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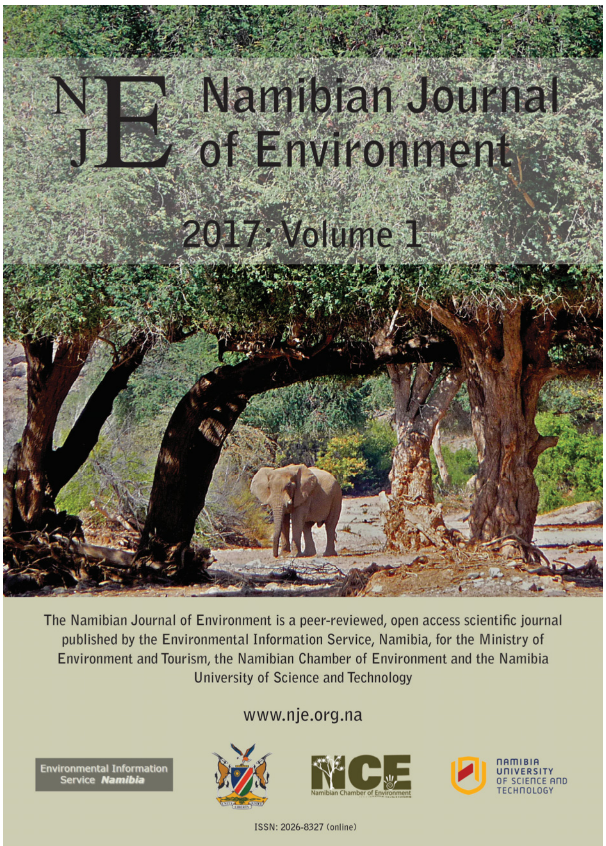

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The influence of two levels of debushing in Namibia's Thornbush Savanna on overall soil fertility, measured through bioassays

I Zimmermann[1], M Nghikembua[2], D Shipingana[1], T Aron[1], D Groves[3] and L Marker[2]

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[1] Namibia University of Science and Technology, Storch St, Windhoek, Namibia. izimmermann@nust.na
[2] Cheetah Conservation Fund, PO Box 1755 Otjiwarongo, Namibia
[3] Columbia University, 116th St & Broadway, New York, NY 10027, USA

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ABSTRACT

A healthy and productive rangeland depends on well-functioning ecosystem services such as effective cycling of water and nutrients. After rangeland has degraded, bushes may encroach in nature's attempt to restore water and nutrient cycling. When bush encroachment is addressed by debushing, with harvested bush wood sold off the land, then nutrient cycling is disrupted and soil fertility is likely to decline. Former debushing activities on different parts of farms of the Cheetah Conservation Fund in central Namibia provided the opportunity to assess the influence of debushing on overall fertility of soil. Sites were selected on the farm representing nine examples of each of uncleared, partially cleared and totally cleared land. The debushing had taken place at different times, varying between two and 13 years previously. Soil was collected from each of these 27 sites and subjected to bioassay by growing barley (*Hordeum vulgare*) and *Moringa oleifera*. Seedling emergence and height at five weeks for both species were greatest in uncleared soil and lowest in totally cleared soil, indicating the loss of soil fertility as debushing intensifies. There was no evidence of restoration of soil fertility, even 13 years after debushing. Nutritious grass is unlikely to grow well after debushing, and more bush is likely to regrow in nature's attempt at restoring fertility over the long term. If faster restoration is sought, then the full spectrum of minerals removed in harvested wood should be replaced on the land.

Keywords: bioassay; bush encroachment; debushing; Namibia; soil fertility; Thornbush Savanna

INTRODUCTION

Much of the rangeland in Namibia has experienced degradation over past decades, with interference in healthy water and nutrient cycling (MAWF 2012). Only a portion of the nutrients grazed by animals get recycled to the soil through dung and urine, with proportions varying greatly between the different elements. The remainder of the nutrients are removed from the ecosystem if milk or animals are sold off the farm. During the first half of the 20th century, Namibia supported a thriving dairy industry, after which live animals took over as the main export through the farm gate. Although the shift from dairy to beef was brought about by imposition of market regulations (Lau & Reiner 1993), it is likely to also reflect decline in quality of grass resulting from both poor grazing management and loss in soil fertility.

