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ORIGINAL PAPER

The impact of black wattle encroachment of indigenous grasslands on soil carbon, Eastern Cape, South Africa

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Abstract Black wattle (*Acacia mearnsii*, De Wild.) is a fast growing tree species introduced into South Africa in the nineteenth century for commercial purposes. While being an important source of timber and firewood for local communities, black wattle is an aggressive invasive species and has pervasive adverse environmental impacts in South Africa. Little is known about the effects of black wattle encroachment on soil carbon, therefore the aim of this study was to investigate the impact of black wattle encroachment of natural grassland on soil carbon stocks and dynamics. Focussing on two sites in the Eastern Cape, South Africa, the study analysed carbon stocks in soil and litter on a chronosequence of black wattle stands of varying ages (up to >50 years) and compared these with adjacent native grassland. The study found that woody encroachment of grassland at one site had an insignificant effect on soil and litter carbon stocks. The second site showed a clear decline in combined soil and litter carbon stocks following wattle encroachment. The lowest stock was in the oldest wattle stand, meaning that carbon stocks are still declining after 50 years of encroachment. The results from the two sites demonstrate the importance of considering changes in soil carbon when evaluating ecosystem effects of invasive species.

Keywords *Acacia mearnsii* · Carbon sequestration · Invasive alien plants · Soil organic matter · Biomass

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Introduction

In South Africa, scientists are increasingly recognizing the potential threats and impacts of invasive alien species on indigenous vegetation, and particularly the ecological services that could be lost as a result (Le Maitre et al. 2000). Black wattle (*Acacia mearnsii*, De Wild.) is a fast growing invasive alien tree species, introduced into South Africa in the nineteenth century as a source of wood-fuel, tannins and timber (De Wit et al. 2001). A recent estimate of the geographical extent of *Acacia* encroachment (including *mearnsii* and two other species) in South Africa, is approximately 440,000 ha (and apparently increasing) (van Wilgen et al. 2011). Due to rapid growth rates, the ability to outcompete indigenous flora and large and persistent seed banks, *Acacia* species have the ability to induce simultaneous changes in above- and below-ground physical and chemical conditions, microclimates and soil moisture and nutrient regimes (Le Maitre et al. 2011; Morris et al. 2011). Black wattle encroachment can therefore have pervasive adverse environmental impacts, particularly on hydrological and carbon cycles and biodiversity loss of indigenous species (De Wit et al. 2001; Rangan et al. 2010; Le Maitre et al. 2011). The impact of *Acacia* species on biodiversity and ecosystem properties has a strong effect on ecosystem service delivery, as demonstrated by Le Maitre et al. (2011). For example, *Acacia* can have a negative impact on water discharge, a critical impact in a dry country such as South Africa, due to higher transpiration than native vegetation. Wattle can thus cause reduced stream flow and water yields, which in turn leads to reduced water availability to e.g. agriculture and industry (Richardson and van Wilgen 2004; Le Maitre et al. 2011). However, black wattle is also recognised as a valuable community resource of firewood and building materials (such as poles or props) in many rural areas in South Africa and is integral to rural livelihood strategies (de Neergaard et al. 2005; Shackleton et al. 2007).

A programme to manage this invasive threat was initiated by the South African government in 1995, called Working for Water (WfW), with the aim of controlling alien plant infestation with the added objective of achieving social upliftment through employment opportunities created as a consequence of activities adopted to control invasive species. de Wit et al. (2001) analysed the costs and benefits of black wattle and found that the negative impacts outweighed the economic benefits. The analysis included an estimated benefit from carbon sequestration of $US24 million, although they did not include carbon from non-plantation (i.e. encroached) land. The exercise of placing an economic value on costs (e.g. reduction in stream flow) and benefits (e.g. charcoal, firewood, timber and carbon sequestration) demonstrates the dualistic nature of the wattle question.

Terrestrial carbon sequestration, where carbon is sequestered in vegetation or recalcitrant organic carbon in soil, has been identified as a process that could make considerable contributions to abating CO_2 increments in the atmosphere, however our understanding of the nature of the changes in soil carbon brought about by such changes in land-cover is limited (Unruh 2008; Smith et al. 2008). Changes in vegetation cover brought about by woody encroachment of grassland will typically alter carbon sequestration and cycling (Hughes et al. 2006). This type of land cover change has been suggested to have the potential to act as a terrestrial global carbon sink (Archer et al. 2001). Woody encroachment of grassland typically increases the amount of carbon stored in the ecosystem due to a greater amount of above ground biomass (Scholes and Archer 1997; Archer et al. 2001). The other major stock change in carbon occurs for soil organic carbon (SOC). The magnitude, and direction, of changes in belowground carbon is less easy to predict (Jackson et al. 2002). Some studies demonstrate increases in soil C (Zavaleta and Kettley 2006; Liao et al. 2006), whilst others show a decrease after woody encroachment into grasslands (Pinno and Wilson 2011; Fuller and Anderson 1993). Li et al. (2012) conducted a meta-study of soil carbon dynamics following afforestation and found that afforestation of natural grassland resulted in an increase in soil carbon for the organic soil layer (litter) and a significant decrease in soil carbon in the mineral layer which, when combined, yielded no net change in total soil carbon stocks on grasslands after afforestation. Given the variability in soil carbon changes following woody encroachment, Jackson et al. (2002) stress that changes in belowground C might either have the potential to enhance or off-set aboveground biomass gains.

To our knowledge, no work has been undertaken about the effect of black wattle encroachment of native grassland on soil carbon. The aim of this study was therefore to investigate the impact of black wattle encroachment of natural grasslands on soil and litter carbon stocks and dynamics.

