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Tagasaste (*Cytisus proliferus* Link.) reforestation as an option for carbon mitigation in dryland farming systems

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ABSTRACT

The Agriculture, Forestry and Other Land Use Sector (AFOLU) plays a major role in national and international strategies to manage increasing global greenhouse gas emissions. This study investigated the option of increasing carbon storage in biomass and poorly productive soils in dryland agricultural systems, while avoiding competition with food production, using tagasaste (*Cytisus proliferus* Link.), a woody N-fixing perennial species. Perennial plants often have deeper and more extensive root systems than annual plants, and therefore may increase soil organic carbon (SOC) stocks deeper than the IPCC standard sampling depth of 0.3m. Above- and below-ground biomass carbon and SOC to a depth of 2 m were measured on a 22-yr-old replicated field experiment in Western Australia (mean annual rainfall, 498 mm yr^{-1}) comparing unmanaged plantations of tagasaste with conventional annual crop and pasture rotations. Carbon sequestration was 2.5 Mg C ha^{-1} yr^{-1} over the 22-yr lifespan for the tagasaste treatments, with a change of 0.9 Mg C ha^{-1} yr^{-1} in SOC and 1.6 Mg C ha^{-1} yr^{-1} in biomass. Tagasaste plots contained significantly larger SOC stocks compared with control plots for soil to 0.9 m, however beyond this depth, treatment differences were not significant. It is recommended that soil sampling be extended to depths of 1 m under such perennial systems with no benefit from sampling to depths deeper than this. In contrast to its current use as a fodder supplement for livestock, this study clearly demonstrates the potential of tagasaste for carbon mitigation within dryland farming systems, especially on soils marginal for conventional agriculture.

1. Introduction

Currently, the Agriculture, Forestry and Other Land Use (AFOLU) sector accounts for almost a quarter (10–12 Pg CO_2–e yr^{-1}) of global anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management (Smith et al., 2014). Considering the accumulation of anthropogenic CO_2 emissions since the beginning of the Industrial Era it has been estimated that 180 ± 80 Pg C were emitted to the atmosphere between 1750 and 2011 due to land use change, including deforestation, afforestation and reforestation (Ciais et al., 2013). These large historic losses and the associated potential to return to pre-deforestation conditions are the reasons many researchers believe there is great potential for agricultural systems to sequester large amounts of atmospheric CO_2 relative to current levels. Mitigation can occur through several pathways such as increasing carbon stocks in biomass and soils through revegetation, afforestation or reforestation (Canadell and Raupach, 2008), by substituting fossil fuel use through the use of bioenergy (Chum et al., 2011) or by reducing agricultural emissions from ruminant livestock and soils (Smith et al., 2014). Similarly, Lal (2004), estimated that adoption of improved agricultural management practices would enable the world's agricultural soils to potentially sequester 0.4–0.8 Pg C per year.

Although there can be positive benefits of mitigation (Bustamante et al., 2014), a major issue with mitigation on agricultural land is the competition with food (Smith et al., 2014) and water (Jackson et al., 2005). Agroforestry – the integration of agriculture and forestry – is one option to increase carbon and increase the sustainability of land use (Watson et al., 2000). Because of its potential to mitigate climate change and its links to agriculture and forestry, agroforestry is gaining particular attention in developing countries (Anderson and Zerriffi, 2012).

Reforestation of agricultural land has been proposed as a way to combat land degradation problems like salinity, wind erosion, water balance issues, and biodiversity reduction (Harper et al.,

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2012b; Lal 2009; Lorenz and Lal 2014). Increasing desertification has affected profitability and livelihoods across agricultural lands globally (Reed and Stringer, 2015) and creating carbon sinks through reforestation with deep-rooted perennial systems and selling the carbon in carbon markets may represent an option for more profitable land uses (Harper et al., 2007) and repair or stabilize degraded land (Lorenz and Lal, 2014).

Carbon mitigation could be achieved by sequestering additional carbon in biomass and soils, or producing biomass for bioenergy production. One option for increasing carbon mitigation with perennials, while avoiding land competition issues, is to use abandoned or marginal farmland (Sochacki et al., 2012). Perennials have extensive root systems, which can grow deep into the soil and thereby increase deep soil organic carbon (SOC) inputs (Lorenz and Lal 2014; Nair et al., 2010). Sequestration rates vary depending on factors such as species, plant age, climate, soil composition, and topography (Polglase et al., 2013). Yet, there are few studies on carbon storage in perennial species suitable for the low-rainfall areas of Australia and other similar Mediterranean environments.

Compared to many northern hemisphere soils, Australian soils are often severely constrained for agricultural production by the lack of nutrients, accumulation of salt, and poor water retention (Chen et al., 2009). In addition, a drying climate may further limit the carbon sequestration potential of Australian soils. However, Sanderman et al. (2010) identified several possible ways to maintain or increase organic carbon in Australian agricultural soils. Some could be achieved by management changes within existing cropping/livestock systems, while others require more radical shifts to different systems such as conversion from cropping to permanent pasture, or other perennial-based systems.

Tagasaste (*Cytisus proliferus* Link.), or tree lucerne, is a hardy evergreen shrub originating from the Canary Islands (Snook, 1982). Its edible foliage provides supplementary fodder for ruminants (Townsend and Radcliffe, 1990). Tagasaste grows well on deep sandy soils, but is intolerant of salt and waterlogging conditions (Wiley and Davey, 2000). Its root system can extend deep into the soil (up to 10 m) (Snook, 1982), where it can access deeper water sources unavailable to annual plants (Lefroy et al., 2001).

