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Survival and growth responses of *Jatropha curcas* L. to three restoration techniques on degraded soils in Burkina Faso

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Abstract. Land degradation is a major problem in the Sahelian countries. Erosion control through establishment of vegetation cover is at important strategy to reverse the trend. Our research objective was to analyse the effects of three restoration techniques on *Jatropha curcas* L. seedlings growth and survivorship. We are conducted two separate field trials, involving the sowing and planting of *J. curcas*, in which several different soil restoration techniques were applied. The trial was monitored using a randomized block study design over a period of two years. The design included ten different treatments, six in the sowing trial and four in the planting trial, each with three replicates. In the first experiment, growth rate was found to be significantly higher in the Sub-Soiling treatment, that received additional organic matter than other treatments. However, overall survival rate was low (18%). In the second experiment, the Half-moon treatment yielded a significantly higher growth both in height ($df = 3$, $F = 56.74$, $p < 0.05$) and diameter ($df = 3$, $F = 31.76$, $p < 0.05$) and survival rate compared to those of the other treatments ($df = 3$, $F = 50.4$, $p < 0.05$). In conclusion, planting seedlings produced a greater survival rate than sowing seeds. Among the soil restoration and water conservation techniques tested in this study, the Half-moon technique was found to be the most effective. This is recommended to be used for improving the revegetation of *J. curcas* in the future.
Keywords soil degradation, land reclamation, water harvesting, water infiltration, afforestation.

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Introduction

Land degradation, defined as the loss of production capacity in terms of loss of soil fertility, soil biodiversity and degradation of natural resources (Lal 2004), remains one of the most serious environmental problems, which continues to threaten the livelihoods of many people worldwide. It is the result of many factors, such as dryness, loss of vegetation, soil erosion, inappropriate land use and poor management. An estimated US $ 42 billion in income and 6 million ha of productive land are lost every year due to land degradation and declining agricultural productivity (UNDP-GEF 2004). More than half of all African people are affected by land degradation, making it one of the continent's urgent development issues with significant cost – Africa is burdened with a US $ 9.3 billion annual cost of desertification (Bationo et al. 2007).

Like other Sahelian countries, Burkina Faso is facing significant and continuous degradation of its natural resources (Zombre 2006). The combined effect of low soil fertility, mismanagement of ecosystems and extreme climatic conditions has resulted in *zipellés*: bare soils that have become sealed and encrusted (Mando et al. 2001). This phenomenon reduces the agricultural potential of the land, resulting in poverty and immigration. Nearly 24% of the soils of Burkina Faso have been reduced to *zipellés*, most notably in the central and northern regions (Zougmoré et al. 2004). This has major economic consequences for the country, as agricultural and pastoral activities are practiced by 90% of the population. Consequently, land rehabilitation is essential to reverse the trend of degradation and to improve the productivity of soils.

Erosion control through establishment of vegetation cover and afforestation, soil fertility management though application of biosolids are important strategies (Lal 2004). Long term remediation efforts can achieve this using species that are able to withstand water-stress for revegetation in degraded landscapes (Lan et al. 1997). For any rehabilitation programme to be successful, it must involve income-generation, with the aim of poverty alleviation (Ogunwole et al. 2008, Bognounou et al. 2010). *Jatropha curcas* L. (JCL hereafter) is a drought-resistant oil-producing plant, occurring throughout tropical and subtropical areas, across Central and South America, Africa, India and South-east Asia (Schmook et al. 1997). It is used in poverty alleviation and income generation initiatives in rural areas of many developing countries. In the Sahel, in West Africa, JCL may be able to combat three of the largest challenges of the countries: energy supply, poverty and greenhouse gas emissions reduction. This enterprise has become extremely profitable for farmers and businessmens using the shrubs. Other benefits include the restoration of ecosystems and poverty alleviation in rural areas in Africa (Li Kun et al. 2007). JCL may be especially beneficial to the restoration of degraded ecosystems, as it is able to grow wild and would not need to compete with conventional agricultural crops (Juwarkar et al. 2008). Thus, JCL could potentially be a useful plant for the afforestation of the *zipellés*.

Despite the heat and drought tolerance of JCL, it has been shown to have a low survival and reproductive rate in barren areas (Li Kun et al. 2007). Thus, optimizing the establishment of JCL on degraded soils may require investigation into the improvement of its growth conditions. The range of species that can be used in this environment is limited, due to water scarcity (Bargali & Tewari 2004). Therefore, the identification of a species able to withstand these conditions will be the most important factor to consider (Kumar et al. 2008). The most effective way to increase soil productivity in the Sub-Saharan Zone is to ensure effective water infiltration and storage in the soil (Lal 1997). Water is not necessarily in short supply in the region; rather, the loss of water through runoff, soil evaporation and drainage below the root zone is highlighted as the cause of water scarcity (Zougmoré et al. 2004). Various studies have demonstrated increases in soil water, as a result of some soil restoration methods such as half-moon, sub-soiling furrows in soil and zaï technique (Zougmoré et al. 2003, Ganaba 2005). These techniques are particularly effective in reducing runoff and improving infiltration. Most research to date has had an agricultural focus. Comparatively, few studies have been conducted in the forestry sector (Ganaba et al. 2006). One element absent from the above studies was an explicit consideration of these methods which may shape seedling responses to guarantee revegetation success through their capacities to store water or nutrients, or to supply them to plants. How are the early survival and growth of JCL seedlings affected by these techniques? What are the implications of these responses for degraded land restoration efforts?

