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ORIGINAL PAPER

# The potential of Eucalyptus plantations to restore degraded soils in semi-arid Morocco (NW Africa)

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**Abstract**

• ***Key message*** **Short-rotation forestry using eucalyptus in degraded oak forests in the semi-arid area of NW Morocco can be a useful strategy to avoid further degradation and carbon loss from this ecosystem, but it might be constrained by nutrient and water supply in the long term.**

• ***Context*** Land degradation and deforestation of natural forests are serious issues worldwide, potentially leading to altered land use and carbon storage capacity.

• ***Aims*** Our objectives were to investigate if short-rotation plantations can restore carbon pools of degraded soils, without altering soil fertility.

• ***Methods*** Carbon and nutrient pools in above- and belowground biomass and soils were assessed using stand inventories, harvested biomass values, allometric relationships and selective sampling for chemical analyses.

• ***Results*** Carbon pools in the total ecosystem were low in the degraded land and in croplands (6–13 Mg ha$^{-1}$) and high in forests (66–94 in eucalyptus plantations; 86–126 in native forests). The soil nutrient status of eucalyptus stands was intermediate between degraded land and native forests and increased over time after eucalyptus introduction. All harvest scenarios for eucalyptus are likely to impoverish the soil but, for the moment, the soil nutrient status has not been affected.

• ***Conclusion*** Afforestation of degraded land with eucalyptus can be a useful restoration tool relative to carbon storage and soil fertility, provided that non-intensive forestry is applied.

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**Contribution of the co-authors** MB initiated the study. MB, LA and MRB designed it. MB and HO collected the data. All co-authors contributed to laboratory analyses and data interpretation. MB and LA wrote the first version of the manuscript, and all co-authors contributed to subsequent versions.

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**Keywords** Afforestation · Carbon pools · Soil nutrients · Cork oak · Eucalyptus

## 1 Introduction

Forest degradation and deforestation are well known for their negative impacts on the storage of organic carbon in the soil (Guo and Gifford 2002; Poeplau et al. 2011; Wei et al. 2014; Achat et al. 2015b). While these well-documented trends are representative of boreal, temperate and tropical regions, they hardly address semi-arid regions despite the surface area of dry forests at global scale (Bastin et al. 2017). For instance, in their recent meta-analysis, Wei et al. (2014) compiled data about deforestation and found that most case studies had a mean annual precipitation value, which was higher than 800–1000 mm year$^{-1}$. In addition, semi-arid regions are under high anthropic pressure (e.g. Vörösmarty and Sahagian 2000; Villamil et al. 2001; Sullivan and Rohde 2002; Seifan 2009). Consequently, there is a wide gap between expected impacts and available knowledge on soil carbon sequestration for dry regions. The main goal of our study was to quantify carbon pools in the semi-arid region of Kenitra, Morocco (NW Africa), hereby reducing this particular knowledge deficit.

In Morocco, deforestation has been a serious issue for decades and recently, the situation has become alarming. Currently, around 30,000 ha of native forests are lost annually (Benabid and Fennane 1999; F.R.A. 2015; Oubrahim 2015). These decreases have many causes, but most are pressures of human origin, such as excessive grazing, foliage harvest for cattle feeding, illegal charcoal production and illegal fuelwood and acorn harvest. All these activities have created areas of open degraded land (Oubrahim et al. 2016). In addition to woodland degradation, the surface area of native forests has diminished because of conversion to croplands that are dedicated to local food supply (Laouina et al. 2010). To cope with this situation, the Moroccan State initiated several plans aiming at restoring forest ecosystems, or just soil fertility (Laouina et al. 2010; Oubrahim 2015). As a first restoration attempt, re-creating hardwood forest is generally the objective. Alternatively, in the case of failure, or if wood production is locally lacking, state agencies sometimes install short-rotation plantations, which are based on fast-growing tree species: mainly eucalyptus but also pines or acacias. Our first objective was to quantify the capacity of short-rotation plantations to restore degraded soils or deforested areas. To do so, we studied carbon pools in four different types of land-use, representative of the semi-arid Moroccan context: (i) native oak forests, (ii) short-rotation plantations of eucalyptus, (iii) croplands for local food supply and (iv) degraded land. We used the soil content in organic carbon (SOC) as a proxy to evaluate the level of soil degradation because, in our context, soil organic carbon was negatively and linearly correlated with forest degradation (Oubrahim et al. 2016).

Because the use of eucalyptus species for intensive forestry is sometimes criticised for impoverishing soils (Michelsen et al. 1993; Tang et al. 2007; Leite et al. 2010; Chanie et al. 2013) due to their large nutrient requirements (e.g. Laclau et al. (2010), our second objective was to investigate the nutritive status under different land uses and to determine if eucalyptus management was compatible with maintenance of soil fertility. Our initial hypothesis was that short-rotation forestry based on eucalyptus could restore organic carbon pools of soils, but at the expense of soil fertility.