In the past, many farmers supplemented their animals' feed with bone meal, which returned largely the elements of Ca and P, but this practice has been banned since 1998 for veterinary reasons (Kaurivi 2013). Currently used supplements return some elements, but unlikely in balance with those removed. The emphasis is usually placed on lick supplementation of P and N, even though the latter can be freely obtained from the air, particularly if a healthy root system feeds free-living nitrogen-fixing microbes in the soil through exudates (Lovel 2014).

Rock salt may return a portion of the micro-elements, which animals tend to seek out by selectively licking bands within the salt block where the micro-elements presumably settled out during crystallisation. However, in the process, animals also tend to consume large amounts of Na and Cl, which may contaminate the soil when excreted in dung and urine, causing physical, chemical and biological harm to the soil (Andersen 2000). This might be partly responsible for the observations of a general accumulation of Na in overgrazed topsoil (Gröngröft et al. 2010) and higher Na in soil of more recently burned woodland (Nghalipo 2016).

Bush encroachment is one of the symptoms of rangeland degradation, caused by a variety of factors including herbivory, tree harvest, fire, carbon dioxide and soil nutrients (Zimmermann et al. 2008, Van Auken 2009) and may reoccur in cyclical patterns (Cunningham 2014). The interplay between these factors is pointed out by Devine et al. (2017), such as soil fertility being both a cause and an effect of woody cover. Farmers often respond to the symptom of bush encroachment by debushing. However, this removes even more nutrients from the system than grazing, if the harvested bushes or their products are sold off the farm, yet there is rarely any attempt to return the lost elements to the debushed land. Many farmers leave some of the harvested material, usually the thinner branches with most of the leaves, on the land (De Klerk 2004, Joubert & Zimmermann 2017). However, this is insufficient to compensate for the elements lost in the larger portion of harvested bush that is removed.

Since debushing had taken place between 13 and two years previously on different parts of the Cheetah Conservation Fund (CCF) farms, and at two different levels of partial and total clearing of bushes, it provided the opportunity to examine the effect of these factors on soil fertility. Sites selected for debushing were expected to have adequate harvestable bush biomass and to be easily accessible for manual harvesting.

Overall fertility of soil can be conveniently measured by bioassay (Olsvig-Whittaker & Morris 1982), which is a measurement based on the responses of living organisms planted in that soil. Species of plants grown in bioassays should be easy to grow in a range of soil conditions. Two species were selected for this study, barley (*Hordeum vulgare*) and Indian moringa (*Moringa oleifera*). The reason for selecting a grass and a tree is that differences can be expected in their root exudates and rhizosphere interactions used for obtaining nutrients. For example, dicots and non-graminaceous monocots tend to exude organic acids that chelate Fe, whereas grass roots tend to exude phytosiderophores with high specificity for certain metals (Marschner & Rengel 2003).

METHODS

The study area is situated approximately 40 km east of Otjiwarongo in Namibia's Thornbush Savanna (Giess 1971), on four commercial farms (Cheetah View, Boskop, Elandsvreugde #367 and Osonanga #368) owned by the CCF, in the Waterberg Conservancy (-20.433 S, 17.078 E; Figure 1). Sites with different post-harvest ages ranging from 2-13 years (mean: 5.6 partially cleared, 4.3 totally cleared) were previously harvested by CCF bush project to promote ideal habitat structure for open-savanna-adapted species, while processing the harvested wood into blocks sold for fuel (CCF Bush Pty. Ltd. 2017). About 89% (n=16) of the harvested sites received aftercare by applying a Picloram active arboricide, commercially known as Access, on the harvested stumps to prevent bush regrowth.