The research objective was to analyse the effects of different restoration techniques through water levels and soils structure on seedling growth and survivorship during the first two years of stand development.

Materials and methods

Study Area

The experiments were conducted in Gampéla, a village near Ouagadougou (12° 25' N; 1° 21' W). Gampéla is situated within the Sudano-Sahelian Zone of Burkina Faso, at an altitude of 270 m, with a low gradient of 1-2% (Figure 1). The soil is classified as Gleyic-Luvisol and forms structural crusts that reduce infiltration and thus increase runoff (WRBSR 2006). Soils are deep (over 150 cm), sandy loam in the A

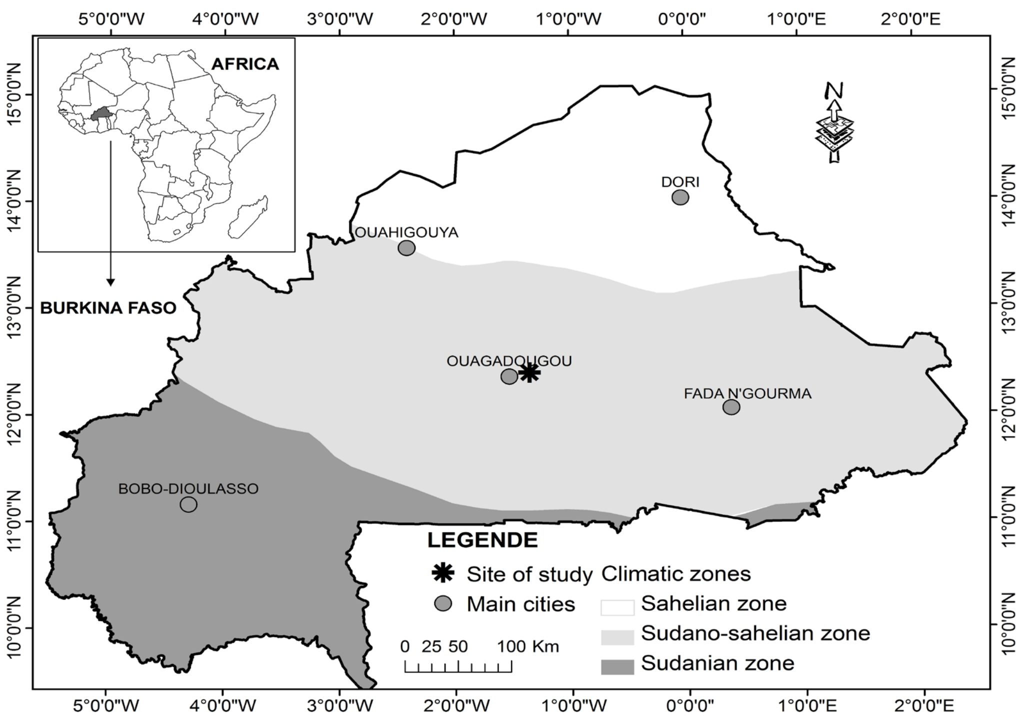

Figure 1 Climatic map of Burkina Faso and the location of the study site

horizon, with low available water capacity and clay loam in the B horizon, with medium available water capacity. An analysis revealed soils to be acidic, and low in organic C, N, available P, sum of exchangeable bases and cationic exchange capacity (Table 1). Agriculture is the dominant land use surrounding the study site. The climate is that of a typical Sudano-Sahelian Zone, with two distinct seasons: a dry season from October to May and a rainy season from June to September. Mean annual long-term rainfall and temperature (1980-2009) for the region are 713 mm and 28.7 °C, respectively. Rainfall is variable, both temporally and spatially. The mean annual potential evapotranspiration exceeds 2000 mm per annum.

The used restoration techniques

Three soil and water conservation techniques were used: sub-soiling, half-moon and 'Zaï'.

The sub-soiling technique involves tilling the soil deeply to break up the sub-soil using a bulldozer or a tractor. The aim of this technique is to loosen the soil for depths up to 40 cm to allow for increased root penetration and water infiltration. In this study, a tractor was used to create furrows 40-60 cm deep and 15 m long, spaced 3 m apart.

The half-moon technique is designed to collect surface runoff by the excavation of hollows on bare and crusted soils with gentle slopes (Zougmoré et al. 2003). Each hollow was 10–15 cm in depth, dug with a hoe or a pick with the excavated earth returned to form a mound in the shape of a half-circle. In this study, half-moons were 2 m in diameter, spaced 1 m apart in rows approximately 3 m apart (Figure 2).