Despite its potential value in grazing systems and also its adaptation to infertile soils in semi-arid climates, the carbon mitigation potential of tagasaste has not been examined in the formal literature, despite promising unpublished studies (Wiley and Davey, 2000). In this paper we examine the changes in biomass accumulation, and quantity and distribution of SOC following a shift in land use from an annual to a perennial-based tagasaste system in a long-term (22 year) replicated experiment (Lefroy et al., 2001). Many previous studies have investigated changes in SOC to only 0.3 m soil depth, as this is the Intergovernmental Panel on Climate Change (Aalde et al., 2006) default. A few studies have reported soil carbon stores to much greater depths (Harper and Tibbett, 2013; Jobbágy and Jackson, 2000). Given the reports of tagasaste roots occurring to depths of several metres (Lefroy et al., 2001) we also examined SOC accumulation to a depth of 2 m. Our results will assist in establishing the potential of this species for carbon mitigation, its potential environmental co-benefits and make conclusions as to whether it is cost-effective to include deep soil sampling in carbon projects.

2. Materials and methods

2.1. Site layout

The study site was located north-west of Moora, a town-site located 177 km north of Perth in the Wheatbelt region of Western Australia (WA) (Fig. 1). This study involved revisiting an experimental site in 2014, which was established in 1992 by Lefroy et al. (2001) to compare the water use and productivity of tagasaste and cereal crops. The soil is classified under the Australian Soil Classification (Isbell, 1996) as a yellow-orthic Tenosol (yellow deep sand). The site has a Mediterranean climate with mean annual rainfall and pan evaporation measured by the Australian Bureau of Meteorology at Moora (12 km distant), over the 22 year period of 498 and 2190 mm yr^{-1}, respectively.

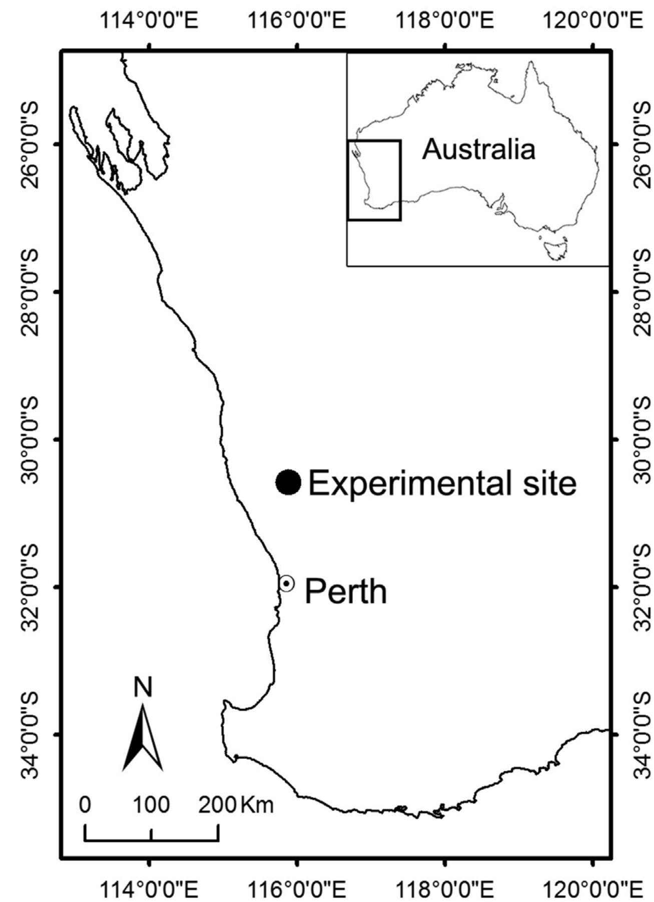

Fig. 1. Location of the study site (30°34′36.34″S; 115°52′23.55″E) near Moora, Western Australia.

The site contained two different types of tagasaste plantings (blocks and alleys) and agricultural controls in plots 50 m by 160 m in size (Fig. 2). The topography of the site was level and no differences in soil profile characteristics were observed. Tagasaste blocks consisted of tree rows 6 m apart and 0.7 m tree spacing within rows to give an effective density of 2300 trees ha^{-1}. Tagasaste alleys contained single tree rows 30 m apart with 0.7 m tree spacing within rows (550 trees ha^{-1}). Trees were left to grow without external interference (other than grazing by sheep) for a period of at least 15 years. Since 2005, the farmland surrounding the tagasaste plantations, and the agricultural control plots, have been under a rotation of wheat, lupins, and annual pasture (grasses and herbs) which is grazed by sheep. The inter-rows are also based on annual pastures but were excluded from any cropping. Grazing by sheep occurred after crop harvest, or during periods of pasture in the surrounding area.

