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Hochschule
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Namibian 'Bush encroachment' in context: an ecological perspective on current and future dryland greening, its causes and consequences



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for



Deutsche Umwelthilfe



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Woodlands in Central Namibia (photo: P.L. Ibisch, April 2016)

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List of acronyms and abbreviations

ANPP	Above ground net primary productivity
C	Carbon
CO ₂	Carbon dioxide
ENSO	El Niño-Southern Oscillation
ESM	Earth System Models
L-VOD	Vegetation optical depth derived from low-frequency passive microwaves
MAP	Mean annual precipitation
MET	Ministry of Environment and Tourism of Namibia
N	Nitrogen
NDVI	Normalized difference vegetation index
NPP	Net primary productivity
P	Phosphorus
Pg	Petagrams
ppm	Parts per million
SAIEA	Southern African Institute for Environmental Assessment
SOC	Soil organic carbon
Tg	Teragrams
VOD	Vegetation optical depth

Zusammenfassung

Bevor weitere Investitionen in die Entwicklung von Strategien und Projekten zur Bekämpfung der "Verbuschung" und sogar zur energetischen Nutzung von Gehölzen in Namibia fließen, wäre eine solide Quantifizierung der Ausbreitung von Gehölzen zwingend erforderlich. Diese muss auf aktuellen Daten und Methoden beruhen, nicht auf fragwürdigen oder veralteten Quellen.

Es bestehen übergeordnete Zweifel an der energetischen Nutzung von holzartiger Biomasse als Beitrag zur Minderung des Klimawandels. Dies hängt mit den Emissionsfaktoren verschiedener Brennstoffe, bei denen Holz ungünstige Werte aufweist, und allgemein überschätzten Substitutionseffekten zusammen. In der hier vorgelegten Studie auf Grundlage internationaler Literatur wird unter anderem deutlich, dass die massive Ernte von holzartiger Biomasse zu Ökosystemveränderungen führen kann, die eine zukünftige Vegetationsentwicklung im Klimawandel sogar ungünstig beeinflussen können. Allemal ist es ist nicht stichhaltig, aus Daten zum Pflanzenwachstum der Vergangenheit auf eine mögliche zukünftige Kohlenstoffbindung zu schließen, da sich die Umweltbedingungen deutlich verändert haben und weitere dramatische Veränderungen bevorstehen.

Auch mit Blick auf die Landnutzung wird deshalb empfohlen, zukünftig die potenziellen positiven Effekte des Ergrünens der Vegetation näher zu untersuchen. Hierzu gehören zuvorderst auch möglicherweise günstige Veränderungen des Landschaftswasserhaushalts sowie vor allem die mikro- und mesoklimatische Kühlung, die angesichts des fortschreitenden Klimawandels immer dringender benötigt wird.

Vom weiteren Verfolgen der Idee eines Buschholzimports aus Namibia wird mit größtem Nachdruck abgeraten.

Ziel dieser Studie

Weltweit werden in verschiedenen Trockengebieten Vegetationsveränderungen beobachtet. Oftmals kommt es dabei zu einer Zunahme von Gehölzen. In diesem Zusammenhang wird von *Verbuschung* gesprochen. Die entsprechende Zunahme von Gehölzen wird in Teilen von Namibia wie auch in anderen Regionen Afrikas und auf anderen Kontinenten als Problem wahrgenommen, da sich mutmaßlich die Lebensbedingungen für bestimmte Arten verändern und auch die Nutzbarkeit von Gebieten reduziert wird. Für Namibia wurde vorgeschlagen, den Gehölzzuwachs für eine energetische Verwendung auszunutzen. Dabei existieren auch Vorschläge, dieses Buschholz als vermeintlich nachhaltiges Brennmaterial nach Deutschland zu importieren.