## 2 Materials and methods

### 2.1 Study region and sites

The region around Sidi Yahya-Gharb (34°18′33″N, 6°18′41″ W) is a low-altitude plain (<18 m asl). The climate is semi-arid (mean annual precipitation, MAP ≈ 550 mm year$^{-1}$) with warm to hot temperatures (mean annual temperature, MAT = 15.8 °C; monthly min and max = 4.3 and 36.5 °C). Rainfall usually occurs during the winter season. The upland soils of this region are sandy and acidic and are classified as *Arenosols* (FAO/IUSS 2006), which have developed in a deep sand layer (0.85–3.20 m). This sand layer was deposited over a clay-rich layer, hardly penetrable by plant root (Bellfontaine et al. 1979), which itself lies on calcareous sandstones.

In a preliminary step, we investigated the Sidi Yahya-Gharb region in order to identify sites representative of the four land uses (eucalyptus forest, cropland, native forest and degraded land) to be studied. Within a 15-km radius around the city, we found nine sites which fulfilled our a priori criteria for selection (Online Resource 1), which were (1) at least 1 ha of homogeneous vegetation or land appearance, (2) similar soil physical properties among sites (all selected sites had same values of soil particle size distribution: clay = 2–3%, silt = 2–3%, sand = 90–95%, stone = 0–4%), (3) sufficient information about land management and (4) with the same land use for at least one decade. We found four eucalyptus stands (*Eucalyptus camaldulensis* Dehnh.), two croplands (non-irrigated cereals), two native stands (medium density stands of *Quercus suber* L., sensu Oubrahim et al. 2016) and one area of degraded land (formally native forest but currently nearly a desert area).

The eucalyptus stands represent a ~48-year chronosequence typical of the study region. Indeed, the first eucalyptuses are planted (1000 trees ha$^{-1}$; the Euca-P1 stand in our study design) before being harvested at the age of 12 years old. Then, because eucalyptuses generally re-sprout after cutting, two successive coppice harvests are carried out every 12 years (stand Euca-C2 at plantation date +24 years and Euca-C3 at plantation date +36 years). Finally, all trees (both above- and below-ground biomass) are harvested 12 years after the third re-sprout (Euca-C4 at plantation +48 years), before a new 48-year-long cycle is initiated by planting seedlings. Seedlings generally receive a single dose of fertilizer at planting (typically 30 kg-N ha$^{-1}$, 35 kg-P ha$^{-1}$ and 30 kg-K ha$^{-1}$, once every 48 years).

Because of our strict selection criteria (see above), we had only two replicates of croplands, two native forests, only one degraded land and one eucalyptus chronosequence. Consequently, our study is a qualitative assessment of temporal trajectories, such as re-afforestation of degraded lands and not a statistical comparison of several land uses. Despite this statistical weakness, we consider our experimental design as representative of studied processes because carbon stock values of our degraded land and of native forests were close to analogues in a nearby region (Oubrahim et al. 2016).

### 2.2 Tree sampling

Because plant biomass was very low in the croplands and in the degraded land, this ecosystem compartment was considered as negligible in these sites and consequently, it was not measured. Indeed, in croplands, vegetation biomass is harvested each year and cannot accumulate in the long term, such as in forests. Similarly degraded lands are, in our study context, almost desert areas.

At each forest site, homogeneous areas representative of the stand were established as squares of 25–100 m aside, depending on stand configuration. In each square, all trees were measured, and basic statistics were performed (Online Resource 2). Intra-heterogeneity of stands was low to moderate, as shown by coefficient variation values of tree size (CV of circumference at breast height (CBH) 33–63% for eucalyptus stands, 30–31% for native oak forests). Then, for native forests, we used published allometric relationships (Oubrahim et al. 2016) to derive tree biomass and carbon. For the eucalyptus stands, we built similar statistical models based on 71 trees (20 from Euca-P1 plantation; and 3 × 17 from coppiced stands Euca-C2 to Euca-C4). For each tree, we measured tree height and stem circumference at breast height. We divided tree biomass into the following compartments: foliage + twigs, living branches, dead branches and stems. The proportion of wood and bark in stems was estimated from a sample of 19 completely debarked stems ($\%\text{bark}_{\text{weight}} = [-0.065 \times \text{CBH}] + 14.6$; respectively in % and cm; $r^2 = 0.94$). The mass of each compartment was determined after drying. This procedure enabled us to calibrate allometric relationships for standing stems of *E. camaldulensis* (Online Resource 3). But, in the Sidi Yahya-Gharb region, eucalyptus stands are subject to illegal harvests. In practice, some stems are cut at the soil surface level. To quantify the amount of illegally harvested biomass, we thus built a relationship between circumference at topsoil level and circumference at breast height ($\text{CBH} = [0.788 \times C_{\text{stump}}] - 2.34$, in cm; $r^2 = 0.95$). This relationship enabled us to estimate stem CBH and in turn the quantity of carbon exported by this kind of human pressure. Finally, we built allometric relationships for the root systems of coppiced trees (Euca-C4). Fifteen root systems (11 alive, 4 recently dead) were excavated, and the biomass of each stump and its adjacent coarse roots was exhaustively collected from 1.5 m around the stump to a depth of 1.0 m. In addition, a volume of 3.5 $m^3$ of soil for each root system was collected close to the stump and sieved to collect fine roots.