2.2. Soil sampling

A mechanised coring apparatus developed by Sochacki et al. (2007) was used for sampling. Soil cores were sampled with a nominal diameter of 115 mm in the following nine depth intervals (in m):

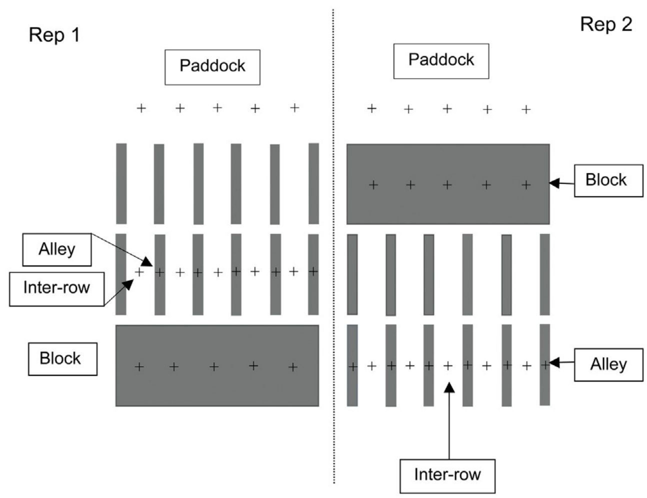

Fig. 2. Schematic site layout indicating position and orientation of the tagasaste plantings on the trial site. Soil sampling positions for controls (inter-row, field) and tagasaste treated plots (alley, block) are marked with '+'.

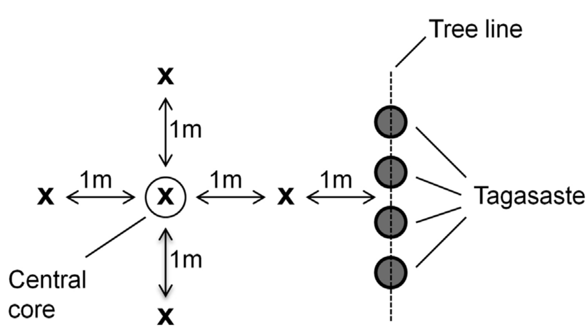

Fig. 3. General core layout for soil sampling at the Moora trial site, representing the tagasaste plot sampling scenario ('X' marks the coring position).

0–0.1; 0.1–0.2; 0.2–0.3; 0.3–0.6; 0.6–0.9; 0.9–1.2; 1.2–1.5; 1.5–1.8; 1.8–2.0.

Soils were sampled from four tagasaste plots and four control plots. The controls were divided into two categories, two plots representing land use outside the experimental area (field) and the other two representing the area between single rows of tagasaste (inter-row). Of the four tagasaste plots two were allocated to the alley treatments and two plots for block plantings (Fig. 2).

Within each plot, five sampling positions were chosen equally distanced along the centre line of the plot, running east to west. The coring layout is illustrated in Fig. 3, located within a 2 m by 2 m grid, which for alley and block plantings was positioned 1 m from and parallel to the tree line. Each sampling grid consisted of one central core sampled to a depth of 2 m, and four additional cores equidistant from the central core, sampled to a depth of 0.3 m.

2.3. Soil processing

All soil samples were air-dried before being passed through a 2 mm sieve. Given that the corer used in this study provided volumetric samples the soil bulk density was also determined following oven drying. The water content of the sieved <2 mm fraction was determined by oven-drying a subsample at 105 °C whereas the >2 mm portion was oven-dried at 75 °C.

Subsamples from each of the five cores from each of the top three depth intervals for the upper 0.3 m were bulked to produce one soil specimen (~250 g) per aforementioned depth interval. This alleviated short-range spatial variation of soil properties. For the remainder of the central core samples (0.3–2.0 m) again a ~250 g sample of each was also obtained for later analysis. Given that each of these deeper cores weighed several kilograms a commercial rotary splitter was used to ensure homogeneity of the soils in these subsamples.

2.4. Soil analysis

Carbon and nitrogen content of these soil samples was analysed on a LECO combustion furnace (Rayment and Lyons, 2010; Method 6B2b) and determined as percentage per gram of the <2 mm soil. Particulate organic C (POC), humic C (HUM) and resistant organic C (ROC) fractions for soil samples were predicted using Mid Infrared Spectroscopy (MIR) (Janik et al., 2007; Sanderman et al., 2011). pH, electrical conductivity and exchangeable cations (Al, Ca, Mg, K and Na; Rayment and Lyons, 2010) and particle size using the pipette method (Gee and Bauder, 1986) were also analysed.

SOC stock for each soil layer was calculated using the equivalent soil mass (ESM) within a specified soil layer (Wendt and Hauser, 2013). With the assumption that there was no transfer of mass (i.e. no deposition or erosion, which cannot be compensated for with volumetric- or mass-based calculations) the ESM calculation was used to compare treatment effects.

2.5. Biomass sampling

Within each of the four alley plots, a subplot consisting of three trees was chosen randomly and destructively sampled to determine tree biomass. A destructive biomass sampling approach was chosen instead of a classical allometric approach due to the condition of the trees. These comprised cramped and multi-stemmed stands that had been left untouched with branches that were tangled with each other.

The results from these subplots were then used to estimate the biomass for plantations with the same tree density. For practicality, an area extending 2 m laterally from each side of the tree row, and for a row length of 2.5 m (three trees) (i.e. a 4 m by 2.5 m rectangle) was marked out for each subplot. Interfering branches from neighbouring trees were carefully removed before sampling commenced on the subplot itself.

In accordance with the method by Snowdon et al. (2002) the sampled above-ground biomass (AGB) of each subplot was separated into five tree components: crown, branch, stem, dead attached, and dead detached (also including surface litter). Dead detached material refers to material like branches and leaves held above ground in the crown or stem forks. The crown component included non-woody elements like leaves, fruits, and twigs. Branches were characterised as woody elements supporting the crown connecting to stems.

The fresh weight of each component was established in the field. Subsamples of crown, branch, and stem material were then taken and placed in calico bags for subsequent laboratory analyses of moisture and carbon content. The weight of the freshly-sampled dead material was considered to be dry weight (climatic conditions were hot and dry at the time of sampling). The C content of the dead material was calculated using the mean values for the C content of the other above-ground components.

