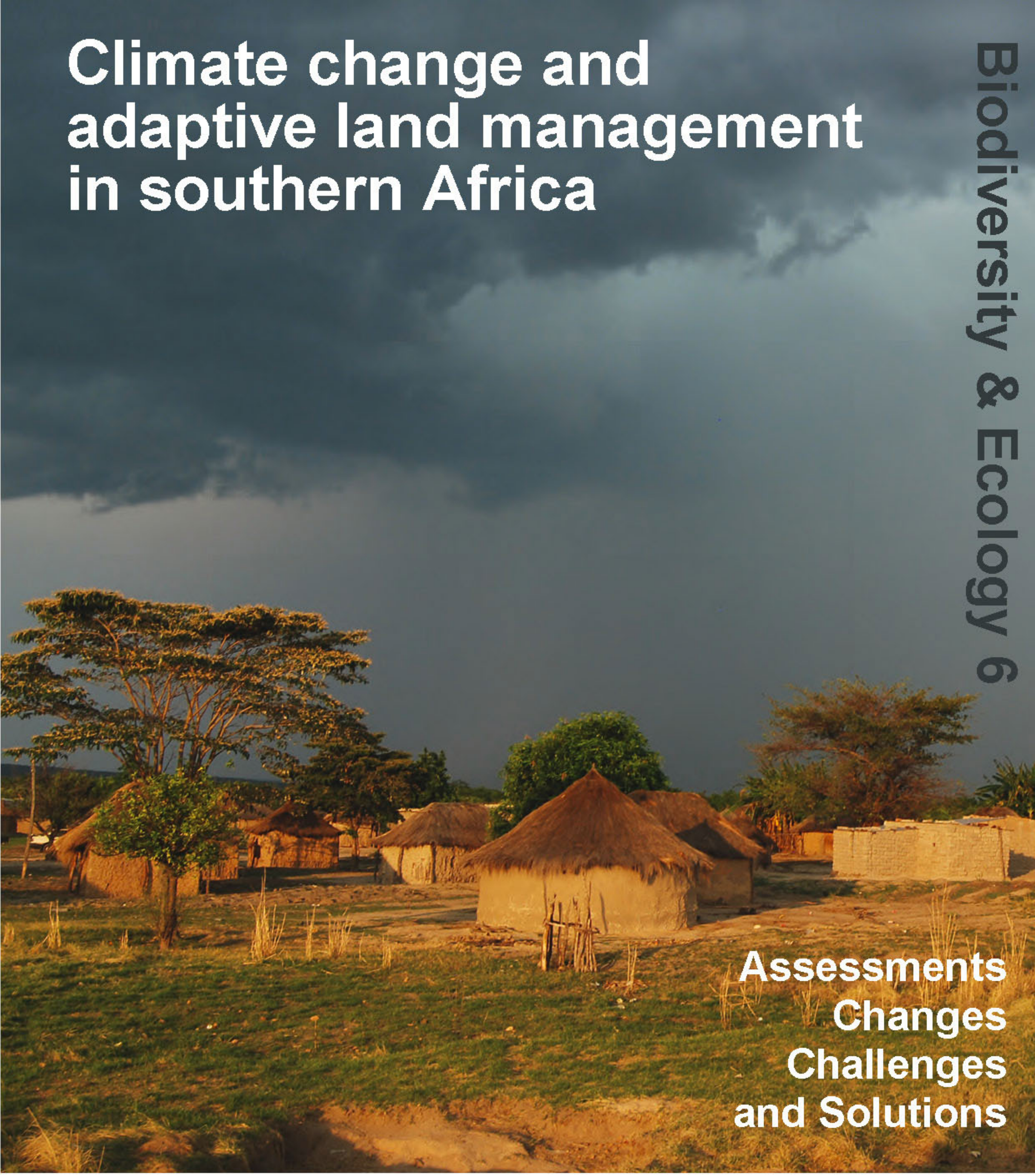
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



Assessments
Changes
Challenges
and Solutions

Product of the first research portfolio of

SASSCAL 2012–2018

Southern African
Science Service Centre for
Climate Change and
Adaptive Land Management

SPONSORED BY THE

Federal Ministry
of Education
and Research

Klaus Hess Publishers
Göttingen & Windhoek
www.k-hess-verlag.de

ISBN: 978-3-933117-95-3 (Germany), 978-99916-57-43-1 (Namibia)

Language editing: Will Simonson (Cambridge), and Proofreading Pal
Translation of abstracts to Portuguese: Ana Filipa Guerra Silva Gomes da Piedade
Page desing & layout: Marit Arnold, Klaus A. Hess, Ria Henning-Lohmann
Cover photographs:
front: Thunderstorm approaching a village on the Angolan Central Plateau (Rasmus Revermann)
back: Fire in the miombo woodlands, Zambia (David Parduhn)
Cover Design: Ria Henning-Lohmann

ISSN 1613-9801

Printed in Germany

Suggestion for citations:
Volume:
Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N. (eds.) (2018) Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Articles (example):
Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 14–21, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Corrections brought to our attention will be published at the following location:
http://www.biodiversity-plants.de/biodivers_ecol/biodivers_ecol.php

Biodiversity & Ecology

Journal of the Division Biodiversity, Evolution and Ecology of Plants,
Institute for Plant Science and Microbiology, University of Hamburg

Volume 6:

Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

Edited by

Rasmus Revermann[1], Kristin M. Krewenka[1], Ute Schmiedel[1],
Jane M. Olwoch[2], Jörg Helmschrot[2,3], Norbert Jürgens[1]

1 Institute for Plant Science and Microbiology, University of Hamburg
2 Southern African Science Service Centre for Climate Change and Adaptive Land Management
3 Department of Soil Science, Faculty of AgriSciences, Stellenbosch University

Hamburg 2018

Please cite the article as follows:

De Cauwer, V., Chaka, M., Chimwamurombe, P.M. , George, D., Ham, H., Heita, H. , Makoi, T., Mashungwa, G., Chaka, M., Reinhold-Hurek, B., & Tshwenyane, S. (2018) Artificial and assisted natural regeneration of socio-economically important southern African tree species. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 324-331, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek. doi:10.7809/b-e.00340

Forest resources

Artificial and assisted natural regeneration of socio-economically important southern African tree species