### 2.3 Soil sampling

For forest sites, soils were sampled in the square used for tree inventory. For croplands and degraded land, we chose a square of 50 m aside that was visually representative of the whole site. Sampling was performed using 20 squares of one $m^2$, distributed along transects located on a systematic grid. When an organic layer was present (i.e. in forest stands), the forest floor was sampled, sorted by hand (foliage, twigs + branches, bark), dried and weighed. The mineral soil of the nine sites was sampled systematically down to 100 cm, from five layers: 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Soil bulk density was determined for each layer using the cylinder method and based on four soil pits. The five layers of mineral soil were sampled as follows: 20 soil cores (1 m long) were collected from a systematic grid. For each soil layer, the 20 samples were mixed, and an aliquot was taken as a composite sample. Finally, each composite sample was sieved (2 mm) and dried to constant weight.

### 2.4 Chemical analyses and calculations

Stem disk samples rather than core samples, and actual values of nutrient concentrations rather than values from the literature, were used to ensure data reliability (Augusto and Bert 2005; Augusto et al. 2009). Plant samples—and forest floor samples—were ground before analysis. The following chemical determinations were performed: total carbon content (C; by a combustion method) and total nitrogen content (N; with HCl after Kjeldahl mineralisation ($H_2SO_4$ with catalyst Se)). Mineralisation in aqua regia (7.5 ml HCl + 2.5 ml $HNO_3$) enabled the determination of Ca, Mg and K by flame atomic absorption spectrometry (GBC 906A) and P by colorimetry using a phosphovanadomolybdate complex.

For the soil samples, the same elements ($C_{org}$, $N_{total}$, $P_{olsen}$, $K_{exch}$, $Ca_{exch}$, $Mg_{exch}$) were analysed (Walkley and Black 1934; Olsen et al. 1954; Bremner 1960; Zhang et al. 2012). In practice, the organic C content was assessed by the acid oxidation method, the total N content by the Kjeldahl method, the available P content by extraction with $NaHCO_3$ and the exchangeable cation content by the acetate ammonium method.

Stocks of elements were calculated, using biomass values and concentration values for plants and using the soil layer weight and concentration values for soils. We used these stocks to evaluate the impact of land-use changes on carbon pools (the first objective) and on soil fertility (the second objective). For carbon pools, we calculated an index of soil degradation. To do so, we used as reference the mean value of soil carbon stocks in dense, healthy, native forests (81.2 Mg-C $ha^{-1}$ in the forest floor layer and in mineral soil layers; cf. Fig. 5 in Oubrahim et al. (2016)). The degradation index value was then calculated as follows:

$$\textit{Degradation index} = 1 - (\text{SOC}_{\textit{stand}} : \text{SOC}_{\text{ref}})$$

The index of soil degradation scales from 0 (i.e. no degradation of SOC stocks) to 1 (i.e. complete loss of SOC).

### 2.5 Scenarios of biomass harvest in eucalyptus forests and in native forests

In a final step, in line with our second objective, we investigated which intensity of eucalyptus biomass harvest was likely to be the best compromise between a high rate of biomass removal and the maintenance of soil fertility. To do this, we estimated the quantities of biomass and elements exported from the ecosystems based on five harvest scenarios (S, SR100, SB, SBR80 and SBR100). Those scenarios were the result of different choices in terms of biomass harvest: B = stem bark is harvested with stem wood (i.e. no in situ debarking); R80 and R100 = 80 or 100% of forest *residues* (here tree canopy) are harvested. In all scenarios, stem wood was harvested down to a diameter of 7 cm (S modality). In the study region, the SBR80 scenario is the usual practice.

In native oak forests, only the bark is exported. The average annual volume exported from the Mamora oak forest is 0.79–1.41 $m^3$ $ha^{-1}$ year.$^{-1}$, depending on the years (HCEFLCD, Morocco: unpublished surveys). Bulk density values of bark piles are 90–150 kg $m^{-3}$ (HCEFLCD). For export calculations, we assumed median values (1.10 $m^3$ $ha^{-1}$ $year^{-1}$; 120 kg $m^{-3}$), resulting in a median bark export of 132 kg $ha^{-1}$ $year^{-1}$.