'Zaï' is a traditional technique used in the Sahel in West Africa for the rehabilitation of degraded and crusted soils. The Zaï technique involves manually digging pits to collect surface runoff, to which are added some form of organic material, usually manure (Roose et al. 1999). In this study, Zaï pits were constructed 20 cm in diameter, 10-15 cm deep and 3 m apart. This study supplied manure at 300 g per pit.

Experimental design

Two experiments were conducted separately: sowing seeds and planting seedlings of JCL. The sowing experiment had a randomized completed block design with six treatments each with three replicates: (i) T0: control (no technique applied), (ii) Zaï: Zaï technique, (iii) HM: half-moon technique, without added manure, (iv) HMan: half-moon technique, with

Table 1 Physical and chemical characteristics of soil profiles of the experimental site (mean ± standard deviation, n = 5)

Soil characteristics	Soil profile	
	A-horizon (0-20 cm)	B-horizon (20-80 cm)
Clay fraction (%)	15.83 ± 0.52	42.83 ± 0.63
Silt fraction (%)	43.75 ± 1.38	46.09 ± 2.04
Sand fraction (%)	39.96 ± 2.48	10.75 ± 0.46
Available water capacity (%)	8.76 ± 0.84	11.61 ± 91.00
Soil pH (H_2O)	5.43 ± 0.39	6.47 ± 1.16
Soil pH (KCl)	4.37 ± 0.10	5.62 ± 1.20
Organic Carbon ($g \cdot kg^{-1}$)	4.80 ± 0.20	3.60 ± 1.20
Organic Nitrogen ($g \cdot kg^{-1}$)	0.40 ± 0.10	0.30 ± 0.10
Available Phosphorus ($cmol \cdot kg^{-1}$)	2.35 ± 0.81	2.23 ± 0.82
Available Potassium ($cmol \cdot kg^{-1}$)	23.30 ± 5.54	21.70 ± 2.43
Sum of exchangeable bases ($cmol \cdot kg^{-1}$)	3.27 ± 1.08	6.75 ± 0.79
Cationic exchange capacity ($cmol \cdot kg^{-1}$)	4.90 ± 0.72	9.38 ± 0.59

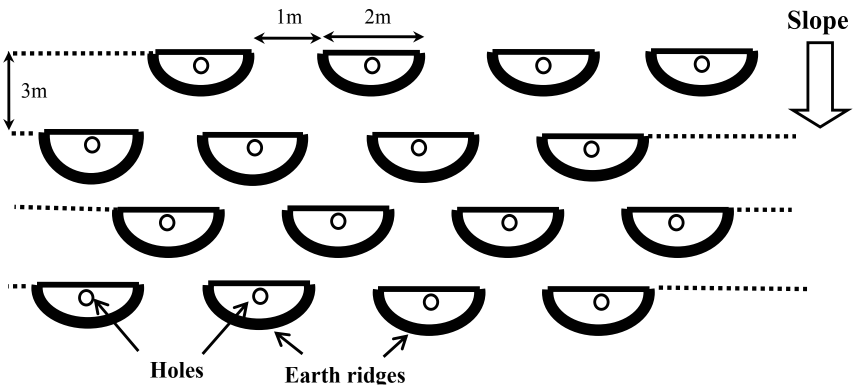

Figure 2 Diagram of half-moon disposition according to the slope

added manure, (v) SS: sub-soiling technique, without added manure, (vi) SSan: sub-soiling technique, with added manure.

The experiment was set up towards the end of the dry season, from the 20th May to the 31st May 2008. The six different treatments, each with three replicates, resulted in a total of 18 plots. Each plot was 15 m by 13 m in size, spaced 4 m apart. Twenty Zai pits and half-moons and five furrows were constructed per plot. Manure was added to half of the hollows and furrows at a dosage of 300 g per hole.

Seeds of *J. curcas* were obtained from the National Tree Seed Centre in Ouagadougou, Burkina Faso. Sowing was performed on the 2nd July 2008. In each plot, 40 seeds were sown in 20 seed-holes at a depth of 5 cm spaced 3 m apart.

The second experiment (planting/seedling) also had a randomized completed block design with four treatments and three replicates: (i) T0: control (no technique applied), (ii) SS: sub-soiling technique, without added manure, (iii) HM: half-moon technique, without added manure, (iv) A: amendment.

The twelve plots in this experiment were identical to those of the sowing experiment in terms of both size and spacing. In half of the treatments, manure was added to the seedling holes at a dosage of 300 g per hole. Seedlings were grown in a nursery from March 2008 to July 2008 at the Laboratory of Plant Physiology and Biology, at the University of Ouagadougou. Planting took place on the 21st July 2008. In each plot, twenty seedlings were planted 3 m apart, in holes with a diameter and depth of 40 cm.

The sowing and planting experiments were carried out simultaneously. The study site was protected to reduce impacts by humans and animals during the restoration trials.

Data collection

Soil water content assessment

During the growing season, soil moisture was measured gravimetrically in mid-August (wet season) and at the end of October (dry season) at five different depths: 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40–50 cm. These measurements were only taken in four of the treatments - T0, HM, SS and Zaï as measurements between treatments, with and without added manure, are assumed not to differ significantly (Zougmoré et al. 2003). However, the measurements occurred in both sowing and planting experiments. Six sampling using sealed tare boxes were taken from randomly chosen locations within each of the four treatments, yielding a total of 120 samples. Soil water content was determined by drying soil samples to constant mass at 105 °C.