The area receives a mean annual rainfall of 400 mm and experiences three major seasons including the wet-hot (January-April), dry-cold (May-August) and dry-hot (September-December). The vegetation type is classified as semi-arid Thornbush Savanna, dominated by encroaching woody species such as *Acacia* (*sensu lato*) mellifera subsp. *detinens* and *Dichrostachys cinerea* (Giess 1971). The Waterberg Plateau, a 4,100 km^2 sandstone uplift on the eastern periphery of the study area, is the dominant geological feature of the region. The study area falls within the Damara sequence geologic stratum, the oldest in the Waterberg region. The soils, which are of sandy loam texture in all study plots, fall into two main associations indicated in Figure 2, the Eutric Regosols and Chromic Cambisols (Mendelsohn et al. 2002). The former is expected to be more fertile, as implied by the name "Eutric", while "Chromic" implies brightly coloured. The topography of the farms is generally flat with slight undulations; consequently, rainfall run-off is slow and there are no permanent river systems on the farms. A number of man-made semi-permanent water reservoirs (earth dams) were developed to provide wildlife and livestock with drinking water.

Sites were selected on the CCF farms (Figure 2) representing nine examples each of uncleared, partially cleared and totally cleared land (Figures 3-5). On uncleared

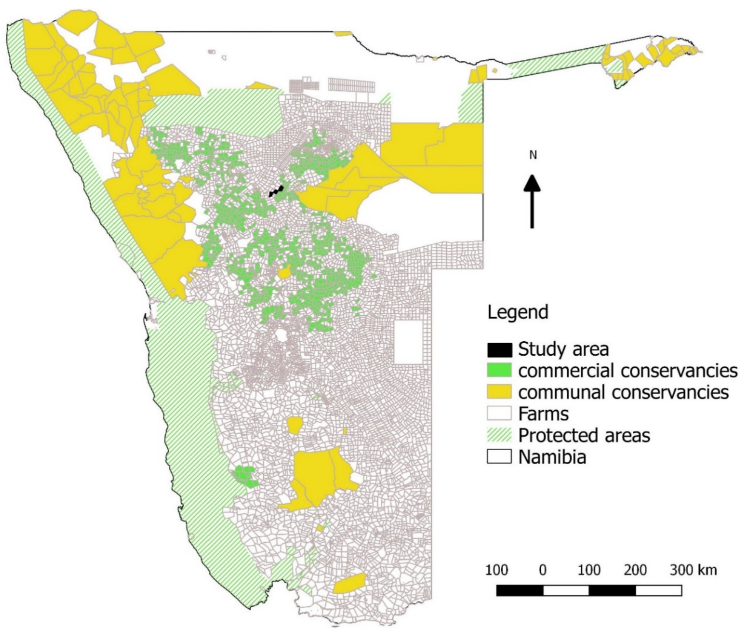

Figure 1: *Location of study area farms of Cheetah Conservation Fund*

land, the overall density was approximately 1,300 bushes/ha. Grass had not been harvested from cleared sites for hay, as is commonly practiced elsewhere. Although the sites were scattered over two soil associations (Figure 2), an equal number of sites from each debushing treatment occurred in each soil association. The debushing had taken place at different times, varying between two and 13 years previously. A composite soil sample was gathered from each of these 27 sites, by collecting three subsamples using a spade to a depth of approximately 30 cm and mixing together in a bucket. The subsample sites were located randomly in each site using the Hawthstools random extensions run in ArchMap GIS 10.3 (Esri, Redlands, CA). A systematic grid of 100 m^2 was laid over each site and random selection was constrained on these grid points. Each mixed soil sample was divided into 27 growing bags of approximately 500 ml capacity, 15 to serve as replicates for barley and 12 as replicates for moringa, the latter being limited by availability of seed.

Each growing bag was sown with either two moringa seeds or three barley seeds and kept moist, for later thinning to one seedling per bag. Bags from which seedlings emerged were recorded daily over two weeks, and height of the tallest stem or tiller per bag were recorded weekly until the fifth week (Figure 6).

The first assessment was of the average treatment effect of total clearing and partial clearing on the percentage of bags with seedlings sprouting and surviving over a five-week period, relative to bags with soil from uncleared sites. P-values and confidence intervals were estimated using randomisation inference (Gerber & Green 2012), with clustering at the site level. Nearly equal results were obtained using OLS regression and Chi-Squared tests.