Das Ziel dieses Dokuments ist es, einen Überblick über die aktuelle internationale Fachliteratur zu geben, die sich mit den Ursachen und Folgen von Vegetationsveränderungen in Namibia und vergleichbaren Gebieten beschäftigt. Die Ergebnisse auf Grundlage von über 200 Studien werden im Hinblick auf die im Rahmen eines deutsch-namibischen Entwicklungskooperationsprojektes vorgeschlagenen Managementoptionen diskutiert. Dazu gehört die kritische Bewertung der UNIQUE-Studie *Greenhouse Gas Assessment of Bush*

Control and Biomass Utilization in Namibia, die die Grundlage für die Bewertung der Machbarkeit einer bioenergetischen Nutzung von Buschbiomasse aus Namibia liefert (Seebauer et al. 2019).

Vorurteilsbehafteter Begriff und ein ökosystemares Konzept der Verbuschung

Viele Bewertungen, die die Ausbreitung von Gehölzen als "Verbuschung" behandeln, stammen aus Studien, die sich auf Weideland konzentrieren und die negativen Auswirkungen auf die Futterproduktion hervorheben. Die Ausbreitung von Gehölzen ist jedoch ein komplexes und vielschichtiges Phänomen, welches ein entsprechend ganzheitlicheres Verständnis erfordert. Zur Bewertung von Ursachen und Folgen ist eine Vielzahl von Ökosystemkomponenten und ökosystemaren Prozessen, Funktionen und -Leistungen zu berücksichtigen. Aus einer neutralen ökologischen Perspektive betrachtet dieses Dokument den Begriff "Verbuschung" als voreingenommen. Daher wird er vermieden und stattdessen von "Gehölzausbreitung" oder "Vegetationsveränderung" gesprochen. Es wird seit langem von verschiedenen Autoren vorgeschlagen, dass die Gehölzausbreitung und das messbare *Ergrünen* der Vegetation in Trockengebieten als ein natürlicher Prozess zu betrachten ist. Er beruht auf dem Wechselspiel von konkurrierenden pflanzlichen Funktionstypen in Savannenökosystemen, nämlich Bäumen und Gräsern. Eine Vielzahl von Faktoren bedingt, dass es zu einem ständigen Wechsel und einer Vermischung von relativ stabilen oder instabilen Ökosystemzuständen kommt.

Veränderungen der Gehölzvegetation und ihre Ursachen

Erste Beobachtungen zur Ausbreitung von Gehölzen erfolgten im Zusammenhang mit politischen Umbrüchen der Kolonialzeit. Dürren, Epidemien und Tierseuchen im späten 19. und frühen 20. Jahrhunderts, demographische Veränderungen sowie Landnutzungswandel in den Savannen Namibias scheinen eine Rolle gespielt zu haben. Lokale Faktoren (Dezimierung von großen Pflanzenfressern und Raubtieren, Unterdrückung von Bäumen, Viehzucht) sowie der globale Faktor der CO₂-Anreicherung in der Atmosphäre lieferten schlüssige Erklärungsansätze für die vergangenen und aktuellen Vegetationsveränderungen.

Neuere Studien stellen fest, dass in den letzten Jahrzehnten eine Kombination der globalen CO₂-Anreicherung in der Atmosphäre, Veränderungen im Niederschlagsregime und ein Rückgang der Feueraktivität das Ergrünen der Vegetation, die Zunahme von Gehölzen und damit auch die Kohlenstoffdynamik in afrikanischen Trockengebieten angetrieben haben. Die verschiedenen Prozesse wechselwirken miteinander, und die Dynamik ergibt sich wesentlich auch durch komplexe Rückkopplungen. Niederschlag, Vegetation und Feuer beeinflussen sich jeweils gegenseitig. Das Ergebnis sind oftmals nichtlineare und überraschende Veränderungen der Vegetation. Hieraus kann gefolgert werden, dass Vorhersagen zur möglichen zukünftigen Ausbreitung von Gehölzen sehr unzuverlässig sind. In diesem Zusammenhang ist es bemerkenswert, dass eine Verlangsamung des Ergrünungstrends in vielen Ökosystemen nicht nur plausibel ist, sondern auch zunehmend festgestellt wird: Neue Ergebnisse stützen keinesfalls die in früheren Jahren veröffentlichten Darstellungen einer CO₂-Düngung und eines dadurch stetig angetriebenen Gehölzwachstums. Während im südlichen Afrika noch immer ein ergrünendes Vegetations-Cluster zu beobachten ist, kann der aktuelle Trend keineswegs in die ferne Zukunft extrapoliert werden. Auch im Zusammenhang mit dem Klimawandel ist die Unsicherheit unermesslich groß.