Materials and methods

Site description

The two study sites, Madlangala (30°10′S; 28°36′E) and Motseng (30°16′S; 28°24′E), are located in the municipality of Matatiele in the Eastern Cape Province of South Africa (Fig. 1). The two study sites were selected as areas that have been subject to black wattle encroachment for a minimum of 50 years. They are both located in the foothills of

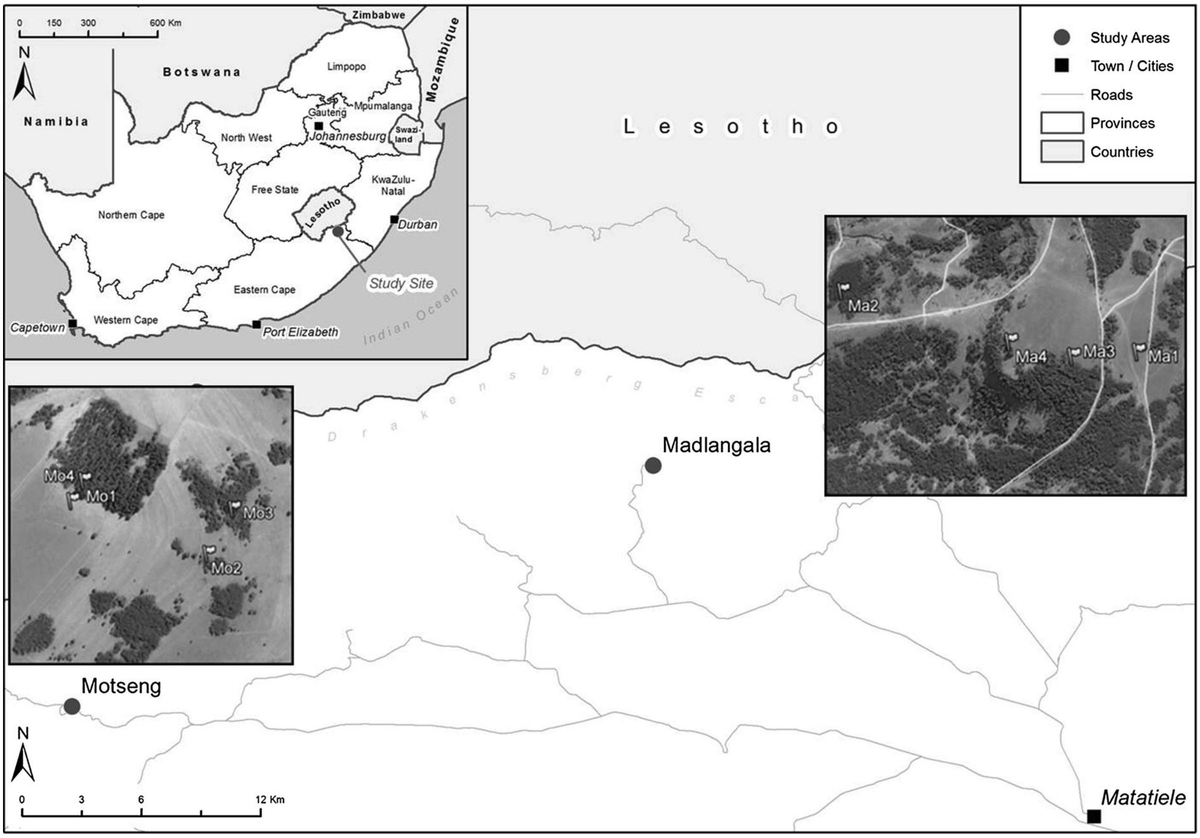

Fig. 1 Map presenting the two locations and sampling sites (*inset* not to *scale*)

the Drakensberg Escarpment near the Kingdom of Lesotho border, at an altitude between 1400 and 1600 m above sea level and fall within South Africa's grassland biome as defined by Mucina and Rutherford (2006). The natural vegetation consists predominantly of alpine and sub-alpine grassland types. The climate in the area is characterized by wet, warm summers (October–March) and cold, dry winters (April–September) with a mean annual precipitation between 710 and 750 mm. The mean annual temperature is 15 °C, with a mean annual minimum of 9 and maximum of 23 °C. Winter frost is frequent. Land-use in the area consists primarily of extensive animal husbandry (cattle and goats) and subsistence and limited semi-commercial crop production in suitable areas (mainly maize, beans, and pumpkin). The landscape is characterised by large areas of hilly grassland, grazed during summer. The soils at the Motseng and Madlangala sites are clay loams, developed from bedrock of sandstones and dolerites. Grasslands provide a number of fundamental ecosystem services that afford support to human well-being and are habitat to a multitude of diverse fauna and flora (Egoh et al. 2011). However, woody plant encroachment and proliferation in this biome is transforming and compromising its characteristics at an ever-increasing rate.

Identification of chronosequences and sample site selection

Using Spot5 Imagery from 2009 and the distribution of wattle, we selected two study areas of 4900 ha (Motseng) and 4100 ha (Madlangala) to represent the general pattern of wattle encroachment into grassland. Following this, we selected two sub-sites, one at Motseng and one at Madlangala. For each sub-site, we analysed historical aerial photos for the proxies 1953, 1966, 1975 and 1995, and Spot5 satellite images for

2006 and 2009. The analysis determined the approximate age of wattle stands in each of the two sub-sites. Based on the analysis of the historical development of wattle, we selected four sampling sites each at Madlangala (Ma1–4) and Motseng (Mo1–4). Each sampling site was selected to provide a chronosequence covering different ages of wattle stands and an adjacent grassland stand (sampling sites presented in Fig. 1 and described in Table 1).