Vera De Cauwer[1]*, Mubita Chaka[1], Percy Maruwa Chimwamurombe[2], Derick George[3], Hannel Ham[4], Hleni Heita[4], Topoyame Makoi[5], Gloria Mashungwa[5], Barbara Reinhold-Hurek[6], Seoleseng Tshwenyane[5]

1 Faculty of Natural Resources and Spatial Sciences, Namibia University of Science and Technology, Private Bag 13388, Windhoek, Namibia

2 Faculty of Health and Applied Sciences, Namibia University of Science and Technology, Private Bag 13388, Windhoek, Namibia

3 Department of Agricultural Research, Private Bag 0033, Gaborone, Botswana

4 Department of Forest and Wood Science, University of Stellenbosch, Private Bag X1, Matieland, Stellenbosch, 7602, South Africa

5 Botswana College of Agriculture and Natural Resources, Private Bag 0027, Gaborone, Botswana

6 Department of Microbe-Plant Interactions, Faculty of Biology and Chemistry, University of Bremen, PO Box 33 04 40, 28334 Bremen, Germany

* Corresponding author: vdecauwer@nust.na

Abstract: Several socio-economically important indigenous tree species of southern Africa show limited natural regeneration while also being threatened by land conversion and overharvesting. Assisted tree regeneration — both artificial regeneration in nurseries and assisted natural regeneration in forests — is needed to allow the sustainable use of forest resources. Five studies of artificial and assisted natural regeneration of indigenous timber and fruit trees were performed independently from one another in Botswana, Namibia, and South Africa. They aimed to investigate and improve cultivation of seedlings, especially by testing the effects of temperature and different seed pretreatments on germination in incubators and the effects of soil inoculation with plant growth–promoting bacteria in nursery conditions. One study compared direct seeding with enrichment planting in the forest. The germination tests showed that the seeds of most indigenous species tested should be given at least six weeks to germinate, with the exception of *Bauhinia petersiana*. Seed pretreatment, especially nicking and/or soaking, can improve germination for *Strychnos cocculoides* (+17%), *Dialium englerianum* (+68%), *Erythrophleum africanum* (+22%), and *P. angolensis* (+24%). *Guibourtia coleosperma* seed germinates well without any treatment. The germination rate of *P. angolensis* seed improved (+21%) after soil inoculation with plant growth–promoting and nitrogen-fixing bacteria. The important fruit tree *Schinziophyton rautanenii* showed poor seed germination (7% to 30%), but the use of cuttings for *S. rautanenii* gave a 100% survival rate after about six months. Broadcasting seeds in the forest and covering them with soil resulted in more surviving seedlings than planting because of damage caused by rodents. Further nursery studies should focus on vegetative propagation and the optimal conditions for seedling growth and establishment of potential agroforestry tree species, while a range of assisted natural regeneration techniques remain to be tested for forests in the region.

Resumo: Diversas espécies de árvores autóctones de importância socio-económica no Sul de África demonstram uma regeneração natural limitada quando ameaçadas pela conversão de terras e sobreexploração. A regeneração assistida de árvores é necessária para permitir o uso sustentável dos recursos florestais, através da regeneração artificial em viveiros e da regeneração natural assistida em florestas. Cinco estudos sobre a regeneração artificial e natural assistida de árvores autóctones de fruto e produtoras de madeira foram realizados de forma independente uns dos outros no Botswana, Namíbia e África do Sul. O objectivo foi investigar e melhorar o cultivo de plântulas, em especial ao testar o efeito da temperatura e dos diferentes pré-tratamentos de sementes na germinação em incubadoras, e o efeito da inoculação do solo com bactérias promotoras do crescimento de plantas em condições de viveiro. Um estudo comparou sementeira directa com plantio de enriquecimento em floresta. Os testes de germinação mostraram que as sementes da maioria das espécies indígenas testadas devem ter, pelo menos, seis semanas para germinar, com excepção da *Bauhinia petersiana*. O pré-tratamento de sementes, em especial o seu corte e/ou imersão, pode melhorar a germinação de *Strychnos cocculoides* (+17%), *Dialium englerianum* (+68%), *Erythrophleum africanum* (+22%), e *P. angolensis* (+24%). As sementes de *Guibourtia coleosperma* germinam bem sem qualquer tratamento. A taxa de germinação de sementes de *P. angolensis* melhorou (+21%) após a inoculação do solo com bacterias fixadoras de azoto e promotoras do crescimento de plantas. A importante árvore de fruto *Schinziophyton rautanenii* mostrou uma baixa germinação por semente (7% a 30%), mas o uso de estacas de *S. rautanenii* resultou numa taxa de sobrevivência de 100% após cerca de seis meses. A colocação de sementes na floresta e a sua cobertura com solo resultou em mais plântulas sobreviventes que através do plantio, devido aos danos causados por roedores. Futuros estudos de viveiro deverão concentrar-se na propagação vegetativa e nas condições óptimas para o crescimento de plântulas e o estabelecimento de potenciais espécies arbóreas agroflorestais, ainda que uma série de técnicas de regeneração natural assistida continue por testar em florestas na região.

Introduction

Several socio-economically important tree species of southern Africa show limited regeneration in their natural environments. *Pterocarpus angolensis* is the most widely harvested timber tree in southern Africa (IRDNC, 2015; Von Breitenbach, 1973), as its wood, referred to as Kiaat and Mukwa in the region, is stable, easy to work, and aesthetically pleasing (ITTO, 2017) (see Figure 5 in De Cauwer et al., 2018). Forest inventories in Namibia and southern Angola show that natural regeneration is limited compared to other woody species (De Cauwer, 2016; Kabajani, 2016), similar to findings in other parts of southern Africa (Caro et al., 2005; Dirninger, 2004; von Malitz & Rathogwa, 1999). Reasons suggested for the lack of regeneration include high fire frequency, grazing and browsing pressure, climate change, and lack of light because of plant competition (Caro et al., 2005; De Cauwer, 2016; von Malitz & Rathogwa, 1999). *Baikiaea plurijuga* is another important timber tree in Zambia, Zimbabwe, and Namibia. Its wood (Zambezi teak or Mukusi) is harder than that of *P. angolensis* and is used for railway sleepers, furniture, and timber (DFSC, 2001). Limited natural regeneration in Zambia, caused by high fire frequency, bush encroachment, and seed predation by rodents, has led to the establishment of two reserves to conserve the species (DFSC, 2001; Gambiza et al., 2005). Plantations of both *B. plurijuga* and *P. angolensis* have been limited to trial plantings (Caro et al., 2005; DFSC, 2001; Piearce, 1979). There is also a high demand for the wood of *Guibourtia coleosperma* (IRDNC, 2015), traded under the generic term Rosewood and named Musivi in the region. Tree inventories in southern Angola, northern Namibia, and Zambia (De Cauwer et al., 2018) show that *G. coleosperma* is not very abundant (< 10% stems), especially not in the smaller size classes. The important fruit trees *Schinziophyton rautanenii* (Manketti, Mungongo) and *Strychnos cocculoides* (Monkey orange, Figure 1) also show limited natural regeneration in northern Namibia (Kabajani, 2016). The major reason may be overharvesting of the fruit, and for *S. rautanenii*, harvesting of the tree for its wood.

