M. 2008. Combined effect of boron and salinity on water transport: the role of aquaporins. *Plant Signaling and Behaviour* 3: 844–845.

Mohamed AKSH, Qayyum MF, Shahzad AN, Gul M, Wakeel A. 2015. Interactive effect of boron and salinity on growth, physiological and biochemical attributes of wheat (*Triticum aestivum*). *International Journal of Agriculture and Biology* 18: 238–244.

Muir JP, Pitman WD, Coombs DF. 2001. Seeding rate, phosphorus fertilization, and location effects on ‘Armadillo’ burr medic. *Agronomy Journal* 93:1269–1275.

Nable RO, Banuelos GS, Paul JG. 1997. Boron toxicity. *Plant and Soil* 193: 181–198.

Nichols PGH, Malik AI, Stockdale M, Colmer TD. 2009. Salt tolerance mechanism at germination of annual pasture legumes: Importance for adaptation to saline environments. *Plant and Soil* 315: 241–255.

Nichols PGH, Teakle NL, Bonython AL, Ballard RA, Charman N, Craig AD. 2012. Messina (*Melilotus siculus*) – a new annual pasture legume for Mediterranean type climates with high tolerance of salinity and waterlogging. In: Acrar Z, López-Francos A, Porqueddu C (eds), New approaches for grassland research in a context of climate and socio-economic changes. Zaragoza: CIHEAM, pp 155–159.

Non-Affiliated Soil Analysis Work Committee. 1990. Handbook of standard soil testing methods for advisory purposes. Pretoria: *Soil Science Society of South Africa*.

Ozturk M, Sakcåli S, Gucel S, Tombuloglu H. 2009. Boron and plants. In: Ashraf M, Ozturk M, Ahmad MSA (eds), *Plant adaptation and phytoengineering*. Dordrecht: Springer. pp 275–311.

Porqueddu C, Ates S, Louhaichi M, Kyriazopoulos AP, Moreno G, Pozo A, Nichols PGH. 2016. Grasslands in ‘Old World’ and ‘New World’ Mediterranean climate zones: past trends, current status and future research priorities. *Grass and Forage Science* 71: 1–35.

Rashid A, Ryan J. 2004. Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: a review. *Journal of Plant Nutrition* 27: 959–975.

Richards LA (ed.). 1954. *Diagnosis and improvement of saline and alkali soils*. *Agricultural Handbook* no. 60. Washington, DC: US Department of Agriculture.

Swanezp PA, Botha PR, du Preez CC, Snyman HA, Labuschagne J. 2015a. Managing cultivated pastures for improving soil quality in South Africa: challenges and opportunities. *African Journal of Range and Forage Science* 32: 91–96.

Swanezp PA, du Preez CC, Botha PR, Snyman HA. 2015b. A critical view on soil fertility status of minimum-till kikuyu-ryegrass pastures in South Africa. *African Journal of Range and Forage Science* 32: 113–124.
Swanepoel PA, Labuschagne J, Hardy M. 2016. Historical development and future perspective of conservation agriculture practices in crop-pasture rotation systems in the Mediterranean region of South Africa. In: Kyriazopoulos A, Lopez-Francos A, Porqueddu C, Sklavou P (eds), *Ecosystem services and socio-economic benefits of Mediterranean grasslands*. Zaragoza: CIHEAM. pp 75–78.

Zhu J-K. 2001. Plant salt tolerance. *Trends in Plant Science* 6: 66–71.