Secondly, we estimated the average treatment effect of total clearing and partial clearing on the height of sprouted seedlings, standardised to the uncleared mean, using ordinary least squares regression. The reported results include non-sprouting seedlings in this estimate, but are robust to their exclusion.

Thirdly, we analysed changes in seedling growth over time since debushing. To test the hypothesis that initial improvements in soil fertility are countered with subsequent declines, we fitted a quadratic polynomial function to allow for a curvilinear effect of years-since-clearing on mean seedling height.

For all of the above, we included controls for soil association and species, and tested for soil and species-treatment interactions.

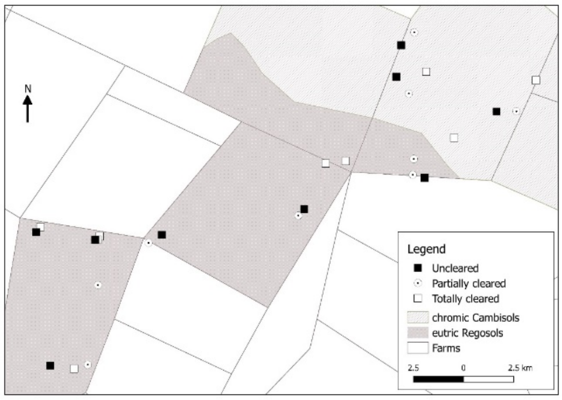

Figure 2: *Locations of sites on Cheetah Conservation Fund farms from where soil samples were collected, in relation to soil associations.*

RESULTS

Seedling Sprouting

Seedlings were significantly ($p<0.05$) less likely to emerge and survive up to five weeks in soil from both fully de-bushed and partially de-bushed sites relative to seedlings in soil from uncleared land. Analysis of heterogeneous treatment effects revealed no statistically significant difference between treatment effects on barley versus moringa seedlings. If soil association is disregarded, there was a 20% and 31% decrease in seedling survival in fully cleared soil for barley and moringa, respectively, and 13% and 15% decrease in seedling survival in partially cleared soil. When controlling for soil association and plant type, the results shift to 12% decrease for partially cleared and 20% decrease for totally cleared sites. However, soil association also had a significant ($p<0.05$) but lesser effect than level of debushing on seedling survival. Figure 7 indicates the effect of soil association on number of surviving seedlings of both species combined, with 30% and 22% decrease in seedling survival in fully cleared soil for Ochric Cambisol and Eutric Regosol respectively, compared with uncleared soil, and 16% and 13% decrease in seedling survival in partially cleared soil for Ochric Cambisol and Eutric Regosol respectively.

Seedling Growth

Decreased fertility is further reflected in the comparison of mean heights of the plants grown in soil samples. The effect of level of debushing was greater than that of soil association for both barley and moringa, which were standardised by height to reflect soil fertility, since moringa grew slower than barley yet exhibited similar patterns. On average, barley seedlings were 18% shorter in cambisol than regosol, and moringa seedlings were 9% shorter ($p<0.05$). Figure 8 combines barley and moringa seedling heights to indicate soil fertility relative to the

***Figure 3:** Uncleared land*

***Figure 4:** Partially cleared land*

***Figure 5:** Totally cleared land*

***Figure 6:** Bioassay of sampled soil using barley (left) and moringa (right)*

most fertile soil in uncleared sites. The drop in fertility from uncleared to partially cleared sites was 28% on Cambisol and 17% on Regosol, while the drop in fertility from uncleared to totally cleared sites was 34% on Cambisol and 29% on Regosol. The difference in soil fertility between fully and partially cleared soils is erased when we control for soil association and species in regression analysis. (In OLS regression controlling for species and soil association, these results are 3 cm decrease for barley in partially cleared and 4.2 cm decrease for barley in fully cleared soils, and a 1.3 cm decrease for moringa in partially cleared and a 1.9 cm decrease for moringa in fully cleared soils.) (Point estimates were obtained using OLS regression and p-values using randomisation inference to account for non-normal distribution of the dependent variable.)

Interaction effects between soil association were small and generally not statistically significant at standard levels. However, the interaction between plant type and clearing level were substantially and statistically significant: the negative effect of full clearing increased by 2.2 cm for barley relative to moringa, and the negative effect of partial clearing increased by 1.7 cm ($p<0.05$ and $p<0.1$).