Figure 1: *Strychnos cocculoides* in woodland of northern Namibia (Source: V. De Cauwer, 2011).

Next to limited tree regeneration, a major threat to all forests in the region is the clearing for agricultural expansion (Pröpper et al., 2010; Rudel, 2013). Many fields are left fallow for 1 up to 30 years (Chidumayo, 2002; Hilukwa, Namibia University of Science and Technology, unpubl. data). A study in northern Namibia showed that the seed density of woody species in the soil seed bank of the fallows was low (0.04 seed·m^{-2}) and that the woody species diversity of the soil seed bank was much lower than that of the above-ground vegetation, which consisted mainly of shrubs and resprouting tree species (Hilukwa, Namibia University of Science and Technology, unpubl. data). Reforestation projects in northern Namibia cannot rely on a quick natural restoration of the forest, especially when no tree root systems remain that allow coppice growth.

The harvesting of wood or fruits of indigenous tree species cannot continue in a sustainable manner if the future of the species' populations is not ensured. Programmes that support tree planting or that deliberately aim to assist natural regeneration are needed if a growing population wants to continue using forest resources. Currently, many rural inhabitants do not see the need for planting indigenous trees as they consider natural regeneration by forests and savannas to be sufficient (Gerhardt & Nemarundwe, 2006). Most trees planted in the region are exotic trees, often because national forestry extension services focused on exotic species for many decades and because knowledge on indigenous tree cultivation is lacking in the region (Erkkilä & Siiskonen, 1992; Gerhardt & Nemarundwe, 2006; Mogotsi & Ngwako, 2011). Earlier studies have shown that some miombo and *Baikiaea* woodland tree species, such as *P. angolensis, S. rautanenii, B. plurijuga, Pericopsis angolensis,* and *Julbernardia paniculata*, are difficult to grow in nurseries and that problems arise at several stages: germination, seedling survival, and seedling establishment (Chidumayo, 1992; Chimbelu, 1983; DFSC, 2001; Vander Heyden, 2014; Vermeulen, 1990; Vyamana et al., 2007). More research is needed to circumvent these difficulties, including determining the optimal physical environment for germination and seedling survival (Ministry of Agriculture, Water and Forestry, 2011) and inoculation with native bacteria and mycorrhizal fungi to improve survival and growth (Schüßler et al., 2016). Such research is especially useful for potential crop trees or trees suitable for agroforestry and would allow the propagation of individuals selected for desired tree qualities such as drought resistance, a long, straight stem for timber trees, or good fruit quality. Assisted natural regeneration is a less expensive technique for landscape restoration (Ministry of Agriculture, Water and Forestry, 2011), but is rarely used in the region. Assisted natural regeneration refers to low-cost methods that can be applied to natural forest stands to enhance natural regeneration, especially through the reduction of barriers to tree regeneration and preferably by involving local people (Ganz et al., 2003; Shono et al., 2007). These include exclusion of grazing, controlling of fire, the use of pioneer shrubs as nurse plants, the removal of plant competition, and enrichment planting (Aerts et al., 2007; Chazdon & Guariguata, 2016; Ganz et al., 2003).

Several SASSCAL projects focused on studies to facilitate artificial and assisted natural regeneration programmes of indigenous tree species. SASSCAL Task 182 focused on the collection and storage of *B. plurijuga* seeds in Zambia. SASSCAL Task 079 is monitoring thinning experiments that aim to encourage juvenile tree growth in state forests in Namibia. This article will describe five independently performed studies on germination and seedling survival of indigenous tree species performed by SASSCAL Tasks 038 and 335. The studies aimed to (1) investigate seedling germination and survival from seed and cuttings in nursery conditions, (2) test the effect of soil inoculation with plant growth–promoting bacteria on the germination of *P. angolensis* in nursery conditions, (3) investigate factors influencing germination in controlled conditions, and (4) compare direct seeding with enrichment planting in the forest.

Methods

Seedling germination and survival from seed and cuttings in nursery conditions — Botswana

The study tested the possibility of cultivating *S. rautanenii* (*n* = 400) and *Bauhinia petersiana* (*n* = 400) from seed, and for *S. rautanenii* (*n* = 450) from cuttings. The seed pretreatments consisted of scarification for *B. petersiana*, and removing the outer shell by cracking the nuts and soaking the kernel for 48 hours for *S. rautanenii*. Cuttings were taken from old-growth wood, young wood, and very young, pliable wood and planted in river sand. The nursery has net shading without artificial lighting. The experiment was performed from December to May 2017, with air temperatures varying between 2°C (May) and 38°C (December) and averaging 22°C. Watering was on a daily basis. Preliminary results are reported as the ratio of seeds that germinated after two months or as the ratio of cuttings that survived after six months. No statistical analysis was performed.

Soil inoculation with plant growth promoting bacteria for *P. angolensis* — Namibia

The effect of soil inoculation with plant growth–promoting and nitrogen-fixing bacteria, particularly rhizobial root nodule symbionts, on the germination of *P. angolensis* seed (*n* = 90) in nursery conditions was tested. In SASSCAL Task 51, wild legumes in Namibia were inspected for root nodules, and their bacterial nitrogen-fixing symbionts were isolated and characterized. A strain of the genus *Bradyrhizobium* that nodulated *P. angolensis* in sterile laboratory culture was tested on soil in Namibia. A factorial design was used with two factors: (1) inoculation/no inoculation and (2) source of the seeds (pods collected from tree or ground). All seeds were removed from the pods and scarred. The soil was a mixture of commercial potting soil with sand. Seeds were raised in pots placed in full sun during March and April with watering when the soil was dry. The average surface temperature over the 7-week experiment was 26°C, while air temperatures varied between 10°C and 29°C. Germination results were analysed using a linear regression with inoculation, source of the pods, and the interaction between the two as variables.