Soil sampling and analysis

Volume specific soil samples were collected in January 2013 using a 100 cm^3 soil ring at four depths from three soil pits at each sampling site. Pits were dug to a depth of 0.60 m, and soil samples were collected, after litter samples were taken, at depths of 0–0.05 m, at 0.10 m representing a 0.05–0.15 m layer, at 0.25 m representing the 0.15–0.35 m layer, and at 0.50 m. Samples were dried for 24 h at 80 °C, weighed, crushed and sieved through a 2 mm mesh. Stones were weighed and the bulk densities of samples containing stones were corrected, assuming stones to have a bulk density of 2.6 g cm^{-3}. Contents of total SOC and isotopic composition of soil carbon were determined with an elemental analyser coupled with a continuous flow isotope ratio mass spectrometer (ANCA 20-20, Europe Scientific, Crewe, UK). Soil samples for particle size analysis were taken at 0.10 m from each pit. Samples were analysed for texture at Soil Fertility and Analytical Services, KwaZulu-Natal using the pipette method and texture classified according to the South African taxonomic system.

Biomass sampling and analysis

Surface litter biomass samples were collected at the same locations as the soil sampling sites (three samples per site, except for Ma4 where two were taken). Grass was sampled from the grassland site for isotopic carbon content determination. Litter was sampled to the mineral soil surface in the wattle stands using a 0.25 m^2 quadrat. The grass and litter samples were dried in a forced air oven at 60 °C for 24 h. The litter was weighed and then passed through a 1 cm sieve, and sorted thereafter into three fractions: <1 cm debris, >1 cm bark and >1 cm wood. The subsample was ground using a ball-mill and then re-dried, after which it was ground using a zirconium ball-mill. In addition to grass and litter samples, samples of wattle bark, wood and leaf were collected for determination of carbon content and $^{13}C/^{12}C$ ratio. Total carbon was determined in all biomass samples in the same manner as the soil samples, using an elemental analyser coupled to a mass spectrometer.

Carbon stocks at the landscape scale

The method applied is based on an interpretation of aerial photos and satellite images, as described above. For each year in the chronosequence a binary map was produced, with the value zero representing no wattle and one representing wattle. The seven maps were then combined using the method described in Birch-Thomsen et al. (2007). This method allows the production of a map for each sub-site, describing the temporal development of wattle. The resulting map of Motseng sub-site is shown in Fig. 6, in which the full temporal information on changes in wattle distribution has been reclassified into only three classes. Based on the area calculation of the three classes, each land class was then multiplied by the total soil and litter carbon stock for each sampling site, corresponding to Mo1 for grassland, Mo4 for wattle older than 20 years, and an average number from Mo2 and Mo3 for the class wattle <20 years.

Table 1 Site descriptions for wattle stands in Motseng and Madlangala

Site name	Madlangala				Motseng			
Site code Type	Ma1 Grass	Ma2 Wattle	Ma3 Wattle	Ma4 Wattle	Mo1 Grass	Mo2 Wattle	Mo3 Wattle	Mo4 Wattle
Slope (°)	2.5	6.2	13.4	6	5	4	6	5
Estimated stand age (years)	–	0–10	10–30	>50	–	0–10	10–20	>50
Average tree height (m)	–	<3	3.5	>10	–	<5	7	10–12

Calculations

SOC stocks were calculated using the equivalent soil mass approach as outlined by Ellert et al. (2001), using the average mass of the densest upper 0.60 m soil layer at each site. Afforestation with wattle can provide insights into the dynamics of carbon in soils as wattle has a C-3 photosynthetic pathway whereas grasslands in the study area have a predominately C_4 photosynthetic pathway. The different photosynthetic pathways result in widely differing $^{13}C/^{12}C$ ratios. The proportion of soil carbon derived from wattle was calculated using the procedure outlined by Bernoux et al. (1998), using Eq. (1):

$$f_{t(W)} = \frac{\delta^{13}C_{(soil)} - \delta^{13}C_{(grass)}}{\delta^{13}C_{(wa)} - \delta^{13}C_{(grass)}} \quad (1)$$

where $f_{t(W)}$ is the fraction of soil organic matter derived from the C-3 species (wattle); $\delta^{13}C_{(soil)}$ is the $\delta^{13}C$ value of the soil sampled; $\delta^{13}C_{(grass)}$ is the $\delta^{13}C$ value of the grassland soil; $\delta^{13}C_{(Wa)}$ is the $\delta^{13}C$ value of the soil organic matter derived from the wattle species. The final ^{13}C signature of SOM derived from wattle is not known as there is no site with a long wattle history. In the absence of a directly measurable $\delta^{13}C$ value for the wattle derived soil organic matter, the isotopic signature of bulk plant material from wattle was used (an average of the $\delta^{13}C$ for wattle stems and leaves was used). Estimated pool size of C derived from wattle, C_W and from grass, C_G were calculated using Eqs. (2) and (3)

$$C_G = \left(1 - f_{t(w)}\right) \times C_{total} \quad (2)$$

$$C_W = \left(f_{t(w)}\right) \times C_{total} \quad (3)$$

where C_{total} is the total content of C in the soil. One and two way analysis of variance tests (ANOVA) were used to determine stand age effects for soil carbon contents and storage and depth; and biomass carbon in litter. The significance level was at $p < 0.05$ and a post hoc test (Tukey) was used to determine significant differences between sites. All statistical analyses were conducted using SPSS 20 (IBM Corp. 2001).

Results

Soil physical properties

Soils in Madlangala are classified as sandy loams (clay content ranging from 18 to 23 %), whilst Motseng has sandy clay loams (clay content ranging from 24 to 28 %) (Table 2). The bulk density of soils generally increased with increasing depth. For all Madlangala sites, there were no statistically significant differences in bulk density at the respective depths. In Motseng, the bulk density at 0–0.05 m for Mo1 (grassland) was significantly higher than Mo3; whilst bulk density at Mo2 at depth 0.5 m was significantly lower than Mo4.