## 3 Results

### 3.1 Impact of land-use changes on carbon sequestration

In forests, C concentrations in standing biomass were close to 500 mg $g^{-1}$. Because there were no large differences in carbon concentrations (eucalyptus = 450–500 mg $g^{-1}$; oak = 520–560 mg $g^{-1}$), it was the difference between biomass values, driven themselves by stand dendrometry (Online Resource 2) that best explained the amounts of carbon sequestrated in trees (Online Resource 4). The standing above-ground biomass and its related carbon stock were of the same order of magnitude for all forest sites, with no clear differences between eucalyptus plantations and native oak forests. On the other hand, when exports were taken into account and not the standing biomass alone, the eucalyptus fixed two to four times more C during the 48-year-long revolution than native forests over the same duration (~113 Mg $ha^{-1}$).

The influence of land use on carbon sequestration was also quite clear in the soils. The degraded land and, to a lesser extent, croplands displayed the lowest values of soil carbon concentrations down to 60 cm (Fig. 1). Conversely, forest soils contained large amounts of organic carbon (34–75 Mg $ha^{-1}$; Table 1). It is worth highlighting the restorative influence of afforestation on degraded lands, even with short-rotation plantations such as eucalyptus plantations. Indeed, topsoil (0–20 cm) carbon concentrations increased gradually from eucalyptus plantation (Euca-P1, planted on formerly degraded land) to Euca-C3 and Euca-C4 stages, resulting in similar concentration values to those found in native forests (Fig. 1). The 20–40-cm layer demonstrated the same restorative pattern, with carbon concentrations increasing with the age of the eucalyptus plantation. In contrast to the topsoil layer, carbon concentrations of the 20–40-cm layer remained lower in eucalyptus forests than in native forests, even in the Euca-C4 soil (Fig. 1). In our context, planting eucalyptus trees on degraded land led to an increase in the soil carbon pool of 2.4 Mg $ha^{-1}$ $year^{-1}$ during the first rotation (calculated as the difference between Euca-P1 and Degraded-9) and 0.8–1.4 Mg $ha^{-1}$ $year^{-1}$ afterwards (from Euca-P1 to Euca-C4). Hence, values of our index of soil degradation progressively decreased during eucalyptus rotations (from 0.58 down to 0.08; Table 1), while this index value was 0.93 in the degraded land.

### 3.2 Soil nutritive status and possible impact of eucalyptus forestry

In a second step, we investigated whether changes in land use had an impact on soil fertility. The fertilisation regime in croplands was clearly visible with an accumulation of phosphorus, potassium and magnesium in the deep soil layers (Fig. 1). The degraded land had the poorest soil in terms of total nitrogen and available forms of phosphorus and calcium (Fig. 1). Conversely, soils under native forest often displayed the highest values of nutrient concentrations, especially in the topsoil layer. Soils under eucalyptus stands were intermediate: in the topsoil, afforestation with eucalyptus had progressively increased the soil contents of total nitrogen, available phosphorus and calcium (Fig. 1). Although the pattern was less obvious for potassium and magnesium, it appeared that the nutritive status of soils after a few decades of eucalyptus presence (i.e. Euca-C3 and Euca-C4) was comparable with, or slightly lower than, those of native forest soils. In other words, eucalyptus growth had no visible negative impact on soil fertility.

In a final step, we evaluated the extent to which this soil pattern could be explained or not by eucalyptus forestry and harvest practices in particular. There were some differences in nutrient concentration between *Q. suber* and *E. camaldulensis* (Online Resource 5). However, because the amounts of biomass exported from native forests were extremely low, and much lower than exports from eucalyptus stands (Online Resource 4), such differences in nutrient concentration did not change the pattern imposed by the biomass values: eucalyptus forestry induced nutrient exports as a result of biomass harvests, which were much higher than those related to the management of native forests. In eucalyptus trees, values of nutrient concentrations in above-ground tissues could be ranked as follows (Online Resource 5): foliage > twigs ≥ branches, bark > wood. Stem wood represented a high proportion of tree biomass (69%, see harvest scenario S in Table 2b) but a lower proportion of tree mineral mass (35–66%, Table 2b). Including in exports, stem bark (scenario SB)