Factors influencing germination in controlled conditions — Namibia

The effects of temperature (26 and 30°C), and seed pretreatments (control, nicking, soaking in cold/warm/hot water, and combinations of these) on the germination of *Dialium englerianum* (n = 540), *Erythrophleum africanum* (n = 540), *G. coleosperma* (n = 540), *P. angolensis* (n = 320), and *S. rautanenii* (n = 362) were tested. All seeds were surface sterilised and placed on filter paper in sterilised petri dishes in an incubator. The seeds were monitored for a period of 14 days, after which seed viability was tested with a tetrazolium solution. Germination results were analysed with a two-way analysis of variance (ANOVA) or Kruskal-Wallis. The research design was based on the results of earlier studies (Moses, 2012; Vander Heyden, 2014), and more information can be found in Younan (2015) and De Cauwer and Younan

(2015), with the latter describing the data analysis methods.

Factors influencing germination in controlled conditions — South Africa

The effects of no (control) and five seed pretreatments on germination were compared for *S. cocculoides* (n = 180) and *G. coleosperma* (n = 180) in an incubator at a constant temperature of 25°C. The seed pretreatments consisted of soaking in cold/warm/hot water, scarification, and immersion in 32% hydrochloric acid (HCl). A blocked factorial design was used, with results reported as the ratio of seeds that germinated after 7 weeks and data analysis done through ANOVA. More details on the methodology are given in Heita (2015).

Comparison of direct seeding with enrichment planting — Namibia

Enrichment planting of nursery seedlings in a state forest in the Otjozondjupa region of Namibia (mean annual rainfall 480 mm) was compared with direct seeding for *P. angolensis, B. plurijuga,* and *G. coleosperma*. Seeds were collected near the study area; hence provenances were from the driest location possible for those species, as advised by Weber et al. (2015). A blocked factorial design was used with as treatments within the blocks and per species: (1) broadcasting of seeds (*n* = 180), (2) broadcasting of seeds and covering with soil (n = 180), and (3) planting of nursery-raised seedlings (n ≤ 180). Seeds of *P. angolensis* were extracted from pods and nicked, seeds of *B. plurijuga* were soaked in warm water for 24 hours, and seeds of *G. coleosperma* were not pretreated. The seedlings in the nursery were grown in 30 cm deep polyethylene bags for four months with watering every second day during the first two months decreasing to two times a week by the time of planting. The experiment was repeated in the early (January) and late (April) rainy season of 2016. Although planting at the start of the rainy season is preferable (Aerts et al., 2007), it does not guarantee that the study area will receive rain for the first months, as rainfall is limited, has a high temporal and spatial variation, and is thus unpredictable. Historical plantings showed that most planted seedlings are destroyed by browsers when all other vegetation is still dry. A small pilot project was also set up to test to what extent tree protectors can prevent small mammals from predating on the seedlings. Tree protectors were applied around 50 nursery seedlings (Fig. 2). Preliminary results are given as the ratio of seeds that germinated or as the ratio of seedlings that survived after 9 to 12 months. Statistical analysis results will be published by Chaka (Namibia University of Science and Technology, unpubl. data).

Figure 2: Tree protector tested around a nursery seedling (Source: M. Chaka, 2016).

Figure 3: *Schinziophyton rautanenii* plants developed from tree cuttings (Source: S. Tshwenyane, 2017).

All seeds were collected in north-eastern Namibia except for study 1, which was performed with seed and cuttings from Botswana.

Results

Seedling germination and survival from seed and cuttings in nursery conditions — Botswana

Seedlings of *B. petersiana* were successfully raised in the nursery with a 100% germination rate after 7 days. Germination rate of *S. rautanenii* was only 30% after 20 days. The survival rate for the cuttings was 100% for the old-wood cuttings and 80% for the young to very young-wood cuttings after 6 months, with the cuttings still growing and shooting by the end of 2017 (Fig. 3). However, no root development had taken place.

Soil inoculation with plant growth–promoting bacteria for *P. angolensis* — Namibia

The inoculation significantly ($p < 0.05$) increased the germination rate from 16% to 37% (Tab. 1). There was, however, a significant ($p < 0.05$) interaction effect between inoculation and the source of the pods: inoculation appeared to have an effect only on the germination success of seeds from pods collected from the ground. The effect of inoculation on germination time was very significant ($p < 0.0001$), with germination time decreasing from 25 to 12 days.

Table 1: Mean total germination rate and mean germination time of *Pterocarpus angolensis* seeds after 7 weeks. Treatments were soil inoculation with plant growth–promoting and nitrogen-fixing bacteria and source of the pods from which seeds were extracted.

	Germination rate (%)			Germination time (days)		
	Pods from ground	Pods from tree	TOTAL	Pods from ground	Pods from tree	TOTAL
Inoculation	50	25	37	11	13	12
No Inoculation	8	25	16	20	27	25
Total	28	25	27	12	19	16

Figure 4: *Guibourtia coleosperma* seedling germinated from broadcasted seed covered by a layer of sand (Source: M. Chaka, 2016).

Figure 5: Holes dug out by small mammals at a site where nursery seedlings were planted (Source: M. Chaka, 2016).

Factors influencing germination in controlled conditions — Namibia

Table 2 shows the germination results for temperature and seed pretreatments combined. *G. coleosperma* seed had the highest germination rate and *S. rautanenii* the lowest. The seed pretreatments showed significant effects ($p < 0.05$) only on the germination capacity of *D. englerianum, E. africanum,* and *P. angolensis* seed (De Cauwer & Younan, 2015), especially pretreatments that included nicking. All treatments did shorten the germination time of *G. coleosperma* by an average of 5 days compared to the control. Germination was slightly better at 26°C but this was significant only for two species and may have been caused by quicker discarding of mouldy seeds during the experiment at 30°C. A tetrazolium test showed that most nongerminated seeds were still viable after two to three weeks.