Soil organic carbon

A one-way ANOVA of the effect of depth revealed a significant decrease in SOC content with depth for all sites at both Madlangala and Motseng (Table 3). No significant effect was found when comparing soil carbon content at the same depth between sites at Madlangala for depths 0–0.05 m ($p = 0.72$), 0.1 m ($p = 0.39$), and 0.25 m ($p = 0.52$). However, for depth 0.5 m, a significant effect was evident, the post hoc test revealing a significant difference between Ma4 (>50 year wattle) and Ma2 (10–30 year wattle) (Table 3). In Motseng, a significant effect of depth on soil carbon was evident between all sites at all four depths (Table 3). For depth 0–0.05 m, soil carbon for site Mo2 was significantly lower than Mo1 and Mo4. At depth 0.1 m, soil carbon decreased significantly according to tree age, Mo1 (grassland) being higher than Mo2, which in turn was higher than Mo3 and Mo4. A similar pattern was evident in Motseng for depths 0.25 m and 0.5 m although Mo1 and Mo2 were not significant. For both of these depths soil carbon content of Mo4 was significantly lower than Mo1.

For Madlangala, a two-way ANOVA revealed a significant effect of depth, but not sampling site ($p = 0.24$) on soil carbon. The interaction between depth and site was not significantly different ($p = 0.68$), indicating no effect of wattle stand age on soil carbon. For Motseng, the two-way ANOVA showed a significant effect of depth and stand age on soil carbon. The interaction between depth and site

Table 2 Soil physical properties for Madlangala and Motseng sites

Site	Description	Soil bulk density (Mg m^{-3}) by depth (m)				Particle size analysis (%)			Texture class
		0–0.05	0.1	0.25	0.50	<2 μm	2–20 μm	20–2000 μm	
Ma1	Grassland	1.39 (0.06)	1.48 (0.03)	1.45 (0.07)	1.54 (0.05)	18	11	71	Sandy loam
Ma2	Wattle 0–10 years	1.21 (0.11)	1.36 (0.04)	1.42 (0.05)	1.58 (0.04)	19	8	74	Sandy loam
Ma3	Wattle 10–30 years	1.25 (0.08)	1.34 (0.23)	1.50 (0.15)	1.56 (0.07)	20	6	74	Sandy loam
Ma4	Wattle >50 years	1.30 (0.05)	1.30 (0.10)	1.39 (0.06)	1.52 (0.19)	23	9	68	Sandy loam
Mo1	Grassland	1.45 (0.05)	1.54 (0.03)	1.51 (0.03)	1.53 (0.06)	24	13	63	Sandy clay loam
Mo2	Wattle 0–10 years	1.36 (0.04)	1.35 (0.08)	1.46 (0.04)	1.36 (0.01)	28	10	62	Sandy clay loam
Mo3	Wattle 10–20 years	1.18 (0.45)	1.50 (0.15)	1.43 (0.01)	1.42 (0.12)	28	8	64	Sandy clay loam
Mo4	Wattle >50 years	1.26 (0.08)	1.46 (0.02)	1.57 (0.06)	1.58 (0.04)	25	14	61	Sandy clay loam

Values for bulk density are given for the different depth ranges while particle size analysis is for the topsoil. Standard deviation for bulk density is given in parenthesis

Table 3 Soil carbon contents (%) for four Madlangala (Ma1–Ma4) and four Motseng (Mo1–Mo4) sites

Site	Description	Mean soil C (%) by depth (m)			
		0–0.05	0.1	0.25	0.50
Ma1	Grassland	2.18 (0.33) aA	1.68 (0.13) aB	1.02 (0.11) aC	0.48 (0.02) abD
Ma2	Wattle 0–10 years	2.45 (0.33) aA	1.62 (0.06) aB	1.05 (0.16) aC	0.28 (0.04) aD
Ma3	Wattle 10–30 years	2.26 (0.30) aA	1.68 (0.26) aAB	1.26 (0.43) aBC	0.53 (0.19) abC
Ma4	Wattle >50 years	2.31 (0.08) aA	1.87 (0.21) aB	1.28 (0.20) aC	0.55 (0.07) bD
Mo1	Grassland	2.56 (0.21) aA	1.84 (0.13) aB	1.34 (0.13) aC	0.54 (0.13) aD
Mo2	Wattle 0–10 years	1.49 (0.12) bA	1.29 (0.14) bAB	0.99 (0.16) abB	0.44 (0.09) abC
Mo3	Wattle 10–20 years	2.10 (0.45) abcA	0.84 (0.13) cB	0.63 (0.25) bcB	0.34 (0.18) abB
Mo4	Wattle >50 years	2.56 (0.11) acA	0.76 (0.26) cB	0.28 (0.06) cC	0.20 (0.06) bC

Mean values are followed by standard deviation in parenthesis

For each site, different lower-case letters in the same column indicate significance differences ($p < 0.05$); whilst different upper-case letters in the same row indicate significant differences ($p < 0.05$)

was also significant, indicating an effect of wattle stand age on soil carbon.