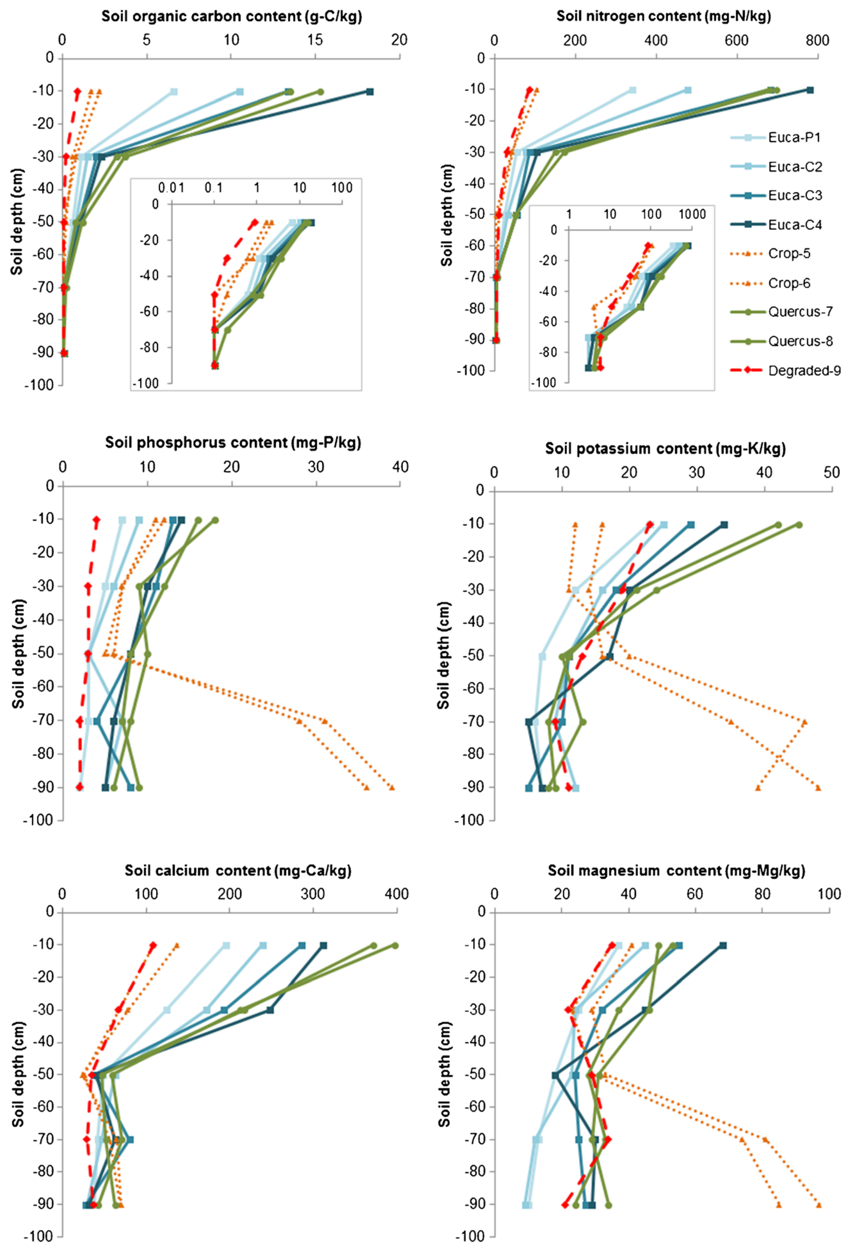


**Fig. 1** Carbon and nutrient concentrations in the soil profiles. $C = C_{org}$, $N = N_{total}$, $P = P_{Olsen}$, *K*, *Ca*, and *Mg* = exchangeable cations, *Euca-P1* eucalyptus plantation, *Euca-C2*, *Euca-C3*, and *Euca-C4* coppiced eucalyptus stands (2nd, 3rd and 4th rotations), *Crop-5* and *Crop-6* croplands, *Quercus-7* and *Quercus-8* native oak forests, *Degraded-9* degraded land (formally a native forest). Graphic program used: Excel-2010

and, above all, harvest residues (scenarios SR100, SBR80 and SBR100) resulted in a small gain in biomass harvest but in large additional losses of nutrients (Table 2). Nutrient exports induced by the most intensive scenario (SBR100) were 653, 107, 993, 2188 and 196 kg ha$^{-1}$ of N, P, K, Ca and Mg, respectively (Table 2a). The possible impact of the SBR80 scenario, which is the usual practice in our study region, was similar to that of the SBR100 scenario. These intensive outputs (SBR80 or SBR100) were of the same order of magnitude as the nutrient pools in the Euca-C4 soil (Table 2c). The similarity between nutrient exports by actual (SBR80) biomass harvests on the one hand, and soil nutrient stocks on the other, leads to the conclusion that eucalyptus forestry is likely to impoverish soils. Fortunately, in our context, this has not been the case so far (Fig. 1), but an explanation for this discrepancy is necessary.