Factors influencing germination in controlled conditions — South Africa

Germination results indicated clear differences between species and certain pretreatments (Tab. 3). The treatment with HCl and scarification resulted in significantly lower ($p < 0.001$) germination rates for both species and a longer germination time for *G. coleosperma*. Seeds of both species responded best to soaking in warm water, although soaking did not significantly improve germination for *G. coleosperma* seed, which germinated well without any treatment. Maximum germination time for *G. coleosperma* was reached after six weeks, while *S. cocculoides* seeds were still germinating after seven weeks.

Table 2: Mean total germination rate and mean germination time of indigenous tree seeds across all treatments after 2 weeks' incubation in an incubator. The age of the seeds refers to the storage period.

	n	Age (years)	Germination (%)	Germination time (days)
Dialium englerianum	540	< 1	41	7.4
Erythrophleum africanum	540	12	20	8.0
Guibourtia coleosperma	540	3	91	7.3
Pterocarpus angolensis	320	1–2	23	6.6
Schinziophyton rautanenii	362	2–12	7	10.8

Table 3: Total germination rate (%) of *Strychnos cocculoides* and *Guibourtia coleosperma* seeds over a period of 7 weeks in an incubator.

	Weeks	Control	Cold water	Warm water	Hot water	HCl	Scarification
Strychnos cocculoides	**2**	0	0	0	0	0	0
	4	27	30	27	17	0	0
	6	57	47	60	23	0	3
	7	63	70	80	40	0	3
Guibourtia coleosperma	**2**	0	7	3		0	0
	4	63	73	70	60	50	57
	6	80	80	83	67	63	63
	7	80	80	83	70	67	67

Comparison of direct seeding with enrichment planting — Namibia

The preliminary results of the early rain season show that regeneration from seeds covered with a layer of soil was much better compared to that of broadcasted seeds and planted nursery seedlings. After the first nine weeks of regeneration, 60% of the covered seeds of all species combined resulted in surviving seedlings (Fig. 4) compared to 0.2% of the noncovered seeds. However, the seedling survival rate of the covered seeds started to decline afterwards. All nursery seedlings were dug out by small mammals within the first 4 weeks after planting (Fig. 5). After a period of 1 year, the seedling survival rate from seeds covered with a layer of soil was 11%, and that from noncovered seeds was 1.3%. Some 16% of the broadcasted noncovered seed were still present and intact on top of the soil.

None of the late rainy-season treatments resulted in surviving seedlings: no germinations were recorded for either direct seeding treatment, and the survival rate of the nursery seedlings after six weeks was 0% because all were destroyed by small mammals. The tree protectors were able to protect the seedlings from small mammals (Fig. 2), as all seedlings could still be observed in the tree protector after a year. However, all those seedlings had died of desiccation by the end of 2016.

Discussion

Seed pretreatment can improve germination for *S. cocculoides, D. englerianum, E. africanum,* and *P. angolensis*. Soaking *S. cocculoides* seed in water overnight increased the germination rate, with 17% after 7 weeks compared to no seed pretreatment (study 4), while the germination rate of *D. englerianum* increased 68% with nicking and soaking in water (study 3). In contrast, the seed of *E. africanum* and *P. angolensis* should only be nicked and not soaked (study 3). Seeds of most indigenous species tested need more than 2 weeks' germination time, at least 6 to 8 weeks, as there were a large number of viable, nongerminated seeds after 2 weeks in studies 2, 3, and 4. Vander Heyden (2014) observed that although germination of *P. angolensis* seeds in controlled laboratory conditions (at 26°C) started after 12 days, it continued for over a year and reached a germination rate of 47%, much higher than that obtained in studies 2 and 3, which lasted less than two months. The only species that showed a high germination rate (> 90%) within two weeks were *B. petersiana* (study 1: 7 days) and *G. coleosperma* (study 3: two weeks). It is not clear why it took *G. coleosperma* 6 weeks to reach a germination rate of 80% in study 4, especially as the seeds were two years younger than those of study 3. Probably, it is caused by a slightly lower incubator temperature and because the seeds in study 4 were thrown away as soon as they developed mould, while study 3 found that many seeds with mould still germinated.

Future studies should investigate the effect of different day lengths and temperatures on germination, especially as study 3 was not conclusive. More studies on seedling growth and establishment are especially needed (Ministry of Agriculture, Water and Forestry, 2011), for example as related to shade conditions, as performed by Graz (2003) for *S. rautanenii*. Additionally, superior genetic material should be collected to cultivate potential agroforestry or crop species with high drought tolerance and desired characteristics such as bole length or fruit yield, such as is being done for *Sclerocarya birrea* (Marula) (Gouwakinnou et al., 2011; Leakey et al., 2002). Propagation of tree species with low germination rates may be better done via tissue culture techniques (Vander Heyden, 2014) or through vegetative propagation in nursery conditions, as demonstrated for *S. rautanenii* in study 1. However, results of study 1 showed that vegetative propagation should be studied over a much longer period (> 1 year). No recent information is available on vegetative propagation of the species.

Mean germination time of *P. angolensis* in nursery conditions declined from 3.5 weeks to 12 days (study 2) when using soil inoculated with nitrogen-fixing bacteria. The results are more promising than a study by Moola et al. (2009) that tested the effects of mycorrhizae on both germination and seedling growth of *P. angolensis* and showed a beneficial effect only on growth; by contrast, this study also showed a positive effect on germination. More experiments are needed to test the use of nitrogen-fixing and other microorganisms on seedling growth of indigenous tree species. The bacteria serve various purposes including quick establishment of root nodules for nodulation of plants, enhancement of root formation, phosphate mobilisation from the soil, and a protective role via the formation of siderophores (Chimwamurombe et al., 2016; Grönemeyer et al., 2012). The use of plant growth–promoting bacteria is more environmentally friendly and sustainable compared to chemical fertilisers.

Direct seeding of woody species in natural forest is a promising propagation method if the seeds are covered by soil. The covering appears to provide protection against predation compared to the noncovered seeds. SASSCAL Task 182 also reported a high predation pressure on *B. plurijuga* seeds by various rodents in Zambia, while Fors (2002) found a high predation of broadcasted *P. angolensis* seeds in forests in Tanzania (66% in 10 days). Timing of direct seeding is crucial for the development of seedlings. Study 5 showed that only direct seeding in the early rainy season worked compared to direct seeding in the late rainy season, but this will have been influenced by the below-average rainfall of 286 mm in the study area during the rainy season of 2015/2016. Optimal is to seed at the start of a long and good rainfall period; this is an unrealistic method, however, because of the unpredictability of rainfall, especially for remote forest areas for which logistics are difficult to organise.