Shoots establishment monitoring

Commencing ten days after seeds were sown (sowing experiment), the number of buds, leaves, seedling height and basal diameter were recorded at two-day intervals in each plot. Measurements were taken over a period of 80 days during the rainy season. To avoid errors, the location of each measurement was marked on the apex of stem with indelible paint. After the rainy season, tree height, basal diameter and survival were recorded at four points, in October, January, April and July.

Planting/seedling performance measurement

In each plot, performance of seedlings was monitored by measuring plant height and stem basal diameter. As in the sowing experiment, the location of each measurement was marked on the stem with indelible paint. Measuring commenced in July 2008. Tree survival, plant height and stem basal diameter were recorded monthly until October (the end of the rainy season) and once every three months from October 2008 onwards (October, January, April and July).

Data analysis

In the sowing experiment, germination rate (GR), the mean height, basal diameter, number of leaves and survival rate of shoots were calculated for each plot, across the different treatments. The temporal change in the growth and survival of shoots has also been analyzed. In the planting/seedling test, the mean height, basal diameter and survival rates were also calculated for each plot. Temporal changes in seedling growth and survival have also been analyzed.

Data from the two experiments were subjected to One-Way Analysis of Variance. Growth increment was analyzed using Generalized Linear Models. These data fulfilled the assumptions of normality and homogeneity of variance. Water content, germination and survival rate were analyzed with Generalized Linear Models with binomial errors; these were also used to account for the non-normal errors and the inconstancy of the variance that are associated with proportion and binary data. Means that exhibited significant differences were compared using Tukey's HSD test at the 5% level. All statistical analyses were performed with JMP 7 Statistical Software (SAS Institute 2007).

Results

Soil water content

Soil moisture content varied significantly between years, at different depths and among treatments. With the exception of the control, soil water content was significantly higher 2008 than in 2009 in all the treatments. Soil moisture content decreased from 0 to 30 cm at the peak of the rainy season (August). However, at the onset of the dry season (October), soil moisture content increased with soil depth from 0 to 30 cm, but remained constant from a depth of 30 to 50 cm (Figure 3). Generally, the soil moisture content was lower in the control plots than in the treated plots at all depths.

In 2008, soil moisture content was significantly higher at all depths in the half-moon (HM) and sub-soiling (SS) treatments than in the Zaï treatment ($df = 3$; $F = 75.6348$; $p < 0.05$). Yet, in 2009, there was significantly higher soil moisture content in the HM treatment in comparison with the other treatments. Most importantly, soil moisture content in the HM treatment at depths 20 to 50 cm at the onset of the dry spell (October 2009) was slightly higher than that obtained at the peak of the rainy season (August 2009).