For the Madlangala site (Fig. 2a), carbon stocks to 0.6 m ranged between 77 Mg ha^{-1} (Ma2) and 97 Mg ha^{-1} (Ma4). There was no statistically significant effect of stand age on soil carbon stocks ($p = 0.15$), therefore there was no evident effect of the transition from grassland to wattle and increasing wattle stand age on soil carbon stocks at this site. In Motseng (Fig. 2b) soil carbon stocks ranged between 44 Mg ha^{-1} (Mo4) and 105 Mg ha^{-1} (Mo1). The statistical analysis showed a significant effect of stand age on soil carbon stocks. The post hoc test demonstrates a clear decline in SOC stocks following the change from grassland to forest (Mo1 was significantly higher than all other sites). A significant

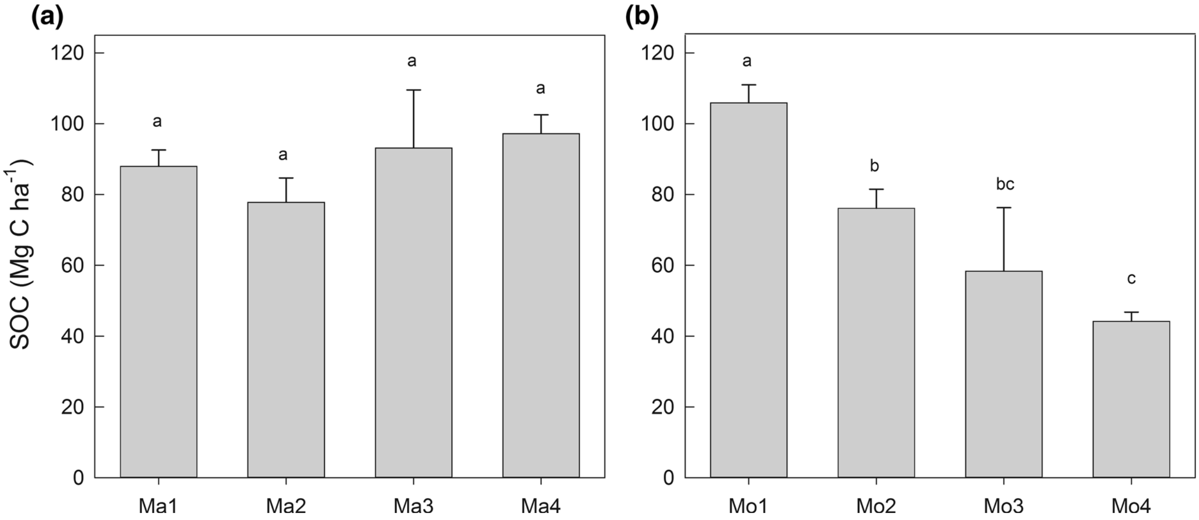

Fig. 2 Mean values for soil organic carbon stocks for Madlangala (**a**) and Motseng (**b**) sites based on the equivalent mass approach for the densest sample to a depth of 0.6 m. *Error bars* indicate the standard deviation. Means with the *same letter* do not differ at $p < 0.05$

decrease in soil carbon stocks with increasing stand age was also observed (Fig. 2b). The grassland (Mo1) had significantly higher stocks than all wattle stands of all ages and the oldest wattle stand, Mo4, was significantly lower than all other sites.

Wattle and grassland derived soil carbon

The proportion of SOC derived from wattle for the respective sampling sites at different depths is presented in Fig. 3a for Madlangala and Fig. 3b for Motseng. The pattern is similar for all sampling sites in both Madlangala and Motseng, with the proportion of wattle-derived carbon decreasing with depth at both sites. However, for Madlangala, there is little difference in the fraction of C derived from wattle for the respective wattle stand ages. At depth 1, the amount of wattle-derived carbon is between 0.42 and 0.47 and decreases with increasing depth to between 0.14 and 0.23 at depth 4. At Motseng, the youngest wattle stand (Mo2) has the lowest proportion of wattle-derived soil carbon, whilst the oldest wattle stand (Mo4) has the highest proportion of wattle derived carbon, except at depth 1, where it is similar to Mo3.

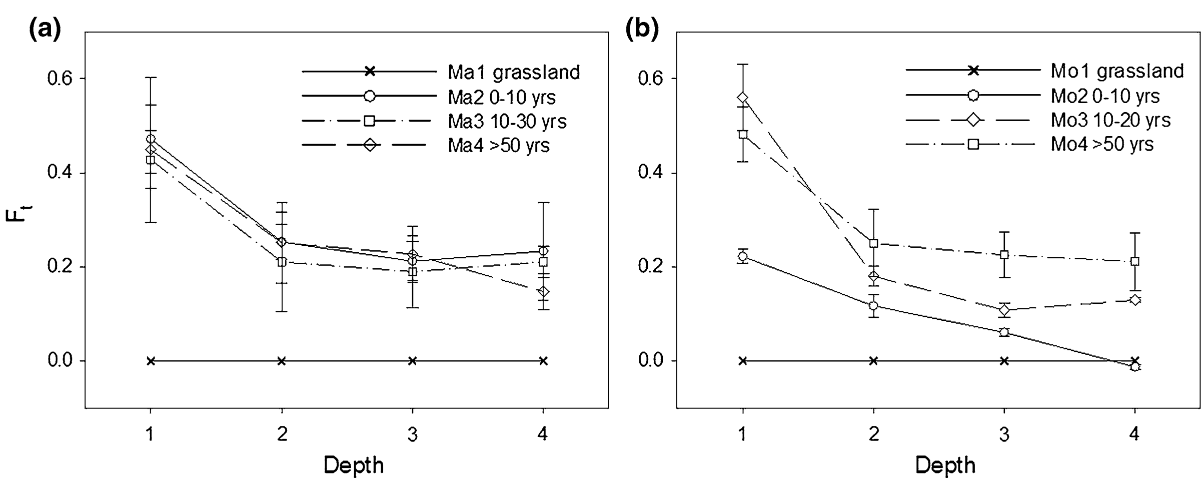

Fig. 3 Proportions of soil organic carbon derived from wattle (Ft) for the respective depths and sites at Madlangala (**a**) and Motseng (**b**). Depth 1 = 0–0.5 m, depth 2 = 0.1 m, depth 3 = 0.25 m and depth 4 = 0.5 m. *Error bars* denote standard deviation

