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Shoot and root responses of woody species to silvicultural management for afforestation of degraded croplands in the Sudano-Sahelian zone of Benin

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ABSTRACT

In the Sudano-Sahelian zone of West Africa, where deforestation and cropland soil degradation occur at alarming rates, the (re-)introduction of trees on degraded lands can improve and sustain farming systems and landscapes. The shoot and root morphological traits of five woody species introduced to degraded cropland were assessed with a particular focus on the survival, early establishment and growth of saplings subjected to manuring (1 kg per plant) and drip irrigation (0.5 L of water per plant per day). Functional traits of the woody above- and belowground organs of field-grown plants were monitored for the first 15 months after planting, covering two growing (rainy) seasons and one dry season. The high survival rate (>60%), combined with a very low incidence rate (<1%), for all species was evidence of successful establishment overall. The highest survival rates (94–100%) were observed in *Jatropha curcas* L., *Leucaena leucocephala* Lam. and *Moringa oleifera* Lam. The mortality rate of the most drought-sensitive species *Parkia biglobosa* Jacq. could be reduced ten-fold through supplemental irrigation during the dry season. The fast-growing *L. leucocephala*, *M. oleifera* and *J. curcas* had higher values for shoot-level traits than did the slow-growing *Anacardium occidentale* L. and *P. biglobosa*. Fertilization and irrigation enhanced the shoot growth of both the fast and slow growers during the dry and growing seasons. In contrast, belowground development was either increased or reduced by fertilization and irrigation during the growing and dry seasons, but the slow growers demonstrated a more plastic response to these treatments than did the fast growers. Among the studied traits, the relative growth rate of plant as a whole (i.e. shoots and roots combined) exhibited the greatest plastic response to resource availability, thus suggesting its application in screening candidate species for afforestation efforts. Overall, the five studied species were considered suitable for the afforestation of degraded croplands, while the early growth and establishment of saplings could be boosted by irrigation and a supply of manure.

1. Introduction

With increasing severity and to an increasing extent, cropland degradation in sub-Saharan Africa has become a major threat to food security, environmental health, and human well-being, particularly in the drylands (Adams and Eswaran, 2000; Eswaran et al., 2001; Bai et al., 2008). To counterbalance this and ease growing food deficits, the farming population is forced to place more pressure on existing land resources, including marginal croplands that are ill-suited for agriculture, thus accelerating environmental degradation and lowering agroecosystem productivity (Vlek et al., 2008).

Reforestation, afforestation, and tree-based farming with multipurpose tree species have been recognized worldwide as a means to reverse land degradation and sustain agricultural systems (Chamshama and Nduwayezu, 2002; Garrity et al., 2010; Khamzina et al., 2012). For instance, *Jatropha curcas* L., a biofuel crop, has been extensively propagated to reclaim wastelands and restore soil productivity on marginal lands in the semi-arid tropics, although with variable success (Francis et al., 2005; Reubens et al., 2011; Baumert and Khamzina, 2015). The cultivation of nitrogen-fixing tree species, such as *Faidherbia albida* Del. and *Leucaena leucocephala* Lam., has been widely promoted to replenish soil nitrogen and alleviate fodder deficits (Orwa et al., 2009; Garrity

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et al., 2010; SPORE, 2015; Noulèkoun et al., 2016). Species with a high commercial value, such as *Moringa oleifera* Lam., *Anacardium occidentale* L. and *Parkia biglobosa* Jacq., have been advocated for use in afforestation (Edinger and Kaul, 2003), but empirical studies on their viability on degraded lands remain scarce.

Practical recommendations regarding the choice of tree species capable of productive growth on degraded croplands, which are characterized by water and nutrient limitations, may be more reliable with a better understanding of the functional traits, resource use strategies, and phenotypic plasticity of candidate tree species. Reich (2014) postulated the coordination of plant growth traits and resource use; rapidly acquiring a given resource at any organ level requires the same for other resources at the same organ level. This coordinated trade-off between functional traits and resource use results in fast- and slow-growing plants (Reich, 2014). The fast growers are exploitative resource competitors and show a more plastic response to increased resource availability than do slow growers. In contrast, slow growers pursue a more conservative resource use strategy, which allows them to maintain growth under resource-poor conditions (Reich et al., 2003b; Reich, 2014). Therefore, understanding the response of plants to the supply of resources involves a consideration of the 'fast-slow' plant economics spectrum which in turn will support the assessment of site-specific silvicultural practices aimed at the establishment of tree plantations on unproductive cropland (Aerts et al., 2007; Khamzina et al., 2008; Reubens et al., 2009).