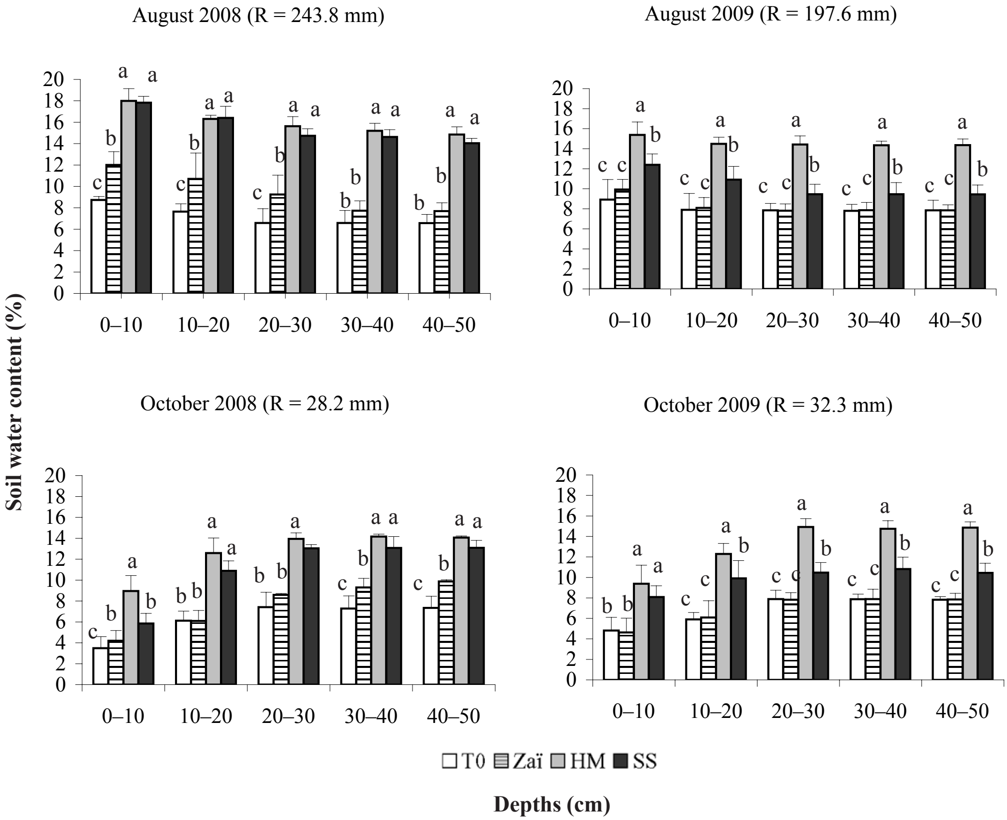

Figure 3 Effect of the four different treatments on soil water content following depths in the 2008 and 2009 rainy seasons at the planting site in Gampéla, Burkina Faso.
Treatments bars carrying the same letter are not statistically different at $p = 0.05$; T0: control, Zaï: Zaï technique, HM: Half-moons technique, SS: sub-soiling technique.

Seeding shoots establishment

Germination rate varied significantly among treatments ($df = 5$; $F = 19.44$; $p < 0.05$). It was significantly higher both in the control and SS seeded treatments (76% and 72% respectively) than in the Zaï and SSm treatments. However the GR difference between Zaï and SS was not significant. The lowest GR was observed in HM and HMm treatments (45.83% and 43.33% respectively).

At the end of the first rainy season, growth parameters of the shoots: height, basal diameter and number of leaves varied significantly among treatments during the wet season (Table 2). There was significant difference in height among treatments ($df = 5$; $F = 676.34$; $p < 0.05$), diameter among treatments ($df = 5$; $F = 259.23$; $p < 0.05$) and number of leaves among treatments ($df = 5$; $F = 269.24$; $p < 0.05$). Shoots growing under the amended sub-soiling (SSm) plots were taller and had more leaves than shoots growing in the SS, Zaï, HMm, T0 and HM plots. However, among the other five treatments, performance was the highest in the SS and Zaï treatments and generally the lowest under HMm, HM and T0 treatments.

Figure 4 illustrates the temporal variation in shoot height, stem diameter and survival rate under different treatments. In the control treat-

Table 2 Effect of treatment on shoot growth parameters after the first rainy season at the study site in Gampéla, Burkina Faso

Treatments	Height (cm)		Diameter (mm)		Number of leaves	
	Mean	SD	Mean	SD	Mean	SD
T0	11.62[c]	1.62	11.85[d]	1.59	9[c]	2.08
Zaï	16.64[b]	1.53	15.76[c]	1.82	19[b]	4.36
HM	10.86[c]	0.46	11.80[d]	1.37	7[c]	1.00
SS	18.16[b]	2.57	19.59[b]	2.24	17[b]	1.73
SSm	38.33[a]	2.52	25.23[a]	0.91	35[a]	5.06
HMm	15.11[b]	0.29	14.52[cd]	2.00	11[c]	2.52

Note: Treatments with mean followed by the same letter for each parameter are not statistically different at $p = 0.05$ according to Tukey's HSD test. T0: control, Zaï: Zaï treatment, HM: half-moon treatment; SS: sub-soiling treatment, SSm: sub-soiling treatment with added manure, HMm: half-moon treatment with added manure.

ment, seedlings did not survive beyond April 2009. However, in all the other treatments, shoots exhibit three growing stages from July 2008 to April 2010. The first stage, from July to October, corresponded to the first rainy season. The second stage, from October to June, occurred during the dry season and the third stage, from July to October, corresponding to the second rainy season. During the first stage, shoots grew rapidly in all treatments. However, shoot height and stem diameter were highest in the Sub-soiling treatment (SSm), where manure was added, followed by those in the SS treatment, where manure was not added. During the second growing stage, corresponding to the dry season, shoot growth - in term of height and diameter - increased slowly in all treatments. In the third stage, shoots again grew rapidly.

By the end of the trial, comparison among treatments revealed significant effects of the different treatments on the height ($df = 5$; $F = 125.15$; $p < 0.05$) and diameter ($df = 5$; $F = 73.83$; $p < 0.05$) of the shoots. Height and stem diameter were significantly greater in the SSm treatment than in the SS, HMm, Zaï treatments and the lowest in the HM treatment. The survival of shoots varied across the different treatments (Figure 4C). Across all treatments, survival rate of the shoots decreased from the beginning of dry season (October) to the beginning of the rainy season (June) after which it remained constant over the rainy season. Comparison amongst treatments showed that the survival rate was greatest in the SS treatment (25.33 %), followed by the SSm treatment (18.74 %). Survival rate was the low in the other treatments (< 4 % in Zaï, HM, HMm and 0 % in control).

Planting/seedling growth and survivorship

The effect of each treatment on seedling growth during the first raining season is shown in Figure 5. Treatment had a significant influence on seedling height ($df = 3$; $F = 23.40$; $p < 0.05$) and diameter ($df = 3$; $F = 24.47$; $p < 0.05$). Height increment was highest in the Amendment treatment (A) (mean of 18.25 cm) followed by the Sub-soiling treatment (12.27 cm) and lowest in the Half-moon treatment (8.63 cm) and control (8.64 cm)(Figure 5A). Seedling diameter was highest in the A treatment (mean of 20.5 mm), followed by SS treatment (18.1 mm) and lowest in HM and T0 treatment (Figure 5B).