Change over time since debushing

The data in Figure 9 are noisy and far less clear than those presented above on level of debushing, so no firm conclusions can be drawn from them. The expectation of increase in soil fertility immediately after debushing was not detected by these results that start at two years after debushing. An immediate increase in soil fertility could be expected from root exudates released in response to harvest. From decomposition of the increased dead leaves, the expected increase in soil fertility would be over the next rainy season. Decomposition of larger roots may continue for several years thereafter. From new inputs provided by regrown bushes and trees, the re-establishment of soil fertility is expected to take several decades, and the data in Figure 9 fail to show any hint of this having started yet 13 years after debushing.

DISCUSSION

The results indicate a decline in soil fertility from debushing that took place at different times between two and 13 years previously in both soil associations. This is not surprising, given the removal of harvested bushes for sale, without return to the soil of minerals contained in those harvested bushes. There is the possibility that large herbivores may also contribute

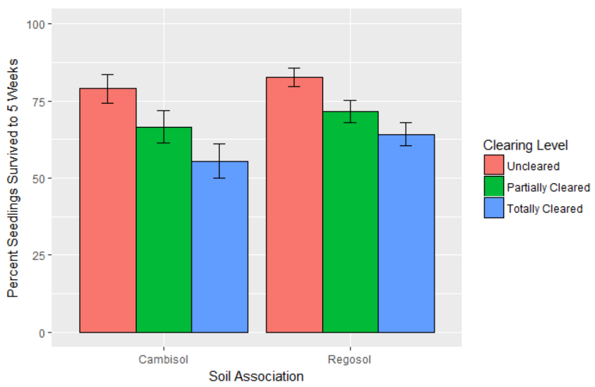

Figure 7: *Percent seedling emergence and survival up to five weeks for barley and moringa combined, as influenced by level of debushing and soil association. Error bars represent standard errors*

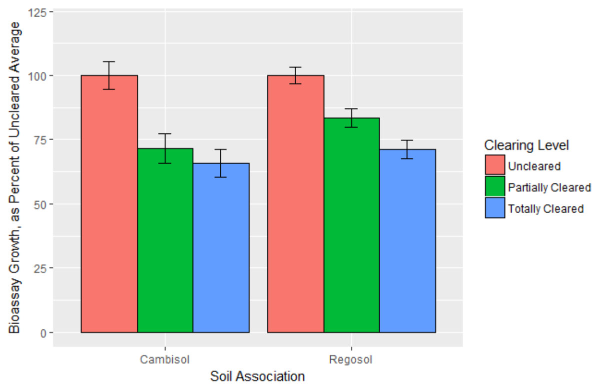

Figure 8: *Mean seedling growth at five weeks as percentages of the mean from uncleared sites, to represent relative fertility in soil with different levels of debushing on each soil association. Error bars represent standard errors*

to fertility loss and gain, if they feed more in certain areas and spread their excrement more in other areas. However, this was not investigated by the current study.

Andrews (2008) points out that as fertility of the topsoil declines, whether through sale of animals or wood or both, more woody plants grow, which bring up minerals from the subsoil. If the established bushes are given the opportunity to replenish soil fertility over decades, then grasses eventually regain their competitive advantage and bushes decline once more. However, if bushes are harvested, then fertility declines further in a vicious circle as bushes regrow with more vigour.

Various authors offer evidence of woody plants leading to higher soil fertility. For example, Sandhage-Hofmann et al. (2015) found higher soil fertility in the bush encroached zone farther from water points of continuously grazed communal land, which they attribute to the increase in *Acacia* bushes. Mills and Fey (2004) found poorer soil quality where succulent thicket had been transformed by goats to savanna. Rothauge et al. (2007) found that grasses occurring in canopied habitats had a significantly higher nutritive value than those occurring in the open, even if they were of the same species. Hagos and Smit (2005) found a gradient in soil nutrient status, from higher near the stem of free standing *Acacia mellifera* trees, to lower further away from the canopy in open ground. Blaser et al. (2014) found that encroachment by *Dichrostachys cinerea* resulted not only in higher soil levels of C and N that cycle through the atmosphere, but also of P that cycles more directly between biota and soil.