When analyzing plant functional traits to understand the differences in growth responses to resource gradients (Chapin et al., 1993; Barbosa et al., 2014), rather than focusing on aboveground traits only, a whole-plant perspective is needed because responses might differ above- and belowground (e.g. Khamzina et al., 2016). For instance, variations in aboveground morphological traits related to leaves or shoots are primarily a response to differences in light interception and the assimilation of carbon, whereas morphological changes in the roots are usually responses to water and nutrient availability (Funk et al., 2007; Valladares and Niinemets, 2008; Coyle et al., 2016). The extent and pattern of changes in functional traits in response to resource availability (e.g., water, nutrients, and light) are commonly assumed to accord with the functional equilibrium theory, which assumes that plants allocate relatively more resources to organs that aid in the acquisition of the most limiting resource (Brouwer, 1963; Poorter et al., 2012). Because the evidence for this growth theory predominantly stems from (very) short-term studies, usually conducted in greenhouses and under artificial conditions to reduce complexity (Shipley, 2000), it is questionable whether these findings apply to woody species over time and in the field (Sack and Grubb, 2001).

Given the inherent risks for smallholder farmers on sub-Saharan African drylands who invest in afforestation, we examined the functional traits of multi-purpose tree species for which there had been little or mixed empirical evidence to date regarding their suitability for planting on degraded lands. Thus, in analyzing the shoot- and root-level morphological traits of five candidate species on degraded cropland in the Sudano-Sahelian zone of West Africa, we aimed to (i) assess plant establishment and growth characteristics on nutrient-poor and water-limited soil, (ii) identify and explain species-specific responses to silvicultural management practices, including supplemental irrigation and manuring during the growing and dry seasons, and (iii) identify species functional traits that may serve as a proxy for longer-term growth trends. On this basis, we identified those tree species and silvicultural management approaches that were most appropriate for use in the afforestation of degraded croplands.

2. Materials and methods

2.1. Study site

The arid Atacora department in northern Benin (Fig. 1) was selected as the study site because this region has been significantly affected by land degradation driven by deforestation and soil nutrient mining (Adegbidi et al., 1999; Mulder, 2000), threatening the sustainability of farming systems and exacerbating rural poverty (Saıdou et al., 2003).

The climate in this region is semi-arid, characterized by one distinct rainy season (May to September) with a long-term average annual rainfall of 987 mm (for 1970–2010) followed by a prolonged dry season (September–May). Over the 15-month observation period, the annual rainfall was 757 mm in 2014 and 833 mm in 2015, below the long-term annual mean (Fig. 2).

The field experiment was carried out in Pouri village (N 10°54′8.4″ and E 1°4′47.4″; altitude 186 m.a.s.l) in Atacora (Fig. 1), which was selected following a four week-reconnaissance survey involving local and international forestry experts and Pouri community members. The selection criteria included (i) cropland impoverishment (judged by low nutrient stocks and crop yields), (ii) homogeneity in site conditions, (iii) site accessibility for regular measurements, and (iv) willingness of land owners to participate in the experiment and allocate croplands for afforestation. The area was savanna forest prior to being clear cut and then cropped with a successional three-year intercrop of either sorghum and cowpea or maize followed by yam for about a decade. Inorganic fertilizer was applied only during the maize-cowpea intercropping period.

The experiment was conducted on epipetric plinthosol (WRB, 2006) typified by a sandy-loam texture in the topsoil and clayey-loam in deeper profiles. The soil was limited to a depth of 50 cm by lateritic concretion and characterized by low water holding capacity, a low concentration of NPK, low cation exchange capacity (CEC), and relatively high acidity (Supporting Information Table S1).

2.2. Tree species and experimental design

Five woody species (Table 1) were selected due to their reported stress tolerance and socio-economic importance for the communities, as determined by a search of the literature, focus group discussions in the community, and an inventory of dominant tree species in the study region. All species are deciduous or semi-deciduous and have a habitat range within (sub) tropical climatic zones (Table 1).

Planting material for the woody species was obtained from a forest nursery near the experimental site where seedlings were grown in polyethylene tubes (ø 5 cm, 15 cm deep) filled with a substrate of local soil mixed with organic material. The seedlings were not fertilized. In July 2014, tree seedlings with an age of 2.5–4 months, were transplanted from the nursery to the experimental plots. During planting, the polyethylene tube was removed, but the substrate left attached to the roots.

Prior to planting, the site was cleared of sparse woody vegetation, ploughed, levelled, and fenced. The experiment compared a control treatment (with neither irrigation nor fertilization) with tree species performance under irrigation and fertilization. The species and irrigation treatments were arranged according to a fully factorial design with three repetitions whilst the manure application was introduced as a nested factor. The trial thus had a total of 30 plots (including the control plots) of $12 \times 8\ m^2$, each containing 48 seedlings at a $2\ m \times 1\ m$ spacing. The stand density at planting was thus 5000 trees ha^{-1}.