## 4 Discussion

### 4.1 Carbon

Afforestation with eucalyptus induced high rates of biomass and carbon accumulation. Eucalyptus plantations under tropical or temperate climates can grow even faster (Bargali et al. 1992b; Laclau et al. 2000; Du et al. 2015; González-García et al. 2015) but, taking into account the low fertility of the sandy soils and the semi-arid climate at this study site, such

**Table 1** Soil organic carbon (SOC) stocks for the ecosystems studied

| Carbon stocks (Mg ha$^{-1}$) | Euca-P1 | Euca-C2 | Euca-C3 | Euca-C4 | Crop-5 | Crop-6 | Quercus-7 | Quercus-8 | Degraded-9 |
|---|---|---|---|---|---|---|---|---|---|
| Forest floor | 0.95 | 1.10 | 1.31 | 1.52 | 0.23 | 0.17 | 1.94 | 3.61 | 0.09 |
| 0–20 cm | 25.1 | 38.1 | 45.0 | 59.6 | 6.29 | 8.62 | 44.0 | 50.8 | 3.56 |
| 20–40 cm | 4.31 | 5.76 | 7.49 | 8.70 | 2.30 | 3.01 | 10.5 | 14.2 | 0.81 |
| 40–60 cm | 2.45 | 3.25 | 3.96 | 4.37 | 0.83 | 0.42 | 3.06 | 4.39 | 0.43 |
| 60–80 cm | 0.85 | 0.42 | 0.42 | 0.43 | 0.43 | 0.43 | 0.42 | 0.82 | 0.45 |
| 80–100 cm | 0.43 | 0.44 | 0.43 | 0.42 | 0.41 | 0.44 | 0.42 | 0.42 | 0.43 |
| Total SOC | 34.1 | 49.0 | 58.6 | 75.0 | 10.5 | 13.1 | 60.4 | 74.3 | 5.77 |
| Index of soil degradation | 0.58 | 0.40 | 0.28 | 0.08 | 0.87 | 0.84 | 0.26 | 0.09 | 0.93 |

The index of soil degradation scales from 0 (i.e. no degradation of SOC stocks) to 1 (i.e. complete loss of SOC). This index was calculated based on properties of similar soils of the same regions and cannot consequently be used in another context (see Sect. 2 for details)

*Euca-P1* eucalyptus plantation, *Euca-C2*, *Euca-C3*, and *Euca-C4* coppiced eucalyptus stands (2nd, 3rd, and 4th rotations), *Crop-5* and *Crop-6* croplands, *Quercus-7* and *Quercus-8* native oak forests, *Degraded-9* degraded land (formally a native forest)

growth rates were remarkably high. This was particularly the case for below-ground biomass with a root/shoot ratio above six. Under temperate to subtropical climates, the root/shoot ratio is typically between two and three (Herrero et al. 2014; Vega-Nieva et al. 2015; Salomon et al. 2016) but may increase to almost six for coppiced stands (Razakamanarivo et al. 2012). Hence, even if it is difficult to quantify root biomass in a reliable way (Ritson and Sochacki 2003; Danjon and Reubens 2008; Augusto et al. 2015), our root/shoot value was plausible and may be the consequence of a high allocation of resources to their roots by coppiced trees (Zadworny et al. 2014) under a dry climate (Canadell et al. 1996). Eucalyptus trees have deep root systems (Laclau et al. 2001; Christina et al. 2011; Pinheiro et al. 2016), so we assume that coppiced eucalyptus trees under dry conditions could exhibit exceptionally high values of root/shoot ratios. In practice, in the region studied, eucalyptus roots are harvested after the final Euca-C4 rotation for local needs (i.e. fuel wood for heating hamams) and villagers frequently cut above-ground biomass of eucalyptus for their domestic needs. Therefore, in addition to the possible use of eucalyptus biomass for the production of paper pulp, and even if some cuts were illegal, we speculate that eucalyptus forestry could reduce the anthropic pressure on native oak forests (Oubrahim 2015).

**Table 2** Exports of biomass and nutrients from eucalyptus stands under different harvest scenarios

| | Biomass | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|
| a. Biomass (Mg ha$^{-1}$) and mineral mass (kg ha$^{-1}$) | | | | | | |
| S (S1) | 143 | 246 | 55 | 660 | 775 | 68 |
| SR100 (S2) | 188 | 601 | 99 | 934 | 1420 | 144 |
| SB (S3) | 162 | 299 | 63 | 718 | 1543 | 120 |
| SBR80 (S4) | 198 | 582 | 98 | 938 | 2059 | 181 |
| SBR100 (S5) | 207 | 653 | 107 | 993 | 2188 | 196 |
| b. Biomass and mineral mass (% of standing stocks) | | | | | | |
| S (S1) | 69 | 38 | 51 | 66 | 35 | 35 |
| SR100 (S2) | 91 | 92 | 93 | 94 | 65 | 73 |
| SB (S3) | 78 | 46 | 59 | 72 | 71 | 61 |
| SBR80 (S4) | 96 | 89 | 92 | 94 | 94 | 92 |
| SBR100 (S5) | 100 | 100 | 100 | 100 | 100 | 100 |
| c. Nutrient stocks in soil for the eucalyptus stands before biomass harvest (kg ha$^{-1}$; 0–100 cm soil layer) | | | | | | |
| Euca-P1 | | 1665 | 80 | 219 | 1771 | 411 |
| Euca-C2 | | 2195 | 119 | 288 | 2112 | 439 |
| Euca-C3 | | 2869 | 167 | 271 | 2287 | 619 |
| Euca-C4 | | 3195 | 162 | 305 | 2524 | 713 |