Although credit for the ability of woody plants to raise soil fertility is usually given to annual leaf fall (Nair et al. 1998), biological soil crusts that tend to develop under protection of bushes (Dougill & Thomas 2004) and termites that feed on fallen twigs and branches (Joquet et al. 2007, Barthès et al. 2015), the less visible role of roots should not be overlooked. Fine roots of trees seem to contribute more to nutrient cycling than leaves, due to their faster release of both N and P (Jose et al. 2000), and root exudates contribute significantly to the pool of soil carbon that feeds the soil food web (Grayston et al. 1997, Clapperton et al. 2003, Bais et al. 2006, Zhang et al. 2017).

The proposition that lower fertility leads to an increase of woody plants is offered by a few authors. The encroachment of leguminous bushes on rangeland in Arizona between 1903 and 1943 is attributed by Albrecht (2005) to the removal of organic fertility by cattle. When analysing data from a wide range of soils over Namibia and South Africa, Mills et al. (2013) found a peak in woody plant cover on soils of intermediate fertility, with lower cover in soils of both low and high fertility, and the latter linked to aridity. They conclude that the abundance of woody plants is partly determined by soil nutrient status, with fertile soil favouring the growth of grasses. After examining tree density in a rangeland subjected to long-term fertilisation trials followed by protection, Mills et al. (2017) found that soil Mg, B, Mn and Cu most likely affected tree abundance, in particular the ratio Mn/Cu, pointing out the "global significance (of these findings) for the practical control of invasive woody plants."

CONCLUSION

Combining the information presented in the above discussion, it seems unlikely that the grass growing on debushed land will be very nutritious from the second year onwards, due to the lower soil fertility found even in sites debushed two years previously. The spectacular flush of grass that often follows debushing is usually short-lived, probably declining