Temporal variation in seedling growth and survival is shown on Figure 6. After the first rainy season (June to October), seedlings grew slowly (in height and diameter). Treatment had a significant effect on both height ($df = 3$; $F = 56.74$; $p < 0.05$) and diameter ($df = 3$; $F = 31.76$; $p < 0.05$). Seedlings were significantly larger under the HM treatment followed by the SS treatment and smallest in the control.

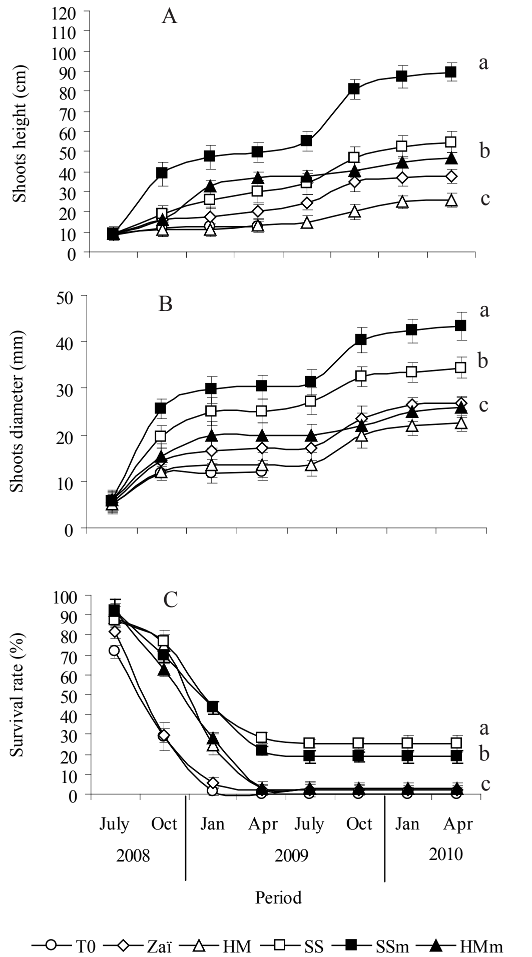

Figure 4 Temporal variation in mean height (A), stem diameter (B) and survival rate (C) of shoots under the different treatments at a study site in Gampéla, Burkina Faso.
T0: control; Zaï: Zaï treatment; HM: Half-moon treatment; SS: sub-soiling treatment, SSm: sub-soiling treatment with added manure, HMm: Half-moon treatment with added manure; $n = 3$). Different letters across treatment curves denote significant differences ($p < 0.05$) according to Tukey's HSD test. Error bars represent standard deviation.

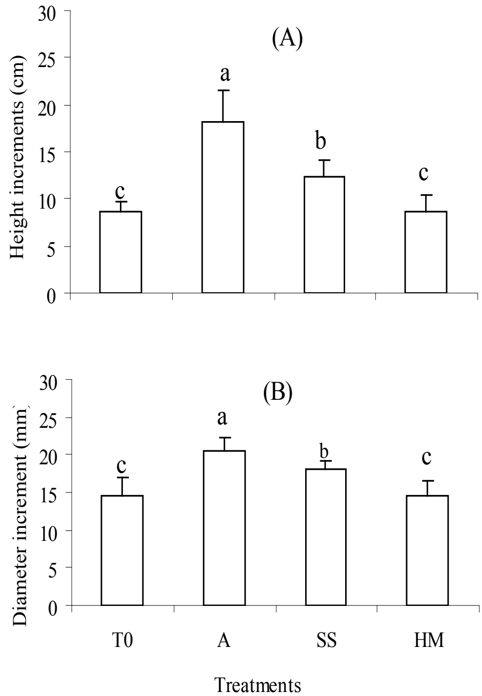

Figure 5 Growth increment in height (A) and stem diameter (B) of seedlings under the different treatments at a study site in Gampéla, Burkina Faso ($n = 3$).
Letters on the bars indicate significant difference ($p < 0.05$) between treatments. T0: control; A: amendment treatment; HM: Half-moon treatment; SS: sub-soiling treatment). Error bars represent standard deviation.

Survival rate of the seedlings differed between treatments (Figure 6C). Survival rates were highest at the early stages in all treatments until January (95% for A treatment and 100% for other treatments). From January 2009 to April 2010, the survival rates decreased variably amongst the treat-ments. In the HM treatment, except for a short decline in survival rate from April, seedling survival was, generally, constantly high (90%), until the end of the trial. Conversely, survival rate decreased slowly in the SS treatment and more quickly in the control. The greatest decline in survival rate was observed in the A treatment, in which all seedlings died between April and May. The different treatments yielded significantly different seedlings survival rates ($df = 3$; $F = 50.4$; $p < 0.05$), but all seedlings wilted in A treatment and died before April 2009.