Below-ground biomass (BGB) was established by excavating the sub-plots to a depth of approximately 1.5 m (no substantial roots were detected beyond this depth). The soil was placed on a sieving table with a mesh size of 50 mm, and then examined for relevant root material. The collected roots were separated in two size classes: 2 to 5 mm, and >5 mm diameter. Roots were not washed as the sites comprised sandy soils and soil could thus be easily separated from the roots by sieving as described by McKenzie et al. (2000).

Table 1
Summary of mean physical and chemical characteristics of the soils used as controls (pasture/cropland).

Depth	Bulk density	Particle size				EC	pH ($CaCl_2$)	Exchangeable cations					TC	TN
		C	S	FS	CS			Al	Ca	Mg	K	Na		
(m)	($kg\,m^{-3}$)	(%)				($dS\,m^{-1}$)		($cmol(^+)\,kg^{-1}$)					(%)	(%)
0–0.1	1.42	2.9	<0.1	6.1	90.9	0.04	5.5	0.10	1.66	0.30	0.05	0.04	1.1	0.06
0.1–0.2	1.97	2.9	1.9	7.2	88.0	0.02	4.7	0.10	0.39	0.07	0.01	0.03	0.3	0.02
0.2–0.3	1.53	2.9	1.0	9.9	86.2	0.01	4.6	0.10	0.24	0.05	0.01	0.03	0.2	0.01
0.3–0.6	1.65	3.9	<0.1	11.5	84.6	0.01	4.5	0.11	0.13	0.03	0.01	0.03	0.1	<0.01
0.6–0.9	1.74	3.9	1.9	13.4	80.8	0.01	4.7	0.10	0.19	0.05	0.02	0.03	0.1	<0.01
0.9–1.2	1.73	2.9	2.9	5.61	88.6	0.01	5.0	0.10	0.22	0.07	0.02	0.03	<0.1	<0.01
1.2–1.5	1.77	3.9	1.0	11.4	83.7	0.01	5.2	0.10	0.21	0.07	0.06	0.03	<0.1	<0.01
1.5–1.8	1.78	3.9	<0.1	10.3	85.8	0.01	5.4	0.10	0.23	0.06	0.02	0.03	<0.1	<0.01
1.8–2.0	1.64	1.9	3.8	12.0	82.2	0.01	5.5	0.10	0.24	0.05	0.02	0.03	<0.1	<0.01

C, clay; S, silt; FS, fine sand; CS, coarse sand; TC, total carbon; TN, total nitrogen.

The <2 mm roots were not separated and included in the fine earth fraction, as described in the protocols of McKenzie et al. (2000) and Snowdon et al. (2002). The fresh weight of all root material was measured in the field and subsamples were taken for further laboratory analyses.

The carbon content of the live biomass components (crown, branch, stem, and roots) was established using the LECO combustion technique.

2.6. Estimation of carbon sequestered

The biomass data from all four subplots measured, each consisting of 3 trees, were averaged and then scaled up to the nominal planting density of 550 trees ha^{-1} for the tagasaste alleys. Carbon sequestered was estimated using total dry biomass, and the estimated values of carbon content of dry biomass for the different plant components. Carbon was converted to carbon dioxide equivalents based on the molecular weight of carbon dioxide.

2.7. Statistical analysis

Data analysis was conducted using IBM SPSS Statistics Version 21. Analysis of variance was conducted to test the significance of treatments (controls, tagasaste alley, tagasaste block), soil depth, and their interaction in regards to SOC.

3. Results

3.1. Soil properties

Soils in control plots were uniformly sandy to 2 m depth with clay contents of 1.9-3.9% and acidic with pH values ranging from 4.5 to 5.5 (Table 1). Concentrations of C, N and exchangeable cations were generally greatest in the top layer and decreased with depth. Tagasaste plots showed significantly higher concentrations (compared with the control plots) of Exch-Mg, Exch-Na, total N and total C for each depth interval, whereas Exch-K was only significantly greater at the 0.1–0.2 m depths (Table 2). Exch-Al and Exch-Ca did not vary significantly between treatments. While electrical conductivity (EC) values were significantly higher for soils under tagasaste for all three surface soil depths, pH values showed no such pattern.

Total SOC ranged from 30.4 Mg ha^{-1} (control) to 59.9 Mg ha^{-1} (block plots) (Table 3). Statistical analysis showed that SOC content was affected by both treatment (controls, tagasaste) and soil depth (Table 3). Tagasaste plots showed significantly higher SOC values compared with controls for soil sample depth intervals to 0.9 m (Fig. 4, Table 3). Beyond this depth, differences due to treatments were not significant. The biggest difference in SOC between controls and tagasaste plots was detected in the 0-0.1 m soil layer. In general, SOC decreased with increasing depth. No significant difference in SOC was detected between the two different control types (inter-row and field) at any depth.

Very similar distribution patterns for the three carbon pools (POC, ROC, HUM) which represent total SOC were detected when comparing inter-row control treatments and plantation block plots (Fig. 5). Significant differences for relative POC in the carbon pool composition were found only within the first two depth intervals, 0–0.1 m and 0.1–0.2 m, with higher proportions observed in plantation plots relative to control plots. Compared to the control plots a lower proportion for HUM was observed within the first depth interval (0–0.1 m) for the tagasaste blocks (Fig. 5).