Figure 6: Seedlings ready for planting at the University of Agriculture and Natural Resources, Botswana (Source: S. Tshwenyane, 2014).

Figure 7: *Schinziophyton rautenenii* tree planting in the garden of the University of Agriculture and Natural Resources, Botswana (Source: S. Tshwenyane, 2014).

Enrichment planting of nursery seedlings in the forest was not successful because of predation and uprooting by small mammals unless the seedlings are protected. Hall (2008) also reported predation and/or uprooting by small mammals of 48% of planted tree seedlings within weeks of planting in a secondary forest in the Central African Republic. He demonstrated how enclosures with chicken wire increased survival of the seedlings. The tree protectors used in this experiment (Fig. 2) did provide protection but were not able to shelter the seedlings from high temperatures during the summer. A tree protector that would allow more air to flow through could be considered for potential crop trees, but planting under nurse shrubs (Aerts et al., 2007) or in between thorn shrubs may be economically more viable. Nursery plants with a large root/shoot ratio should be used, as they have a better chance of survival in the field (Weber et al., 2015).

Considering the limited results with forest seeding and planting, other assisted regeneration measures should be tested in the region, especially fire and browsing protection, forest thinning, and protection of root systems on fallow lands. Programmes to promote the cultivation of indigenous trees should focus on potential agroforestry species and include raising community awareness of the need for indigenous tree planting. Cultivation can be encouraged through demonstration plots and community nurseries (Figs. 6 and 7), as is already done in Botswana (Mogotsi & Ngwako, 2011). This approach demonstrates the potential to domesticate indigenous woody species and build the capacity of local populations in indigenous tree cultivation.

Acknowledgements

The research was carried out in the framework of SASSCAL and was sponsored by the German Federal Ministry of Education and Research (BMBF) under promotion numbers 01LG1201D and 01LG1201M. The authors are grateful to the National Botanic Research Institute (NBRI) of Namibia for providing the facilities in which study 3 was conducted, and to the Namibian Directorate of Forestry for allowing us to do research in the state forests of Namibia and providing seeds for study 3. We want to thank Rebecca Younan, who performed the germination tests of study 3. We would also like to thank Abhijit Sarkar and Wiebke Bünger, University of Bremen, for isolating and characterizing the *Bradyrhizobium* strain. All seeds were collected with the required research permits, and export to the University of Stellenbosch was done with the required export/import permits.

References

Aerts, R., Negussie, A., Maes, W., November, E., Hermy, M. & Muys, B. (2007) Restoration of dry Afromontane forest using pioneer shrubs as nurse-plants for *Olea europaea* ssp. *cuspidata*. *Restoration Ecology*, **15**, 129–138.

Caro, T.M., Sungula, M., Schwartz, M.W. & Bella, E.M. (2005) Recruitment of *Pterocarpus angolensis* in the wild. *Forest Ecology and Management*, **219**, 169–175.

Chazdon, R.L. & Guariguata, M.R. (2016) Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica*, **48**, 716–730.

Chidumayo, E. (1992) Seedling ecology of two miombo woodland trees. *Plant Ecology*, **103**, 51–58.

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626.

Chimbelu, E.G. (1983) A germination and survival study of mugongo under laboratory and greenhouse conditions. *Indian Forester*, **November**, 804–808.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92**.

De Cauwer, V. (2016) Autecological aspects of the African timber tree *Pterocarpus angolensis* in support of its sustainable management. PhD thesis, KU Leuven, Leuven.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume.

De Cauwer, V. & Younan, R. (2015) Seed germination of Namibian woodland tree species. *Dinteria*, **35**, 43–52.

DFSC (2001) *Conservation plan for genetic resources of Zambezi teak (*Baikiaea plurijuga*) in Zambia*. Danida Forest Seed Centre, Humlebaek, Denmark.

Dirninger, P. (2004) *Natural regeneration and management implications of the miombo forests in Tanzania.* I-TOO Working Paper no. 25. University of Natural Resources and Applied Sciences, Vienna.

Erkkilä, A. & Siiskonen, H. (1992) *Forestry in Namibia 1850–1990*. University of Joensuu, Faculty of Forestry, Joensuu, Finland.

Fors, L. (2002) *Tree seed survival across a miombo woodland fragmentation gradient in Tanzania*. Uppsala University, Uppsala, Sweden.

Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.

Ganz, D., Durst, P., Dugan, P. & Mc Kenzie, P. (2003) Assisted natural regeneration: an overview. FAO Regional Office Asia and Pacific, Bangkok.

Gerhardt, K. & Nemarundwe, N. (2006) Participatory planting and management of indigenous trees: lessons from Chivi District, Zimbabwe. *Agriculture and Human Values*, **23**, 231–243.

Gouwakinnou, G.N., Assogbadjo, A.E., Lykke, A.M. & Sinsin, B. (2011) Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. *Scientia Horticulturae*, **129**, 777–783.

Graz, F.P. (2003) The growth of *Schinziophyton rautanenii* seedlings under different shade conditions. *Dinteria*, **28**, 44–46.

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant and Soil*, **356**, 67–82.

Hall, J.S. (2008) Seed and seedling survival of African mahogany (*Entandrophragma* spp.) in the Central African Republic: implications for forest management. *Forest Ecology and Management*, **255**, 292–299.

Heita, H.T.N. (2015) *Propagation of indigenous species: the effects of various seed pre-treatments to improve germination in* Strychnos cocculoides *and* Guibourtia coleosperma *from Kavango West Region, Namibia.* Stellenbosch University, Stellenbosch, South Africa.

IRDNC (2015) Timber trade in Namibia. Poster. IRDNC, Windhoek.

ITTO (2017) Muninga (*Pterocarpus angolensis*). *International Tropical Timber Organization: lesser used species*. International Tropical Timber Organization, Yokohama, Japan.

Kabajani, M.W. (2016) An assessment of the natural regeneration of valuable woody species in the Kavango regions of north eastern Namibia. Master thesis, Namibia University of Science and Technology, Windhoek.