Discussion

Treatments affect soil moisture content

Soil moisture content varied across treatments and soil depth. The variation in soil moisture content can be understood in the context of a combination of several hydrological processes, including infiltration, vertical and lateral redistribution, and evapotranspiration (Qiu et al. 2001). The observed differences in soil moisture content were driven by soil water infiltration, followed by depletion through evapotranspiration (Brandes & Wilcox 2000). Indeed, soil surface compaction and crusting are serious limiting factors to water infiltration in these soils (Zougmoré et al. 2003). Soils in this region are characterized by low water storage capacity, as a result of kaolinitic clay, gravels, and ferruginous hardpan near

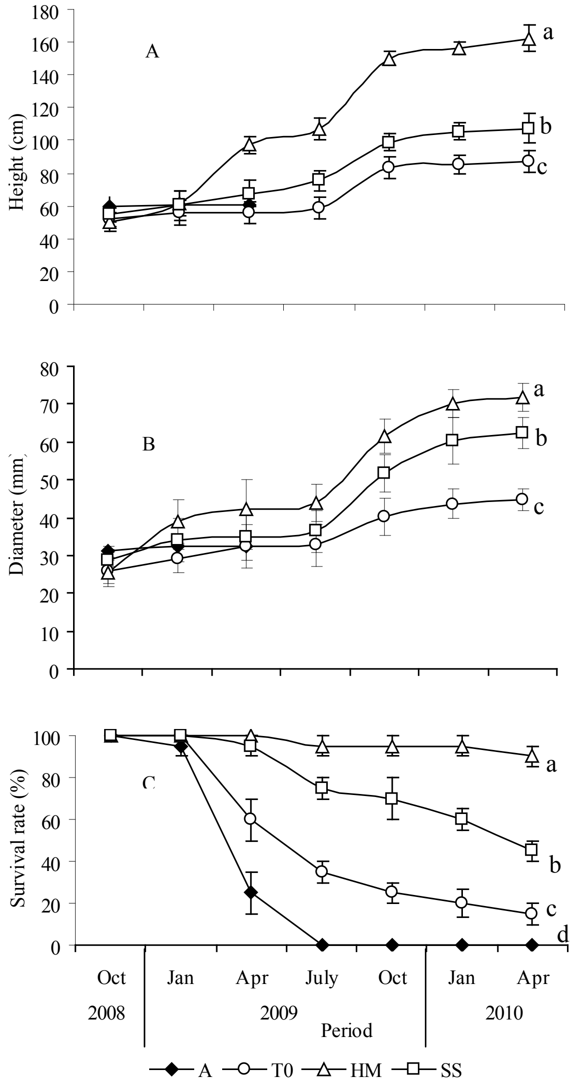

Figure 6 Temporal variation in height (A), stem diameter (B) and survival (C) of planted seedlings under the different treatments from July 2008 to April 2010 at a study site in Gampéla, Burkina Faso. T0: control, A: Amendment Treatment, HM: Half-moon Treatment, SS: Sub-soiling Treatment. Letters in the curves indicate significant difference between. Error bars represent standard deviation.

the surface (Roose et al. 1999). Therefore, soil physical characteristics need to be modified by mechanical interventions, in order to enhance porosity and infiltration. Destroying the surface crust by stripping away the surface horizon temporarily improved soil porosity and hence infiltration (Casenave & Valentin 1992). However, variation in soil moisture content, obtained under the different treatments, could be attributable to differences in the water storage capacity of the mechanical treatments used (HM, SS and Zaï). The earth ridge running around the curve edge of the half-moon retains runoff water in the basin (Zougmoré et al. 2003). The furrows of from the Sub-soiling treatment reach depths of 40 cm, thereby increasing infiltration. However, this treatment captured less surface runoff than the HM treatment, because of high levels of erosion caused. Zaï pits collected the surface runoff, but had a smaller surface area than that of HM and SS treatments. This could explain why soil moisture content was the highest under the HM treatment, followed by the SS treatment during the first year (2008). In the second year, 2009, soil water appeared to be more rapidly depleted in SS and Zaï treatments (Figure 3). Furthermore, SS and Zaï treatments had quickly moving as the result of erosion lead the soil to reform its original state, whilst the Half-moon's hollows did not occurred great change in their structure. This is reflected by the lack of change in soil moisture content in the HM treatment between 2008 and 2009. The combined effect of capturing and allowing for the infiltration of surface runoff resulted in the Half-moon technique make it being the most effective method for improving soil moisture content on degraded soils.

Seeding shoots establishment responses to treatments

The results show that the treatments differentially affected the establishment of the shoots. Henning (2007) reported that shoots growth in JCL is intermittent, sympodial and follows the architectural model of Leeuwenberg; fluctuations in rainfall, temperature and light induce dormancy. The most likely explanation for the differences in growth and survival rate between treatments is that of soil moisture content. Soil moisture is a key factor influencing the growth and the survival rate of plant communities in dry areas (Hienaux et al. 2006, Zida et al. 2008). During the first rainy season, soil moisture content was higher in the HM and SS treatments than in the Zaï treatment and lowest in the control. This best explains the high success of shoot establishment in all treatments except for HM and HMm. Another two likely factors playing a role in establishment success are nutrient provision, through added manure, and soil compaction. Growth, in terms of height, diameter and number of leaves was highest under the amended Sub-soiling treatment (SSam), followed by the SS and Zaï treatments. It has been shown that if water content is not a limiting factor, shoot growth is driven by nutrient levels (Penning de Vries 1982). Differing nutrient levels may explain the higher performance of shoots in the SSm than the SS treatment, and the relatively high success in the Zaï treatment. The best performances of shoots during the first rainy season in the SS treatment may be attributed to soil structure and porosity because of ploughing.