Table 2
Mean values of major soil attributes for different land uses for the 0-0.3 m sampling depth. Values for tagasaste were averaged for both alley and block plots. Numbers in bold indicate significant differences ($P < 0.05$) between controls and tagasaste plots for each depth interval.

Soil attribute	Depth interval (m)					
	0–0.1		0.1–0.2		0.2–0.3	
	Land use					
	Crop/pasture	Tagasaste	Crop/pasture	Tagasaste	Crop/pasture	Tagasaste
EC ($dS\,m^{-1}$)	0.04	**0.08**	0.02	**0.04**	0.01	**0.02**
pH	5.5	4.9	4.7	4.6	4.6	4.6
Al ($cmol(^+)\,kg^{-1}$)	0.10	0.10	0.10	0.10	0.10	0.10
Ca ($cmol(^+)\,kg^{-1}$)	1.66	1.91	0.39	0.52	0.24	0.24
K ($cmol(^+)\,kg^{-1}$)	0.05	0.09	0.01	**0.03**	0.01	0.02
Mg ($cmol(^+)\,kg^{-1}$)	0.30	**0.89**	0.07	**0.20**	0.05	**0.12**
Na ($cmol(^+)\,kg^{-1}$)	0.04	**0.11**	0.03	**0.06**	0.03	**0.05**
TC (%)	1.1	**2.5**	0.3	**0.6**	0.2	**0.3**
TN (%)	0.06	**0.21**	0.02	**0.04**	0.01	**0.02**

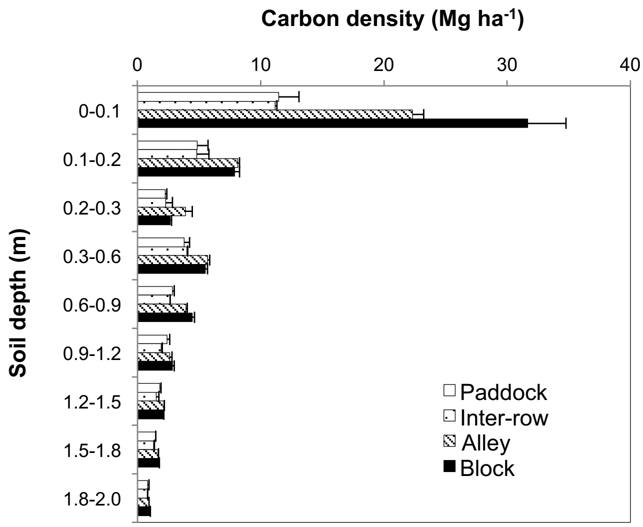

Fig. 4. Mean values of SOC content over depth for control and tagasaste treated plots (alley, block). Error bars indicate SE.

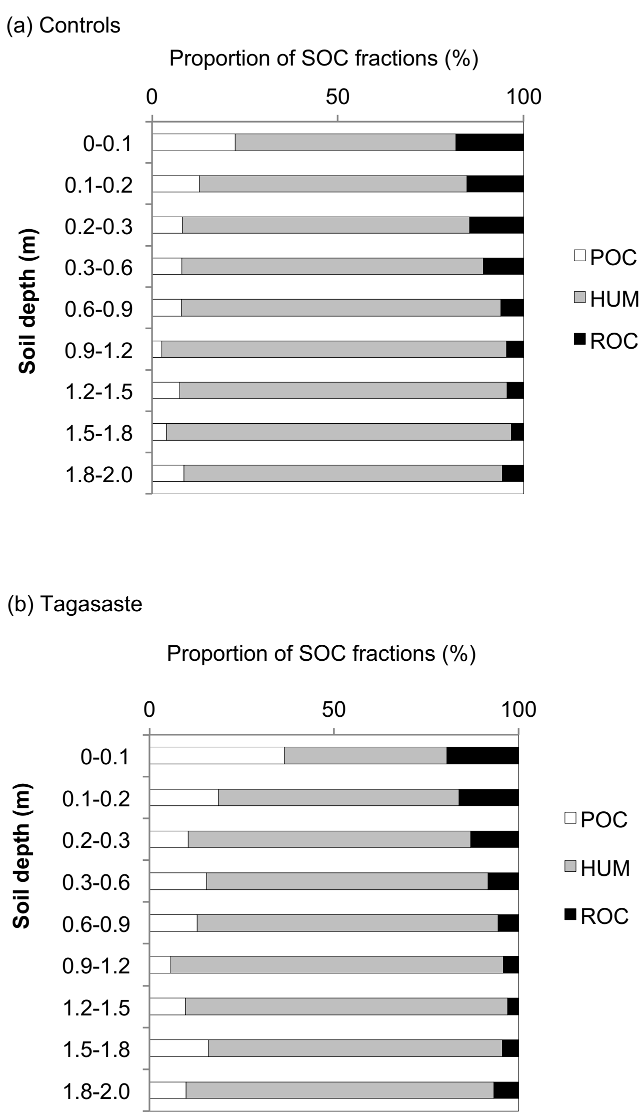

Fig. 5. Differences in concentrations of particulate organic C (POC), humic C (HUM) and resistant organic C (ROC) in (a) the surface 2 m under inter-row control and (b) tagasaste block plots.

Table 3
Summary of SOC mass density (t ha^{-1}) at different depth increments calculated for the site. Means in bold indicate significant variation between controls and tagasaste plots ($P < 0.05$).