Carbon from surface litter

Total carbon amounts in surface litter were not statistically different for the Madlangala sites ($p = 0.21$) (Fig. 4a). Furthermore, the one way ANOVA revealed no effects of wattle age on debris ($p = 0.27$) or wood ($p = 0.32$). A significant effect was evident for bark, where Ma4 has significantly more carbon in bark than Ma3. In Motseng, the one way ANOVA showed a significant wattle age effect on total litter carbon, bark and debris, whilst no significant effect was found for wood ($p = 0.18$) (Fig. 4b). The highest amount of surface litter carbon was at Mo3 (wattle 10–20 years), whilst there was no difference between Mo2 and Mo4. M02 had significantly less carbon in debris than Mo3, whilst Mo4 had significantly more carbon in bark than Mo3. Surface litter consisted primarily of fine debris at both sites (55–74 %).

Total carbon stocks for SOC and litter and landscape analysis

Total carbon stocks including carbon in the soil and litter are presented in Fig. 5a, b. Combined litter and soil carbon stocks were not statistically different between any of the sites in Madlangala ($p = 0.07$). For Motseng, the combined litter stocks in the litter and soil pools were significantly different for the different sites ($p = 0.001$). Grassland (Mo1) had a significantly higher stock than other sites, whilst the two oldest wattle stands (Mo3 and Mo4) had the lowest contents.

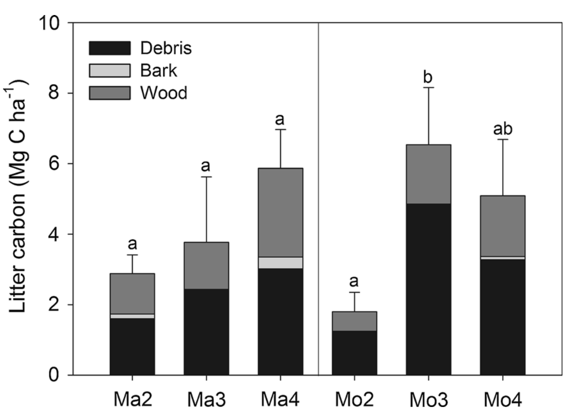

Fig. 4 Mean carbon stocks of surface litter, total and for various components for Madlangala (*a*) and Motseng (*b*) wattle sites (grassland sites were zero). *Error bars* indicated standard deviation of total mean. Means with the *same letter* for wattle stand age within each site do not differ at $p < 0.05$

An image of the Motseng sub-site analysed for the land classification according to wattle stand age is presented in Fig. 6. The total area of the sub-site was 906 ha, 64 % of which was grassland, 15 % wattle over 20 years and 21 % wattle under 20 years. The carbon density in soil and litter for the area, with the current land-cover distribution was 92 Mg C ha^{-1}, with the grassland containing the most substantial amount of carbon. Based on the current land-cover distribution, we calculated a number of scenarios based on potential encroachment or clearing. If the area was never encroached by wattle, i.e. if it still was grassland, the sub-site would theoretically have a carbon intensity of approximately 109 Mg C ha^{-1}). A second scenario, projecting that the full area was covered in wattle (older than 20 years), would result in a belowground carbon stock of 49 Mg C ha^{-1}.

Discussion

Soil carbon content and stocks

The pattern in soil carbon content, presenting a decline with increasing depth for each sampling site, was reflected at both Madlangala and Motseng, is well documented in the literature (Li et al. 2012; Don et al. 2011). Analysis of the effects of wattle age indicated a marked difference in effects of wattle encroachment between Madlangala and Motseng. In Madlangala, other than at 0.5 m in the oldest wattle stand (Ma4), there was no observed effect of wattle stand age on carbon content at the respective depths, whilst in Motseng, a significant effect of depth and stand age was found. Here, the carbon content by depth generally declined with increasing wattle stand age. Davis and Condron (2002) found an initial decrease in soil C following afforestation, primarily in the top 0–0.1 m of soil. However, this effect was only evident in young forest stands <20 years old. For older stands, there was little difference in soil C levels. Their results indicate that the reduction in mineral soil C following afforestation is a rapid but brief process and there is generally little effect below 0.10 m.

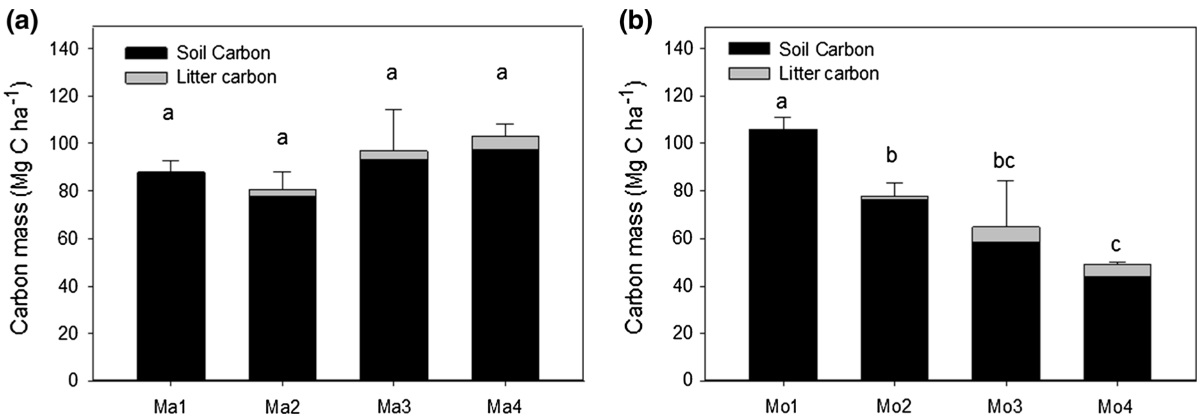

Fig. 5 Total carbon stocks in soil and litter for sampling sites in Madlangala (**a**) and Motseng (**b**). *Error bars* indicated standard deviation of total mean. Means with the same letter for wattle stand age within each site do not differ at $p < 0.05$