However, temporal change in shoot establishment can be explained by the climatic regime. From October to the end of May, a dry spell occurred. In spite of the drought, in contrasts with other deciduous tree, shoots of JCL maintained part of their leaves for several weeks during the dry spell (Holbrook et al. 1995, Borchert & Rivera 2001). Its are able to maintain their growth for several weeks during periods of drought by using stem water reserves (Borchert 1994). This explains the observed establishment in all treatments until January. However, after January, growth rate slowed and mortality rate increased. Seeds of

JCL were sown at a depth of 5 cm. Even if water content was higher at certain depths in some treatments - HM, SS - *J. curcas* is generally a shallow rooting plant in young stage (Maes et al. 2009). Shoots roots are generally situated in the surface soil layers reaching a maximum of 20 cm, especially in the early stage of plant development. Then, the period from March to April corresponds with high temperatures and evapotranspiration which was fatal to plants in all treatments. Hence soil restoration treatments of the zipellés, despite improving soil aeration and water infiltration, did not insure the establishment of shoots through sowing.

Planted seedlings differ in their responses to restoration techniques

As expected, growth rates varied significantly across treatments at the end of the first rainy season (Figure 5). The differences in seedling growth among treatments may be explained by differential water and nutrient availability. During the first rainy season, soil moisture content was highest in the HM and SS treatments and lowest in both the A treatment and the control. Despite water content being highest in the HM and SS treatments, there is no significant difference in height between them and the control. This seems to indicate that water was not a limiting factor during this period, the rainy season. Even if water is the major growth-limiting factor in dry seasons, only a small amount of water needs to be available for seedling to establish (Khurana et al. 2001, Zida et *al.* 2008). The highest growth rate under the A treatment could be related to the nutrient additions. Enhancement of seedling growth due to nutrient amendment has been observed in several species. The growth performance under organic amendment are consistent with the findings of Francis et al. (2008) who reported that JCL responds better to organic amendment than mineral fertilizer on degraded soils in India.

Temporal change in the growth and survival rates of seedlings was also influenced by type of treatment. Seedling establishment is dependent on environmental conditions (Burdett 1990). Soil moisture is the key factor influencing the growth and the survival rate of plant communities in dry areas (Hienaux et al. 2006, Zida et al. 2008). The ability of a seedling to take up water is affected by its root system size and distribution (Grossinickle 2005, Shaxson & Barber 2003). Thus, the observed differences between treatments in seedling growth may be explained by the ability of the roots of seedling to reach moisture during the drought period. Seedlings were planted at depths of 15-20 cm, where they exhibit a well developed tap root, reaching a depth of 40-50 cm and highest density of roots around the root stock. At the onset of the drought, soil moisture content was the highest at depths of 20 to 50 cm in HM and SS treatments, and the lowest, in A and control treatments. This explains the higher growth and survival rates of seedlings in the HM and SS treatments. Seedlings of JCL were able to maintain their growth several weeks into drought by using their stem water reserves (Borchert 1994). However, in the same treatments, in the middle of the dry season (March to April), seedling growth rate and survival rate decreased. No seedlings survived in the A treatment. This was thought to have been a result of termites that were observed to feed off the root and the stem of the seedlings, causing high mortality. However, in both the HM and SS treatments, seedlings continued to grow. HM and SS treatments were able to trap water which resulted in water being stored for the drought. This may explain the high success rates of seedlings. However, as soil water seems to be more rapidly depleted in the SS treatment, this may explain the better performance of seedlings in the HM treatment. Despite variable success rates, the general trend between April and June was that stress caused by drought resulted in a universal decrease in the growth rate of seedlings.

Conclusion

The results of the present study indicate that the soil restoration and water conservation techniques employed increase overall soil water content, thereby improving the growth and survival rates of *Jatropha curcas*. There are two major outcomes of this study, both of which have important implications for the future use of this specie. Firstly, it appears as though planting seedlings guarantees better survival than sowing seeds. Secondly, the Half-moon technique, with its ability to increase and maintain soil water content for extended periods, is the most effective restoration technique. The second most effective was the Sub-soiling technique. Adding organic matter was shown to significantly enhance the growth rate of seedlings. However, termites resulted in high mortality rates amongst seedlings. Future trials should consider protective measures against termites. The results of this study have direct implications for future attempts at revegetation of degraded soils with *Jatropha curcas*.

In the face of carbon markets, C storage becomes an additional output that landowners might consider in their management decisions. This suggests that further laboratory and field studies are needed to assess C storage in the plants biomass and soils through the use of these technologies.

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