Leakey, R., Shackleton, S., du Plessis, P., Pate, K. & Lombard, C. (2002) Characterization of phenotypic variation in marula (*Sclerocarya birrea*) fruits, nuts and kernels in South Africa and Namibia. Unpublished report, James Cook University, Cairns.

Ministry of Agriculture, Water and Forestry (2011) *A forest research strategy for Namibia (2011–2015)*. Ministry of Agriculture, Water and Forestry, Windhoek, Namibia.

Mogotsi, K.K. & Ngwako, S. (2011) *Towards afforestation and livelihoods improvement: MSB-UPP contribution in Botswana*. Nairobi, Kenya. Botswana College of Agriculture, Gabarone.

Moola, S.W., Muimba-Kankolongo, A. & Kangwa, J.M. (2009) Growth performance of *Pterocarpus angolensis* seedlings in mycorrhizae colonized and uncolonized soils from high-rainfall area of Zambia. *Journal of Applied Biosciences*, **19**, 1054–1064.

Moses, R. (2012) Seed physiological aspects of large seeded species of the Kavango woodland, Namibia. BSc Honours thesis, University of Pretoria, Pretoria.

Piearce, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of *Pterocarpus angolensis* in Zambia. *Pans*, **25**, 37–45.

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M. O., Huettich, C., Hurek, T., Kangombe, F. N., Keil, M., Kirk, M., Mapaure, C., Mills, A., Mukuya, R., Namwoonde, N. E., Overmann, J., Petersen, A., Reinhold-Hurek, B., Schneiderat, U., Strohbach, B. J., Lück-Vogel, M. & Wisch, U. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by Hoffman, M. T., Schmiedel, U. & Jürgens, N.), pp. 1–31, Klaus Hess Publishers, Göttingen & Windhoek.

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405.

Schüßler, A., Krüger, C. & Urgiles, N. (2016) Phylogenetically diverse AM fungi from Ecuador strongly improve seedling growth of native potential crop trees. *Mycorrhiza*, **26**, 199–207.

Shono, K., Cadaweng, E.A. & Durst, P.B. (2007) Application of assisted natural regeneration to restore degraded tropical forestlands. *Restoration Ecology*, **15**, 620–626.

Vander Heyden, F. (2014) Germination experiments with the southern African tree species *Pterocarpus angolensis*: in-vivo and in-vitro. MSc Thesis, University of Ghent, Gent.

Vermeulen, W.J. (1990) *A monograph on Pterocarpus angolensis*. Department of Environment Affairs, Water Affairs, and Forestry, Pretoria.

Von Breitenbach, F. (1973) *Pterocarpus angolensis.* A monograph. Trees in South Africa. *Journal of the Tree Society of South Africa*, **XXV**.

von Malitz, G.P. & Rathogwa, H.R. (1999) Dynamics of *Pterocarpus angolensis* (kiaat) in South Africa. Natural Forests and Savanna Woodlands Symposium II, Knysna, South Africa.

Vyamana, V.G., Chamshama, S.A.O. & Mugasha, A.G. (2007) Effect of nursery practices on seedling survival and growth of selected miombo tree species, Morogoro, Tanzania. *Discovery and Innovation*, **19**, 122–138.

Weber, J.C., Montes, C.S., Kalinganire, A., Abasse, T. & Larwanou, M. (2015) Genetic variation and clines in growth and survival of *Prosopis africana* from Burkina Faso and Niger: comparing results and conclusions from a nursery test and a long-term field test in Niger. *Euphytica*, **205**, 809–821.

Younan, R. (2015) *Germination experiment. Final report.* SASSCAL, Windhoek.

References [CrossRef]

Aerts, R., Negussie, A., Maes, W., November, E., Hermy, M. & Muys, B. (2007) Restoration of dry Afromontane forest using pioneer shrubs as nurse-plants for *Olea europaea* ssp. *cuspidata*. *Restoration Ecology*, **15**, 129–138. CrossRef

Caro, T.M., Sungula, M., Schwartz, M.W. & Bella, E.M. (2005) Recruitment of *Pterocarpus angolensis* in the wild. *Forest Ecology and Management*, **219**, 169–175. CrossRef

Chazdon, R.L. & Guariguata, M.R. (2016) Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica*, **48**, 716–730. CrossRef

Chidumayo, E. (1992) Seedling ecology of two miombo woodland trees. *Plant Ecology*, **103**, 51–58. CrossRef

Chidumayo, E.N. (2002) Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography*, **29**, 1619–1626.

Chimbelu, E.G. (1983) A germination and survival study of mugongo under laboratory and greenhouse conditions. *Indian Forester*, **November**, 804–808.

Chimwamurombe, P.M., Grönemeyer, J.L. & Reinhold-Hurek, B. (2016) Isolation and characterization of culturable seed-associated bacterial endophytes from gnotobiotically grown Marama bean seedlings. *FEMS Microbiology Ecology*, **92**. CrossRef

De Cauwer, V. (2016) Autecological aspects of the African timber tree *Pterocarpus angolensis* in support of its sustainable management. PhD thesis, KU Leuven, Leuven.

De Cauwer, V., Knox, N., Kobue-Lekalake, R., Lepetu, J.P., Matenanga, O., Naidoo, S., Nott, A., Parduhn, D., Sichone, P., Tshwenyane, S., Yeboah, E. & Revermann, R. (2018) Woodland resources and management in southern Africa. This volume. CrossRef

De Cauwer, V. & Younan, R. (2015) Seed germination of Namibian woodland tree species. *Dinteria*, **35**, 43–52.

DFSC (2001) *Conservation plan for genetic resources of Zambezi teak (*Baikiaea plurijuga*) in Zambia*. Danida Forest Seed Centre, Humlebaek, Denmark.

Dirninger, P. (2004) *Natural regeneration and management implications of the miombo forests in Tanzania*. I-TOO Working Paper no. 25. University of Natural Resources and Applied Sciences, Vienna.

Erkkilä, A. & Siiskonen, H. (1992) *Forestry in Namibia 1850–1990*. University of Joensuu, Faculty of Forestry, Joensuu, Finland.

Fors, L. (2002) *Tree seed survival across a miombo woodland fragmentation gradient in Tanzania*. Uppsala University, Uppsala, Sweden.