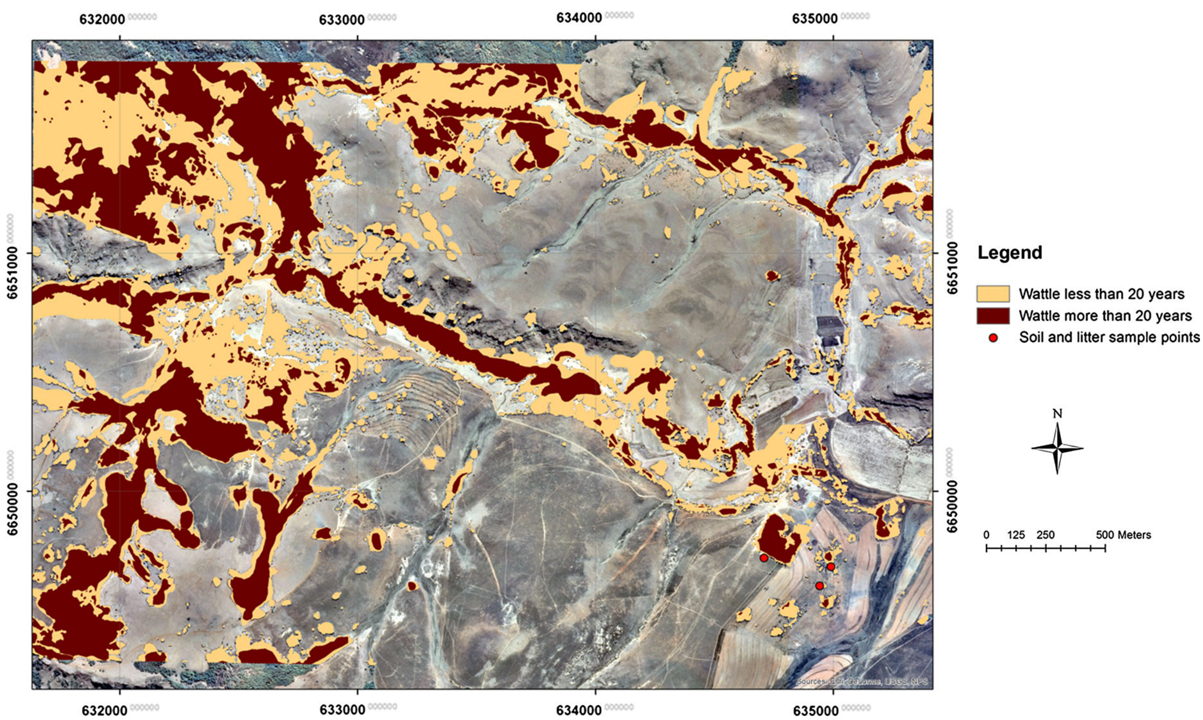

Fig. 6 Overview of the landscape analysis undertaken at the Motseng sub-site using a unique value based classification

The differences between Motseng and Madlangala are reflected in the total soil carbon stocks to a depth of 0.60 m. No significant differences were observed between grassland (Ma1) and all wattle ages in Madlangala, although Ma2 (wattle 0–10 years) was slightly lower. In Motseng, the grassland had significantly more carbon than wattle of all ages—the grassland contained just over twice as much carbon than the oldest wattle stand. Pinno and Wilson (2011) studied (in a temperate climate) the effect of woody encroachment on grasslands and found total soil C to a depth of 0.6 m was highest in grassland at approximately 75 Mg ha^{-1} C, whilst the forest (22–44 years old) had approximately 50 Mg ha^{-1} C—values in a similar range to those observed in the current study. Mills et al. (2005) measured soil carbon contents of grasslands at a study site in close proximity to the current study and found carbon stocks to a depth of 0.5 m above 150 Mg C ha^{-1}—higher than those observed in our study.

The isotopic analysis of the wattle-specific contribution to new soil carbon shows that grassland derived carbon in the surface layer is replaced rapidly by wattle, with just under 50 % the carbon in the top 5 cm of the mineral soil being wattle derived for all sites in Madlangala and the older two wattle sites in Motseng. The observed effect in the top layers is due to the addition of carbon from litter biomass from wattle and mineralisation of organic matter from grass. The observed patterns in proportion of carbon derived from wattle were similar for Madlangala and Motseng sites, however, at the Madlangala site, wattle derived C constituted a large fraction of the soil C earlier than we expected. For example, the youngest wattle stand contributed approximately 20 % of new carbon at the 0.5 m depth, which is a surprisingly rapid change. Contrary to this, the Motseng site demonstrated a wattle-stand age differentiated change in wattle-derived carbon, where the youngest stand had the lowest amount of wattle derived carbon, which decreased by depth and was zero at the lowest depth. Comparing the two sites, it is evident that all the stands in Madlangala show profiles of the fractions of wattle derived C resembling the old stands at the Motseng highlighting the rapid changes occurring at the Madlangala sites. Both sites demonstrate that at lower depths (0.5 m), changes in soil carbon induced by landscape change occur very slowly, with only approximately 20 % of soil carbon coming from wattle after 50 years. Boutton et al. (2009), using a similar chronosequence approach to study tree encroachment of grassland in Texas, witnessed a similar trend. They found that 130 years after tree encroachment, the soil still contained between 60 and 80 % of grassland derived carbon (at a depth of 0.15–0.30 m), demonstrating that this fraction is highly resistant to decomposition and may constitute an important pool for long-term storage of carbon.