Depth	Control field		Control inter-row		Alley		Block	
(m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE
0–0.1	11.5	1.6	11.2	0.2	**22.3**	0.9	**31.7**	3.1
0.1–0.2	4.8	0.9	4.8	1.0	**8.1**	0.1	**7.9**	0.4
0.2–0.3	2.3	0.1	2.3	0.6	**3.9**	0.5	2.7	0.1
0.3–0.6	3.8	0.4	4.0	0.1	**5.7**	0.2	**5.5**	0.2
0.6–0.9	2.8	0.1	2.6	0.0	**3.9**	0.1	**4.4**	0.2
0.9–1.2	2.4	0.2	1.9	0.2	2.6	0.2	2.8	0.2
1.2–1.5	1.8	0.1	1.5	0.2	2.1	0.1	2.1	0.1
1.5–1.8	1.5	0.0	1.3	0.1	1.7	0.0	1.7	0.05
1.8–2.0	0.8	0.1	0.8	0.0	0.9	0.0	1.05	0.0
Total	31.7	0.0	30.4	2.0	**51.4**	0.9	**59.9**	3.1
	Aggregated depths							
0–0.3	18.6	0.6	18.2	1.7	**34.4**	0.5	**42.2**	2.8
0.3–2.0	13.2	0.7	12.2	0.3	**17.0**	0.4	**17.6**	0.3
0–0.9	25.2	0.3	24.9	1.6	**44.0**	0.8	**52.2**	2.8
0.9–2.0	6.5	0.4	5.6	0.4	7.4	0.2	7.7	0.3

Table 4
Carbon content, dry mass (DM), and carbon yields of above (AG) and below ground (BG) biomass components for tagasaste alley plots.

Biomass component		C (% DM)		DM (Mg ha^{-1})		C (Mg ha^{-1})	
		Mean	SE	Mean	SE	Mean	SE
AG	Dead attached	45.8	0.8	15.6	4.5	7.1	2.5
	Dead detached	45.8	0.8	5.1	0.7	2.4	0.4
	Stem	45.8	0.8	7.2	1.4	3.3	0.7
	Branch	48.3	0.7	25.3	2.3	12.2	1.2
	Crown	43.4	0.8	11.3	1.5	4.9	0.5
	Sum			**64.4**	**1.7**	**29.9**	**0.9**
BG	Fine root (2–5 mm)	46.0	0.1	0.3	0.0	0.1	0.0
	Coarse root (>5 mm)	45.1	1.1	11.0	1.3	5.0	0.5
	Sum			**11.3**	**0.4**	**5.2**	**0.2**
	Total			**75.7**	**6.9**	**35.1**	**3.5**

3.2. Biomass

The mean above-ground mean dimensions of the tagasaste plants sampled for biomass were: height 6.18 ± 0.23 m; length 6.51 ± 0.25 m and width 10.80 ± 0.29 m. Carbon contents of above ground biomass components ranged from 43.4 to 48.3%, and for roots 45.1 to 46.0% (Table 4); these values are similar to those reported in the literature for other species (Gifford, 2000). The estimated mean carbon yield (Table 4) of 35.1 Mg C ha^{-1} amounts to an average annual rate of 1.6 Mg C ha^{-1} yr^{-1}, or 5.9 Mg CO_2–e ha^{-1} yr^{-1} for the 22-yr lifespan of this plantation. The calculated dry mass root:shoot ratio of 0.18 ±0.02 is similar to reported values for forestry, where root:shoot ratios generally range from 0.2–0.3 (Penman et al., 2003).

Table 5 summarizes the additional carbon storage when comparing the tagasaste plots with the control plots. Comparing tagasaste alley plots with controls the difference in total carbon mass, including SOC and biomass carbon, was 55.4 Mg C ha^{-1}. This equates to an average annual sequestration rate of 2.5 Mg C ha^{-1} yr^{-1}, or 9.2 Mg CO_2-e ha^{-1} yr^{-1}, for the 22-yr lifespan of the trial site.

The biomass of the denser tagasaste block plots was not measured in this study, due to problems with access. Nonetheless, the plots contained greater amounts of SOC accumulation (28.8 Mg C ha^{-1}) compared to the alley plots (20.3 Mg C ha^{-1}).

Table 5
Summary for SOC (aggregated depths), biomass carbon yields, and the difference (Δ) between tagasaste alley plots and controls. Biomass was not measured in block plots. The "Control" is the mean of the field and inter-row control plots. All values are means.

Component	Control	Alley	Block	Δ Alley	Δ Block
	C ($Mg\ ha^{-1}$)				
AG BM	0.0	29.9		29.9	
BG BM	0.0	5.2		5.2	
Sum Biomass	**0.0**	**35.1**		**35.1**	
SOC (0–0.3 m)	18.4	34.4	42.2	16.0	23.8
SOC (0.3–2.0 m)	12.7	17.0	17.6	4.3	5.0
Sum SOC (0–2.0 m)	**31.1**	**51.4**	**59.9**	**20.3**	**28.8**
Total	**31.1**	**86.5**		**55.4**	

4. Discussion

4.1. Carbon sequestration

The integration of the perennial shrub tagasaste (*C. proliferus)* as an alley system into a dryland farming environment sequestered 55.4 Mg C ha^{-1} over a period of 22 years. This included 35.1 Mg C ha^{-1} in biomass and 20.3 Mg ha^{-1} in soil. Given the loss of carbon as a result of land clearing for agriculture and land degradation such as wind erosion for sandy soils in these dryland farming systems (Harper et al., 2010) the integration of this perennial species into these farming systems could restore lost carbon, provide additional environmental benefits and improve the profitability and sustainability of dryland farming systems on poorly productive sandy soils. The data are only from a single site and thus there should be some caution about the applicability of the results more broadly. Nonetheless, the results presented here point to the need to more comprehensively examine the utility of this species for carbon mitigation.