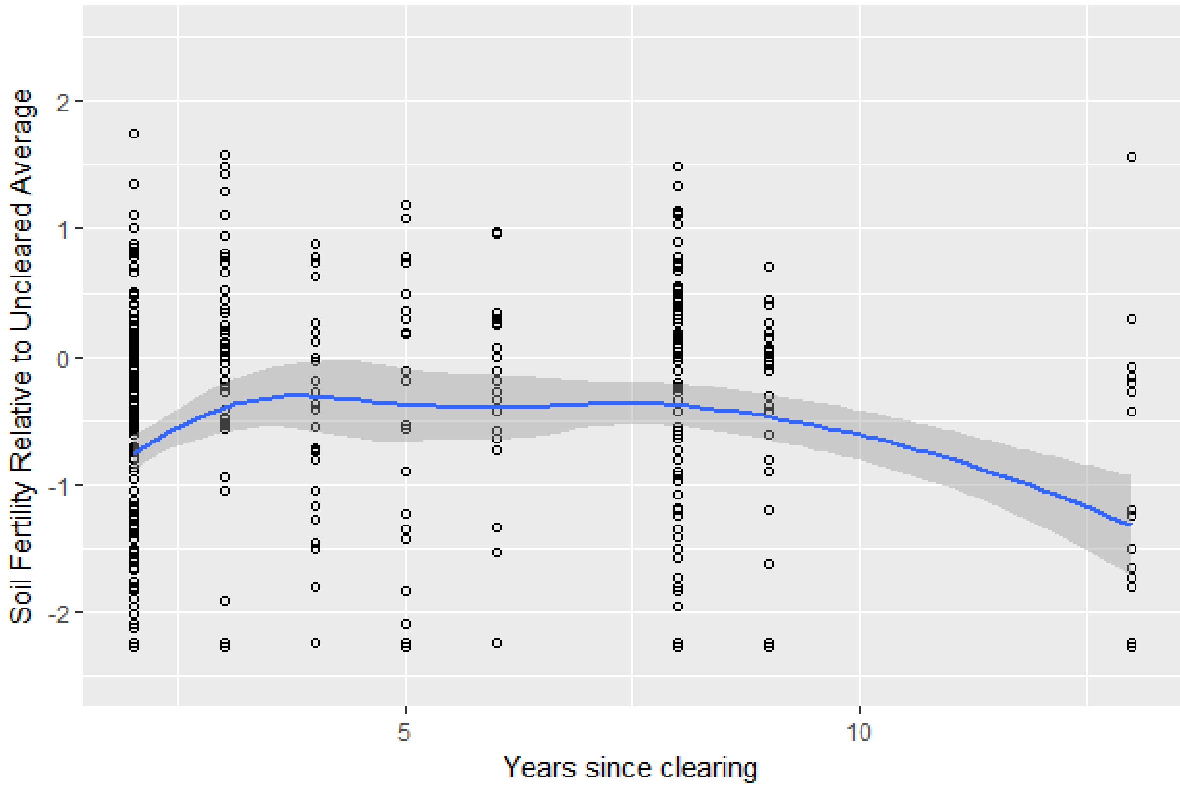

Figure 9: *Seedling growth over time since debushing*

as organic material from dead leaves and twigs become depleted. According to Rothauge (2014) "Farmers report much more grass after bush control, but not much better-quality grass". The expectation would be a rise in soil fertility soon after harvesting, due to release of nutrients from root exudates and decaying leaves, followed by a decline due to lack of further inputs from smaller parts of bushes. However, this study provides a slight hint that the initial decline two years after debushing may be followed by a gentle rise in fertility for a few more years before declining again (Figure 9). If this is the case, it might be explained by slow decomposition of larger bush roots contributing to fertility long after the fast decomposition of increased dead leaves, twigs and root exudates, probably during the first rainy season after the debushing. Many years later, a slow rise in fertility could be expected when regrown or newly established bushes are large enough to contribute significant inputs. However, this natural restoration of fertility through regrowth of bushes seems to be extremely slow, with no evidence of restoration yet after 13 years in this study. The use of arboricide on stumps of harvested bushes is likely to have contributed to this lack of restoration of fertility.

If farmers seek faster restoration of fertility, then the full spectrum of minerals removed in harvested wood should be returned to the land. Animals could only assist with this if they were to do most of their gazing elsewhere, while depositing much of their dung and urine on the debushed land. This could be achieved over small areas by overnight kraaling (Powell et al. 1996, Sibanda et al. 2016), to effect a transfer of nutrients at the expense of the grazed land. Alternatively, animals could be supplemented with minerals for distributing over the land in excrement, as was achieved by Joseph et al. (2015), where biochar fed to cattle was excreted in their dung and taken into the soil by dung beetles. Ocean products tend to be rich in the full spectrum of minerals (Walters 2005) and, if processed into dry form, could be transported inland from the coast at lower cost than bulkier supplements. The abundance of kelp along Namibia's coast provides the opportunity, if harvested sustainably, to supplement animals with kelp meal. This not only provides animals with a wide spectrum of micro-elements (McHugh 2003), but also a diversity of bioactive compounds with performance-enhancing benefits for animals (Evans & Critchley 2014) and great potential to reduce methane emissions (Kinley et al. 2016).

If debushing is to take place, then partial debushing will allow slower loss in soil fertility than total debushing. The pattern of partial debushing could influence the outcome. If bushes are cleared in strips, then the strips of uncleared bushes could serve as windbreaks and fertility generators, while the cleared strips could provide alleys for animals to graze and run, and for farmers to drive through should they have the need. In very sandy soil where rainwater infiltrates straight into the soil, the alignment of strips could be at right angles to the prevailing, or most destructive, wind to reduce evaporation and erosion. On soil that experiences runoff during intense rain, the cleared strips should be aligned on contour (Bruwer 2014) to encourage infiltration and improve water cycling. This could be further facilitated by placing some of the harvested bushes as filter lines on contour, to favour the growth of grass underneath and mimic the natural pattern of banded vegetation (Tongway et al. 2001). If harvested wood is burnt as an energy supply, then ideally the ashes that remain after the burn should be returned to the land from where the bushes were harvested (Pitman 2006), which could effectively be aligned on contour (Bruwer pers comm.).

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