Gambiza, J., Campbell, B.M., Moe, S.R. & Frost, P.G. (2005) Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe: research letter. *South African Journal of Science*, **101**, 239–244.

Ganz, D., Durst, P., Dugan, P. & Mc Kenzie, P. (2003) Assisted natural regeneration: an overview. FAO Regional Office Asia and Pacific, Bangkok.

Gerhardt, K. & Nemarundwe, N. (2006) Participatory planting and management of indigenous trees: lessons from Chivi District, Zimbabwe. *Agriculture and Human Values*, **23**, 231–243. CrossRef

Gouwakinnou, G.N., Assogbadjo, A.E., Lykke, A.M. & Sinsin, B. (2011) Phenotypic variations in fruits and selection potential in *Sclerocarya birrea* subsp. *birrea*. *Scientia Horticulturae*, **129**, 777–783. CrossRef

Graz, F.P. (2003) The growth of *Schinziophyton rautanenii* seedlings under different shade conditions. *Dinteria*, **28**, 44–46.

Grönemeyer, J.L., Burbano, C.S., Hurek, T. & Reinhold-Hurek, B. (2012) Isolation and characterization of root-associated bacteria from agricultural crops in the Kavango region of Namibia. *Plant and Soil*, **356**, 67–82. CrossRef

Hall, J.S. (2008) Seed and seedling survival of African mahogany (*Entandrophragma* spp.) in the Central African Republic: implications for forest management. *Forest Ecology and Management*, **255**, 292–299. CrossRef

Heita, H.T.N. (2015) *Propagation of indigenous species: the effects of various seed pre-treatments to improve germination in* Strychnos cocculoides *and* Guibourtia coleosperma *from Kavango West Region, Namibia.* Stellenbosch University, Stellenbosch, South Africa.

IRDNC (2015) Timber trade in Namibia. Poster. IRDNC, Windhoek.

ITTO (2017) Muninga (*Pterocarpus angolensis*). *International Tropical Timber Organization: lesser used species*. International Tropical Timber Organization, Yokohama, Japan.

Kabajani, M.W. (2016) An assessment of the natural regeneration of valuable woody species in the Kavango regions of north eastern Namibia. Master thesis, Namibia University of Science and Technology, Windhoek.

Leakey, R., Shackleton, S., du Plessis, P., Pate, K. & Lombard, C. (2002) Characterization of phenotypic variation in marula (*Sclerocarya birrea*) fruits, nuts and kernels in South Africa and Namibia. Unpublished report, James Cook University, Cairns.

Ministry of Agriculture, Water and Forestry (2011) *A forest research strategy for Namibia (2011–2015)*. Ministry of Agriculture, Water and Forestry, Windhoek, Namibia.

Mogotsi, K.K. & Ngwako, S. (2011) *Towards afforestation and livelihoods improvement: MSB-UPP contribution in Botswana*. Nairobi, Kenya. Botswana College of Agriculture, Gabarone.

Moola, S.W., Muimba-Kankolongo, A. & Kangwa, J.M. (2009) Growth performance of *Pterocarpus angolensis* seedlings in mycorrhizae colonized and uncolonized soils from high-rainfall area of Zambia. *Journal of Applied Biosciences*, **19**, 1054–1064.

Moses, R. (2012) Seed physiological aspects of large seeded species of the Kavango woodland, Namibia. BSc Honours thesis, University of Pretoria, Pretoria.

Piearce, G.D. (1979) A new vascular wilt disease and its relationship to widespread decline of *Pterocarpus angolensis* in Zambia. *Pans*, **25**, 37–45.

Pröpper, M., Gröngröft, A., Falk, T., Eschenbach, A., Fox, T., Gessner, U., Hecht, J., Hinz, M. O., Huettich, C., Hurek, T., Kangombe, F. N., Keil, M., Kirk, M., Mapaure, C., Mills, A., Mukuya, R., Namwoonde, N. E., Overmann, J., Petersen, A., Reinhold-Hurek, B., Schneiderat, U., Strohbach, B. J., Lück-Vogel, M. & Wisch, U. (2010) Causes and perspectives of land-cover change through expanding cultivation in Kavango. *Biodiversity in southern Africa. Volume 3: Implications for landuse and management* (ed. by Hoffman, M. T., Schmiedel, U. & Jürgens, N.), pp. 1–31, Klaus Hess Publishers, Göttingen & Windhoek.

Rudel, T.K. (2013) The national determinants of deforestation in sub-Saharan Africa. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **368**, 20120405. CrossRef

Schüßler, A., Krüger, C. & Urgiles, N. (2016) Phylogenetically diverse AM fungi from Ecuador strongly improve seedling growth of native potential crop trees. *Mycorrhiza*, **26**, 199–207. CrossRef

Shono, K., Cadaweng, E.A. & Durst, P.B. (2007) Application of assisted natural regeneration to restore degraded tropical forestlands. *Restoration Ecology*, **15**, 620–626. CrossRef

Vander Heyden, F. (2014) Germination experiments with the southern African tree species *Pterocarpus angolensis*: in-vivo and in-vitro. MSc Thesis, University of Ghent, Gent.

Vermeulen, W.J. (1990) *A monograph on Pterocarpus angolensis*. Department of Environment Affairs, Water Affairs, and Forestry, Pretoria.

Von Breitenbach, F. (1973) *Pterocarpus angolensis.* A monograph. Trees in South Africa. *Journal of the Tree Society of South Africa*, **XXV**.

von Malitz, G.P. & Rathogwa, H.R. (1999) Dynamics of *Pterocarpus angolensis* (kiaat) in South Africa. Natural Forests and

Savanna Woodlands Symposium II, Knysna, South Africa.

Vyamana, V.G., Chamshama, S.A.O. & Mugasha, A.G. (2007) Effect of nursery practices on seedling survival and growth of selected miombo tree species, Morogoro, Tanzania. *Discovery and Innovation*, **19**, 122–138.

Weber, J.C., Montes, C.S., Kalinganire, A., Abasse, T. & Larwanou, M. (2015) Genetic variation and clines in growth and survival of *Prosopis africana* from Burkina Faso and Niger: comparing results and conclusions from a nursery test and a long-term field test in Niger. *Euphytica*, **205**, 809–821. CrossRef

Younan, R. (2015) *Germination experiment. Final report.* SASSCAL, Windhoek.