Eucalyptus stands: four rotations of 12 years (one plantation, followed by three coppiced stands)

*Euca-P1* eucalyptus plantation, *Euca-C2*, *Euca-C3*, and *Euca-C4* coppiced eucalyptus stands (2nd, 3rd, and 4th rotations), *S* stem wood (stems with circumference at breast height > 7 cm) harvested, *B* stem bark harvested, *R80* and *R100* 80 or 100% of harvesting residues exported

Similarly to carbon in standing plants, afforestation is well known to substantially increase stocks of soil organic carbon (SOC) when starting from croplands or degraded land (Singh et al. 2000; Paul et al. 2002; Nogueira et al. 2006; Poeplau et al. 2011; Li et al. 2012; Barcena et al. 2014). Our study agreed perfectly with this global pattern, with forest soils being up to one order of magnitude richer in carbon than croplands or degraded land. What was rather surprising was the rapidity of the restoration of SOC pools of degraded land induced by eucalyptus forestry (i.e. 0.8–2.4 Mg ha$^{-1}$ year$^{-1}$) because, even if plantations with species of the *Eucalyptus* genus are generally good at storing organic carbon in soils (Li et al. 2012; Boca et al. 2014), this is far from being always the case (Du et al. 2015; Hernández et al. 2016b). We explain such a high rate of SOC accumulation as a consequence of the initial SOC pool in degraded land. Based on a large survey of eucalyptus stands in Brazil, Cook et al. (2016) have shown that the effect of eucalyptus plantation depended primarily and negatively on the initial SOC stock: afforestation with eucalyptus caused an increase, no change, or even a decrease when the initial SOC stock was below, equal to or above ~20–40 Mg ha$^{-1}$ in the 0–30-cm soil layer (see Fig. 4 in Cook et al. (2016)). With a SOC stock of ~4 Mg ha$^{-1}$ in the 0–30-cm soil layer, our degraded site was expected to accumulate 1.0–1.5 Mg ha$^{-1}$ year$^{-1}$ of SOC due to eucalyptus afforestation. This expectation, based on Brazilian eucalyptus stands, was consistent with our Moroccan results (0.8–2.4 Mg ha$^{-1}$ year$^{-1}$). The SOC accumulation was mainly observed in top-soil and mid-soil layers, suggesting that both the litterfall flux (≈2.2 Mg ha$^{-1}$ year$^{-1}$ at 12 years, Boulmane, unpublished data; see Turner and Lambert (2016) for comparison) and the fine roots have contributed to SOC stabilisation (Clemmensen et al. 2013; Hatton et al. 2015).

All in all, we conclude that planting fast-growing eucalyptus is a winning strategy to restore SOC pools of degraded, mineral, arenosols in semi-arid areas of Morocco. Nevertheless, despite being an important ecosystem service provided by soils, carbon sequestration is not the only one and others exist, such as soil fertility, soil biodiversity or nutrient cycling (Nogueira et al. 2006; Adhikari and Hartemink 2016). Because negative effects of eucalyptus forests are recurrently reported in the literature (e.g. Ferreira et al. 2016; Leite et al. 2010; Michelsen et al. 1993; Nogueira et al. 2006), we also evaluated the extent to which eucalyptus afforestation may alter the soil nutrient status in our study region.

### 4.2 Soil fertility

Although deforestation for crop production clearly reduced SOC pools (this study; see Wei et al. (2014) for a larger perspective), this was not the case for nutrients such as K, P and Mg (Fig. 1), likely as a result of fertiliser application in croplands. The vertical distribution of calcium was an exception that might be the consequence of the absence of liming practices in local agriculture.