Folgen der Ausbreitung von Gehölzen

Es gibt eine Vielzahl wissenschaftlicher Studien, die die Ausbreitung von Gehölzen mit der Degradation von Trockengebieten in Verbindung bringen. Dennoch, haben viele Studien gezeigt, dass die Ausbreitung von Gehölzen in Trockengebieten auch erhebliche positive Effekte haben kann. Der Boden unter Sträuchern zeichnet sich oftmals durch einen höheren Gehalt an Wasser, organischem Substrat, Samen und Nährstoffen aus als der Boden zwischen Gehölzen ("fruchtbare Insel"-Effekt).

Es gibt immer mehr Belege dafür, dass die Überweidung durch Vieh die Ökosystemfunktionen in Buschland reduziert, aber dass Sträucher die negativen Auswirkungen der verstärkten Beweidung abpuffern können. Böden unter Sträuchern und mit geringerer Beweidung zeigten sich stabiler und hatten einen höheren Gehalt an Bodennährstoffen.

Das Ergrünen von Trockengebieten führt in der Regel zu einem besser gepufferten Mikro- und Mesoklima, wodurch günstigere Bedingungen für die weitere Vegetationsentwicklung geschaffen werden. Studien zufolge war die Luft unter Baumkronen (und in geringerem Maße auch unter Strauchkronen) tagsüber kühler als die Bodengrenzschicht unter Gräsern - und zwar insbesondere in den wärmeren Monaten. Winddurchlässigkeit, Luftbewegungen und Konvektion werden durch Gehölze reduziert. Gehölzvegetation führt zu einer Kühlung der Landschaft.

Ein zentrales Thema bei der Ausbreitung von Gehölzen ist die Rolle des Wassers und des Landschaftswasserhaushalts. Es sind widersprüchliche Ergebnisse veröffentlicht worden. Mehrere Studien haben darauf hingewiesen, dass das Ergrünen der Vegetation die Verdunstung erhöhe und zu einem übermäßigen Wasserverbrauch führen sowie zu stärkeren Dürren beitragen könnte. Mehrere neuere Studien haben jedoch gezeigt, dass die Gehölzvegetation oftmals die ökologischen Funktionen der Wasserrückhaltung bzw. -speicherung verbessert und sogar günstig auf Niederschläge wirken kann. Dadurch kann eine stärkere Verdunstung kompensiert werden. Unter anderem verbessern Sträucher die Aufnahme von Wasser in den Boden.

Vegetationsentwicklung, Produktivität und Kohlenstoffhaushalt in Ökosystemen sind untrennbar miteinander verbunden. In Namibia wurde festgestellt, dass die oberirdische Nettoprimärproduktivität dort, wo Gehölze die Gräser verdrängt haben, linear mit dem mittleren Jahresniederschlag anwächst. Gerade unter feuchteren Bedingungen steigt die Kohlenstoffsenkenleistung von Gehölzen weiter an, während sie im Falle von Grasvegetation ab einem bestimmten Punkt stagniert.

Im Falle von Weideland in der Kalahari wurde gezeigt, dass die Speicherung und Konzentration von Kohlenstoff und Stickstoff im Boden und die mikrobielle Aktivität unter Sträuchern und Bäumen im Vergleich zu Gräsern signifikant höher waren.

In der Folge der Ausbreitung von Gehölzen können Veränderungen der Bodeneigenschaften, der Vegetationsstruktur und des Mikroklimas die Ansiedlung von Pflanzen- und Tierarten erleichtern. Die höchste Artenvielfalt in Savannen wird oft dort beobachtet, wo sowohl Gehölze als auch krautige Pflanzen gut vertreten sind oder wo die Zunahme neuer Gehölz- und Krautarten den Verlust von ursprünglich mit Grasland assoziierten Arten kompensiert.