4.2. Soil organic carbon

Previous studies of tagasaste have not reported the potential of this deep rooted species to sequester soil carbon at depth. In sampling to a depth of 2.0 m, we found significant ($P < 0.05$) differences in SOC for tagasaste treatments, not only for the current IPCC standard sampling depth of 0–0.3 m, but also to depths of 0.9 m. These results support the hypothesis that the more extensive root systems of perennials can help to increase SOC deeper in the soil profile. Beyond this depth observed differences between treatments were not significant, perhaps reflecting the need for greater sampling intensity (Table 3).

Although previous work examining the water use of tagasaste at this site (Lefroy et al., 2001) demonstrated water uptake to depths of 4 m, and thus evidence of the presence of tagasaste roots, this was not reflected in a significant change in SOC at depths beyond 0.9 m. For example, the SOC stored in the 0.9–2.0 m increment was 6.5 ± 0.4 t ha^{-1} in the control plots compared to 7.4 ± 0.2 t ha^{-1} under the tagasaste alleys (Table 3). However, our results show that sampling to depths below the existing 0.3 m IPCC standard sampling depth is required in order to measure the full potential benefit of perennial shrubs on SOC. Harper and Tibbett (2013) also showed that significant stores of soil carbon occurred at depths greater than 0.3 m. Thus, we recommend that sampling depth under such perennial species be extended to 1 m to account for the additional carbon in the 0.3 m to 0.9 m zone. There is no apparent benefit in sampling deeper than this.

When assessing soil condition and its potential for carbon mitigation it is important to consider the SOC fractions, as they indicate susceptibility of SOC stocks to changes in management or land use (Baldock et al., 2012). Generally, susceptibility will increase as the proportion of energy-rich and decomposable POC (organic carbon associated with particles >50 μm, excluding charcoal carbon) increases, and will decrease as the proportions of the more stable HUM and ROC fractions of SOC increase. POC decomposes relatively quickly (years to decades) and provides an important source of energy for soil microorganisms. It also plays an important role in maintaining soil structure and providing soil nutrients (Chan et al., 2010).

A significantly higher proportion of the less-permanent POC fraction was observed for the surface 0.2 m on the tagasaste plots relative to the controls (36.5% and 22.4% respectively), which is consistent with a shrub biomass source. This is also consistent with findings by other authors indicating that most of the SOC differences following land-use change occur in the more labile POC fraction (Chan et al., 2010; Sanderman et al., 2010), especially in the short-term.

Interestingly, this study showed notable increases in SOC mass storage following the establishment of a woody perennial species, whereas in two other locations in south-western Australia there was no significant difference in SOC 26 years after establishing several species of eucalypts on pasture (Harper et al., 2012a). Similar results were also found by Lawes and Robertson (2012) who compared the SOC content under perennial pasture to that under annual crops or pastures in the northern agricultural region of Western Australia. Although perennials showed larger amounts of SOC, the difference was not significant. These authors noted that greater differences in SOC were observed between sites in their study, rather than between annual and perennial species.

It is important to consider that our findings may be representative of not only SOC sequestered through root-derived C inputs, but also potentially from input of organic matter (i.e. shoot-derived C), as suggested by our results for particulate organic matter in the surface soil. Further, the observed increase of SOC on tagasaste plots may also partially be related to a decline in C loss or redistribution compared with the cropping treatment. These possibilities underline the importance of appropriate reference points for comparison between annual and perennial systems. The ability to detect spatial as well as temporal variance is important in quantifying changes in SOC. For this reason, the availability of genuine replicates in a randomised block design was important in determining statistically significant changes.

Although shifting from annual- to perennial-based plant species has been suggested as an option to maintain or increase SOC in agricultural systems (Sanderman et al., 2010), insufficient experiment-based evidence and knowledge is currently available, particularly in agroforestry systems. Ward et al. (2012) used micrometeorology techniques to demonstrate that the inclusion of belts of trees occupying about 15% of the landscape increased net carbon assimilation by 0.9 Mg CO_2 ha^{-1} yr^{-1}. However, they did not measure soil carbon. More research is required to enable adequate understanding of SOC sequestration processes, and to identify and apply site- and landscape-specific soil management and land-use practices using perennials.

4.3. Biomass carbon

Previous research on tagasaste has mainly focused on its palatability for livestock and influences on farm productivity. Snook (1982) reported an annual yield of around 11.2 Mg ha^{-1} edible dry matter (DM) for a mature 700 stem ha^{-1} system in Western Australia, growing on deep sands, with 875 mm average annual rainfall. A study in New Zealand by Townsend and Radcliffe (1990) estimated an annual yield of 2.5–3.4 Mg edible DM ha^{-1} for tagasaste, based on a 7500 stems ha^{-1} system on silt loam soil with 684 mm average annual rainfall. Tagasaste yields influenced by factors such as plantation layout, age, climate and other site factors.