Changes in soil carbon following afforestation depend on previous land-use, climate and type of forest established (Paul et al. 2002). De Deyn et al. (2008) highlight water availability, fire and grazing as major controls of carbon input quantity and quality in grassland. Clay mineralogy and soil texture might have an effect as some minerals may offer more protection than others and as soils with more clay typically contain higher levels of carbon. However, we attempted to overcome these issues by selecting sampling sites within close proximity of each other. The observed different patterns in changes in soil carbon across the chronosequence at Motseng and Madlangala were surprising. The Motseng site bears evidence of a seemingly strong effect of wattle encroachment on soil carbon, whilst Madlangala showed little effect. On the other hand, the fraction of wattle derived C is increasing very rapidly at Madlangala and more slowly at Motseng. The increment in wattle derived C in the soils corresponds to a wattle-derived C stock in the soil profile of 5.4 t C ha^{-1} in the youngest age class (Mo2), 14.1 t C ha^{-1} in Mo4, suggesting a maximum wattle derived storage rate of 0.5–1 t C in the first years after wattle encroachment. In the Madlangala site, wattle-derived C in the soil profile reached 20 t ha^{-1} already within the first 10 years of conversion (Ma2), and remained at that level in Ma3 and Ma4. This implies quite high storage rates of wattle derived C of approximately 2 t C $year^{-1}$ for the first 10 years. The differences between the two sites in terms of changes in SOC stocks could be explained by a range of factors including soil type and water availability which may affect equilibrium levels of SOC under grassland and wattle. However, we speculate that the primary reason is management differences between the two sites. The Motseng site is located in a more remote location than Madlangala, with a lower population density and less landscape disturbance. WfW has operated in the Madlangala area since the late 90s, whilst there have been no activities in Motseng. In this regard, Motseng can be considered as undisturbed, whilst Madlangala sites have been subject to more burning (practiced at times to facilitate clearing) and general cutting activities. For Madlangala, we speculate that the lack of differences in soil carbon contents is due to the effect of clearing and burning. The very high accumulation of wattle derived carbon may be explained by burning which will generate black carbon (i.e. charcoal) from wattle which will be incorporated in the soil, so that the proportion of wattle derived carbon will increase substantially compared to a non-burnt site, as the black carbon is resistant to degradation (Bruun et al. 2014; Lehmann et al. 2015). This is evident in the amount of soil carbon derived from wattle at the Madlangala site, where, for example Ma2 has as much wattle derived carbon as the oldest stand (Ma4).

Surface litter

Carbon in surface litter biomass in all wattle stands at both sites ranged between 1.8 and 6.5 Mg C ha^{-1}. Forrester et al. (2004) report a litter amount of 2.8 Mg ha^{-1} in a 10 year old black wattle stand, which equates to 1.3 Mg C ha^{-1} (using a carbon content of 0.47 found in this study), whilst Caldeira et al. (2003) report values of 2.3 and 4.5 Mg C ha^{-1} for a 4 and 6 year old stand of black wattle in Brazil. These values lie in a similar range to the findings in the present study. Litter is an important input of carbon to soil through decomposition (De Deyn et al. 2008). For example, decomposition trials undertaken with wattle leaves by de Neergaard et al. (2005) demonstrated a relatively fast C mineralization of the litter, releasing 27–35 % of the initial C content during 5 months of decomposition. It is however, important to note that wattle litter is a heterogeneous mix of bark, leaves, seeds and wood which will decompose at different rates.

Landscape analysis

The land use classification for extrapolation of soil and litter carbon stock measurements provided an idea of the differences in magnitude of carbon storage when scaling measurements up to the landscape scale. The simple scenarios depicted that the current composition of grassland and wattle of different ages has resulted in a decrease in carbon stocks in soil and litter of 20 % when compared to a pure grassland scenario, whilst a scenario of full cover of the sub-site of wattle would result in less than half the amount of carbon in litter and soil compared to if the area was all indigenous grassland. The method was only conducted in Motseng as this was a test of this method for extrapolation of carbon measurements. It is clear, however, that the changes at Madlangala would have been much smaller and therefore caution should be used when extrapolating the results. However, the method offers potential for the scaling up of such a methodology applied in this study to larger areas which can allow for a broader quantification of changes in total stocks. The methodology requires further testing and ground truthing to overcome scaling errors, for example brought about by differences in soil characteristics.

Conclusion

The study set out to investigate how black wattle encroachment of natural grasslands in South Africa effects soil and litter carbon stocks and dynamics. The study found that woody encroachment of grassland at the Madlangala site had no significant effect on soil and litter carbon stocks. The Motseng site showed a clear decline in combined soil and litter carbon stocks following wattle encroachment. The lowest stock was in the oldest wattle stand, meaning that carbon stocks are still declining after 50 years of encroachment. The results from the two sites demonstrate the importance of considering changes in soil carbon, in particular for Motseng. For example, the soil carbon reduction with increasing wattle stand age in Motseng may off-set aboveground biomass gains. We speculate that the lack of differences between grassland and wattle stands of varying ages in soil carbon in Madlangala may be due to management effects and burning, however the refutation or corroboration of this would require further study of more chronosequences as the differences between the two sites may also be explained by soil type or water availability.

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