Auswirkungen der Gehölzentfernung

In einer kürzlich durchgeführten globalen Meta-Analyse zu den Auswirkungen der Entfernung von Gehölzen in Trockengebieten wurde festgestellt, dass die Ergebnisse der Gehölzentfernung stark von den Umweltbedingungen und den Eigenschaften der Gehölze abhingen. Berichte in der Literatur deuten auf eine Diskrepanz zwischen den Auswirkungen auf Gehölze und Ökosystemprozesse hin. Während die Effektivität der Entfernung von Gehölzen relativ kurzlebig war (ca. 5 Jahre), waren die Auswirkungen auf die Ökosystemfunktionen im Allgemeinen groß, eher negativ und langlebiger (bis zu 10 Jahre).

Die Effekte von Gehölzentfernung auf die Biomasse in der Laubstreu und den organisch gebundenen Bodenkohlenstoff ergaben in einer globalen Meta-Analyse gemischte Befunde.

Die Auswirkungen der Gehölzentnahme – in Kombination mit dem Klimawandel - hängen von dem Ausmaß der Buschernte ab. Während eine moderate Ernte unter Umständen einen positiven Effekt auf die Artenvielfalt haben kann, hat eine intensivere Entfernung von Gehölzen starke negative Auswirkungen - sowohl direkt auf die Gehölze als auch auf baumbewohnende Tierarten und solche Lebewesen, die Kleinstlebensräume und Schutz benötigen, die von Gehölzen bereitgestellt werden. Die Bedeutung des Schutzes durch Gehölze etwa für Kleinsäuger oder Reptilien könnte mit fortschreitendem Klimawandel deutlich zunehmen.

UNIQUE-Studie und entsprechende Ideen für die Ernte von Gehölz-Biomasse

Es gibt zwei grundlegende Missverständnisse, die das Potenzial haben, die gesamte Studie in größte Zweifel zu ziehen. Der erste Irrtum ergibt sich aus der Wahl der jährlichen Zuwachsraten von Gehölzen. Die Autoren stützen ihre Annahmen auf eine Masterarbeit, die eine jährliche Verbuschungsrate von 3,18% pro Jahr ermittelte. Im Vergleich zu neueren und wissenschaftlich begutachteten Studien, die hochauflösende Satellitenbilder verwenden, um das Ausmaß der Gehölze zu erfassen, erscheint die geschätzte Zuwachsrates viel zu hoch. Eine Studie über die Ausbreitung von Gehölzen im südafrikanischen Grasland zwischen 1990 und 2013 verzeichnete beispielsweise eine jährliche Zunahme von 0,22 %. Die Ergebnisse dieser Studie zeigten zudem, dass die Veränderungen landesweit sehr unterschiedlich ausfielen; Gebiete mit mehr als 500 mm mittlerem Jahresniederschlag zeigten höhere Raten der Ausbreitung der Gehölze als Regionen mit weniger als 500 mm (0,31 % pro Jahr bzw. 0,11 % pro Jahr). Der in der UNIQUE-Studie erwartete Kohlenstoffsenken-Effekt durch die Gehölzentfernung wird sich vermutlich ins Negative umkehren, wenn die realistischen Wachstumsraten von 0,5 % bis 1,0 % verwendet werden. Auswirkungen des Klimawandels könnten das Problem sogar verschärfen.

Die zweite Fehleinschätzung der UNIQUE-Studie betrifft das erwartete flächige Ausmaß der so genannten "Verbuschung". Neuere Studien, die hochauflösende Satellitenbilder verwenden, haben gezeigt, dass die Gebiete, die in Namibia zwischen 2000 und 2013 signifikante Vegetationsveränderungen erfahren haben, räumlich recht begrenzt waren (vor allem im Norden Namibias, wo die jährlichen Niederschläge am höchsten sind). Die Studie von Seebauer et al. (2019) geht von einer weit verbreiteten Zunahme von Gehölzen in ganz Namibia aus, basierend auf groben Karten, die nicht durch aktuelle, hochwertige Daten gestützt werden.