In this study we calculated a mean carbon yield of 35.1 Mg ha^{-1} for an alley stand which has been unmanaged for 15 years. However, management regimes and the integration of tagasaste into farmland landscapes could potentially be applied in a range of scenarios which would have differing outcomes with regard to mitigation potential. In the unmanaged alley system measured in this study, tagasaste occupied approximately 37.5% of the landscape based on crown cover, with the remaining farmland available for grazing by livestock. The benefits of alley farming systems have been described by Lefroy et al. (1997) and benefits reported as "land equivalent ratios", to quantify the additive benefits by integrating trees into farmland systems compared with a monoculture. Unmanaged stands of tagasaste would have additive benefits via livestock grazing, shelter, reduced wind erosion while mitigating carbon via soil and biomass carbon. Such integrated agroforestry systems may improve sustainability of dryland farming in these regions and restore landscape carbon while accommodating typical farming enterprises without excessively competing with food production or landuse.

If tagasaste is managed as a mature tree stand, biomass production attained in this study is comparable with results from a 26-yr-old reforestation experiments containing four *Eucalyptus* species in two areas with around 450 mm annual rainfall in south-western Australia (Harper et al., 2012a). The amount of accumulated carbon in these 816 trees ha^{-1} plots ranged from 23 to 60 Mg ha^{-1} for tree biomass and 19–34 Mg ha^{-1} for surface litter. This comparison shows that tagasaste, although considered a shrub, can grow to a large size and accumulate substantial amounts of biomass when left unmanaged. Lefroy et al. (1997) projected that approximately 1.3 Mha of land in Australia would be suitable for tagasaste. Given that we estimated carbon sequestration of 9.2 Mg CO_2-e ha^{-1} yr^{-1} over the 22-yr lifespan for the ungrazed tagasaste alley plots (accounting for both SOC as well as above- and below-ground biomass), we conclude that this species could have a valuable role to play both in Australian agriculture and also as a mitigation mechanism for greenhouse gas emissions. Importantly, although this study shows that unmanaged tagasaste can be effective in sequestering C, this might not hold for tagasaste managed for agricultural production. This is clearly an avenue for future research.

4.4. Bioenergy and biofuel

The average annual above ground biomass production over the 22-year period was modest and amounted to 2.9 Mg ha^{-1} yr^{-1} for the alley planting. Potential biomass feedstock has also been reported for other dryland tree crop systems, elsewhere in south-western Australia. (Harper et al., 2014) reported annual biomass yields of 2.1 to 6.7 Mg ha^{-1} yr^{-1} from 5-year eucalypt tree phases planted at 4000 trees ha^{-1} in a low rainfall (300 mm yr^{-1}) area, whereas mallee eucalypts planted in alleys had estimated biomass yields of 5–15 Mg ha^{-1} yr^{-1} with 350–550 mm yr^{-1} annual rainfall (Huxtable and Bartle, 2007).

Management regimes of tagasaste stands will have an impact on growth and the average annual yield over 22 years presented here may be improved via management. This was demonstrated in the original study by Lefroy et al. (2001), where at the stand age of 5 years trees were cut and dry matter accumulation recorded over a 24 month period for the coppiced trees. Above-ground biomass accumulation was estimated at 17.5 Mg ha^{-1} for the 24 month period for alley plantings. With stand management biomass yields could be optimised for biomass feedstock production. Although there is increasing interest in bioenergy in Australia, production from dedicated tree crops is yet to be developed (Crawford et al., 2012; Mitchell et al., 2012), the contribution of bioenergy to total energy production is 5%, of which a small proportion is from the combustion of waste wood products.

4.5. Environmental co-benefits

Tagasaste can provide fodder from the large areas of unproductive sandy soils in southern Australia (Lefroy et al., 2001). Additionally it can protect these sandy soils from periodic wind erosion, and offer obvious sustainability benefits while mitigating CO_2 emissions. Tagasaste can fix atmospheric N, and can also extract nitrogen from the soil when it is available. Studies undertaken at a trial site in Western Australia on a similar soil type found high rates of N fixation (83–390 kg N ha^{-1}) in a young stand of tagasaste (Unkovich et al., 2000). It has been argued that N-fixing plants can help to increase biomass production of mixed-planting systems by changing the microbial community composition in the soil, which may lead to greater retention of relatively stable SOC (Lorenz and Lal, 2014). Furthermore, if the soil has a low fertility status (e.g. is low in N), then its soil organic matter cannot increase unless additional N is provided (Kirkby et al., 2014).

4.6. Future research

Further work is warranted to understand the carbon dynamics related to land-use change, e.g. from cropping to afforestation with perennials like tagasaste. Of major importance here would be the establishment of additional long-term replicated research sites across a range of conditions. This would not only enable appropriate comparisons, but would also provide valuable and much-needed insight into the temporal aspects of carbon dynamics associated with land use change. If grazing with ruminants is part of tagasaste-based farming systems a life cycle analysis that takes this into account is required.

Detailed economic analyses are also required to assess the effects of emissions-abatement plantings and their impacts on profitability of farming enterprises, including stand-alone and mixed-farming systems. Such analyses should include modelling of managed and unmanaged systems, and consider all important biological and environmental inputs such as plant species, plant age, climate, soil composition, topography and emissions, as well as operations-related inputs like establishment, maintenance and other costs. Ideally such modelling would then allow for the individual landowner to identify appropriate types of farming or business models and costs, therefore greatly supporting the decision-making process.

5. Conclusions

Although tagasaste has been predominately used as fodder supplement for livestock, our research clearly shows its potential for carbon mitigation. Growing tagasaste as part of an emissions abatement strategy will restore carbon into dryland farming environments on predominantly deep sands, which are marginal for cropping. Integrating tagasaste as alley systems will also improve the sustainability of these farming systems.

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