Our initial expectation was that afforestation of degraded land with a nutrient demanding species, such as *E. camaldulensis*, could lead to more soil degradation (Leite et al. 2010). However, on the contrary, the contents of total N and available forms of P, K, Ca and Mg in the soil were progressively improved by eucalyptus forestry (see Nogueira et al. 2006 and Jeddi et al. 2009 for similar trends). Because atmospheric nitrogen deposition is quite low in the study region (Lamarque et al. 2005), we assumed that the increase of N in the ecosystem pool was due to asymbiotic (Reed et al. 2011) and symbiotic $N_2$ fixation. The local presence of N-fixing shrubs (i.e. *Genista linifolia*, formally named *Teline linifolia*; Oubrahim et al. 2016) and high rates of fixation of plants growing in poor soils (Augusto et al. 2005) such as in our context (Hracherrass et al. 2013) support the idea that symbiotic $N_2$ fixation was partly responsible for the effect of afforestation on soil N dynamics.

The increase of the soil pool of exchangeable K, Ca and Mg was unexpected (Berthrong et al. 2009) but could be explained by two processes. First, in sandy forest soils, most of the soil cation exchange capacity (CEC) is due to the presence of organic matter (Turpault et al. 1996; Johnson 2002; Augusto et al. 2010). As afforestation improved the SOC content, it probably increased soil CEC and, in turn, the pools of exchangeable cations (Cook et al. 2016). A second explanation, which is not in contradiction with the one based on CEC, is related to tree rooting depth. Roots of eucalyptus species can penetrate to great depths: down to 10 m and probably even deeper (Laclau et al. 2001; Christina et al. 2011; Pinheiro et al. 2016). In our study region, arenosols rely on deep clay-rich or calcareous layers (cf. Materials and Methods), which are likely to contain substantial amounts of cation- and P-bearing minerals (phyllosilicates, feldspars, carbonates, apatites, etc.). It is therefore possible that eucalyptus trees have developed root systems to access these layers and that they have been able to take up K, Ca and Mg from them. With this idea in mind, trees could be seen as biological pumps, lifting nutrients from deep soil layers to the topsoil by root uptake, allocation to foliage and finally litterfall. The same reasoning could apply to the available phosphorus soil pool. In addition, afforestation of degraded land may have improved soil P status, particularly by increasing organic forms of available P (De Schrijver et al. 2012). To sum up, as opposed to our initial hypothesis (see Lemenih et al. 2004; Berthrong et al. 2009 and Temesgen et al. 2016 for negative effects of afforestation), planting eucalyptus in degraded land has not impaired soil fertility but has improved it.

A comparison of the foliage nutrient contents of our study with other eucalyptus species throughout the world showed that our results were in the same range, or sometimes slightly higher (N, P, Ca), than in other contexts (Bargali et al. 1992a; Hopmans et al. 1993; González-García et al. 2015; Gomez-Garcia et al. 2016; Hernández et al. 2016a; Turner and Lambert 2016), suggesting that the eucalyptus stands of our study were not severely nutrient stressed. However, taking into account (i) the high demand for nutrients of eucalyptus species (Laclau et al. 2003; Laclau et al. 2010) and (ii) the intrinsically low resilience of arenosols, we considered that nutrient outputs due to forest management may reduce soil fertility in the long term. Because intensive harvests have been shown to be detrimental to SOC pools (Achat et al. 2015b) and to ecosystem functioning (Achat et al. 2015a; Rocha et al. 2016), intensive management of eucalyptus remains questionable in semi-arid Morocco. That is why, we suggest that foliage—a compartment rich in nutrients (Augusto et al. 2008)—should not be exported from eucalyptus stands, because this kind of cropping has the highest environmental impact (Achat et al. 2015a; Augusto et al. 2015).

In addition to soil fertility, water supply remains a source of concern because eucalyptus species are known for their capability to forage water deeply and consequently to negatively impact river fluxes (Poore and Fries 1986). It is particularly the case in dry regions such as in the Gharb region, where our study took place. On the other hand, eucalyptus plantations may have also positive effects in our context, especially during the winter season. Indeed, in the Gharb region (dominated by croplands and degraded lands), lowlands (dominated by vertisols; Billaux and Bryssine 1967) can be flooded because heavy rains cannot completely infiltrate soils of uplands, with low vegetation cover (Lakrikba 2015). Because eucalyptus plantations probably reduce water run-offs and severity of winter floods, an assessment of their impact on water fluxes and stocks is necessary.

## 5 Conclusion

Our qualitative investigation has suggested that short-rotation forestry using eucalyptus can be a useful tool for restoring degraded land, both in terms of carbon sequestration and soil fertility. Nevertheless, our study lacked site replicates, and the extent to which local soils can support intensive eucalyptus production in the long term is unknown. That is why, despite their positive effects at present, we conclude that eucalyptus afforestation should be further assessed before promoting this kind of short-rotation forestry as being the best solution in semi-arid, degraded forests. Meanwhile, applying non-intensive harvest scenarios in existing eucalyptus stands and preserving the remaining native forests seem to be the most sustainable options.

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**Compliance with ethical standards**

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