Da die UNIQUE-Studie auf falschen Annahmen und veralteten wissenschaftlichen Erkenntnissen beruht und folglich die Fläche und das Ausmaß der Gehölzausbreitung grob überschätzt, erscheint es müßig, auf andere Argumente, die zur Rechtfertigung des Projekts vorgebracht werden, näher einzugehen. Die umfangreiche internationale Literatur zeigt, dass die ökohydrologischen und biodiversitätsrelevanten Folgen der Gehölzexpansion sehr viel differenzierter diskutiert werden müssen, als es UNIQUE tut.

Unsere Ergebnisse stellen die Kohlenstoffbilanzen und die Nachhaltigkeitsbewertungen der Buschholzernte ernsthaft in Frage.

Executive summary

Before further investment is made in developing strategies and projects to combat "bush encroachment" in Namibia and even to use woody plants for energy, it would be imperative to have a solid quantification of the spread of woody plants. This must be based on current data and methods, not on questionable or outdated sources.

There are overriding doubts about the use of woody biomass for energy as a contribution to climate change mitigation. This is related to the emission factors of various fuels, where wood has unfavourable values, and generally overestimated substitution effects. In the study presented here, based on international literature, it becomes clear, among other things, that the massive harvesting of woody biomass can lead to ecosystem changes that may even have an unfavourable influence on future vegetation development under climate change. In any case, it is not valid to infer possible future carbon sequestration from past plant growth data, as environmental conditions have changed significantly and further dramatic changes are imminent.

Therefore, also with regard to land use, it is recommended that the potential positive effects of greening vegetation be investigated more closely in the future. These include, first and foremost, potentially favourable changes in the landscape water balance and, above all, micro- and mesoclimatic cooling, which is increasingly needed in the face of advancing climate change.

The idea of importing bush wood from Namibia is strongly discouraged.

Aim of this study

Vegetation changes are observed in various arid regions around the world. This often leads to an increase in woody plants. In this context, the term bush encroachment is often used. The corresponding increase in woody plants is perceived as a problem in parts of Namibia as well as in other regions of Africa and on other continents, as it presumably changes the living conditions for certain species and also reduces the usability of areas. For Namibia, it has been proposed to exploit the woody growth for energy use. There are also proposals to import this bush wood to Germany as a supposedly sustainable fuel.

The aim of this paper is to provide an overview of the current international literature dealing with the causes and consequences of vegetation change in Namibia and comparable areas. The results based on more than 200 studies are discussed with regard to the management options proposed in the context of a German-Namibian development cooperation project. This includes a critical evaluation of the UNIQUE study *Greenhouse Gas Assessment of Bush Control and Biomass Utilization in Namibia*, which provides the basis for assessing the feasibility of bioenergetic use of bush biomass from Namibia (Seebauer et al. 2019).

Prejudiced term and concept of bush encroachment

Many assessments that treat the proliferation of woody plants as "bush encroachment" come from studies that focus on pastureland and emphasise the negative impacts on forage production. However, the proliferation of woody plants is a complex and multidimensional phenomenon that requires a correspondingly more holistic understanding. To assess causes and consequences, a multitude of ecosystem components as well as ecosystem processes, functions and services have to be taken into account. From a neutral ecological perspective, this document considers the term "bush encroachment"

to be biased. Therefore, it is avoided and "woody plant proliferation" or "vegetation change" is used instead. It has long been suggested by various authors that woody plant proliferation and measurable greening of vegetation in drylands should be regarded as a natural process. It is based on the interplay of counteracting plant functional types in savannah ecosystems, namely trees and grasses. A multitude of factors causes a constant change and mixing of relatively stable or unstable ecosystem states.

Woody vegetation changes and their drivers

The first observations on the proliferation of woody plants were made in connection with political changes during the colonial era. Droughts, epidemics and animal diseases in the late 19th and early 20th century, demographic changes as well as land use changes in the savannahs of Namibia seem to have played a role. Local factors (decimation of large herbivores and predators, suppression of trees, livestock) along a climatic gradient as well as the global factor of CO₂ accumulation in the atmosphere provided conclusive explanations for past and present vegetation changes.

More recent studies find that in recent decades a combination of global atmospheric CO₂ accumulation, changes in the precipitation regime and a decline in fire activity have driven the greening of vegetation, the increase in woody plants and thus also the carbon dynamics in African drylands. The different processes interact with each other, and the dynamics also result from feedbacks. Rainfall, vegetation and fire each influence the other. The result is often non-linear and implies surprising changes in vegetation. From this it can be concluded that predictions of the possible future spread of woody plants are very unreliable. In this context, it is noteworthy that a slowdown of the greening trend in many ecosystems is not only plausible but also increasingly observed: New results in no way support the accounts of CO₂ fertilisation and woody plant growth suggested in earlier publications. While a greening vegetation cluster can still be observed in southern Africa, the trend can by no means be extrapolated into the distant future. Climate change increases uncertainty immeasurably.

Consequences of woody plant proliferation

There are many scientific studies that link the proliferation of woody plants to the degradation of drylands. However, many studies have shown that the spread of shrubs in drylands can also have substantially positive effects. The soil under shrubs is often characterised by a higher content of water, organic substrate, seeds and nutrients than the soil between shrubs ("*fertile island*" effect).

There is growing evidence that overgrazing by livestock reduces ecosystem functions in bushland, but that shrubs can buffer the negative effects of increased grazing. Soils under shrubs and with less grazing were found to be more stable and had higher soil nutrient content.

Greening of drylands usually leads to a better buffered micro- and mesoclimate, creating more favourable conditions for further vegetation development. According to studies, the air under tree canopies (and to a lesser extent under shrub canopies) was cooler during the day than the soil boundary layer under grasses - and especially in the warmer months. Wind permeability, air movement and convection are reduced by woody vegetation. Woody vegetation leads to a cooling of the landscape.

A central issue in the spread of woody plants is the role of water and the landscape water balance. Conflicting results have been published. Several studies have indicated that vegetation greening would increase evapotranspiration and may lead to excessive water use and contribute to more severe droughts. However, several recent studies have shown that woody vegetation can also improve the ecological functions of water retention or storage and can have even a favourable effect on rainfall. This can compensate for increased evaporation. Among other things, shrubs improve the absorption of water into the soil.

Vegetation development, productivity and carbon balance in ecosystems are inextricably linked. In Namibia, it was found that above-ground net primary productivity increases linearly with mean annual precipitation where woody plants have displaced grasses. Especially under wetter conditions, the carbon sink capacity of woody plants continues to increase, whereas in the case of grass vegetation it stagnates after a certain point.

In the case of grasslands in the Kalahari, it was shown that soil carbon and nitrogen storage and concentration and microbial activity were significantly higher under shrubs and trees compared to grasses.

Following the spread of woody plants, changes in soil properties, vegetation structure and microclimate can facilitate the establishment of plant and animal species. The highest species diversity in savannahs is often observed where both woody and herbaceous plants are well represented or where the increase in new woody and herbaceous species compensates for the loss of species originally associated with grasslands.

Impacts of woody plant removal

A recent global meta-analysis on the effects of woody plant removal and thinning in drylands found that the outcomes of woody plant removal were highly dependent on environmental conditions and woody plant characteristics. Reports in the literature indicate a discrepancy between impacts on woody plants and ecosystem processes. While the effectiveness of woody plant removal was relatively short-lived (about 5 years), the effects on ecosystem functions were generally large, rather negative and more long-lived (up to 10 years).

The effects of woody vegetation removal on leaf litter biomass and soil organic carbon yielded mixed findings in a global meta-analysis.

The effects of woody vegetation removal - in combination with climate change - depend on the extent of bush harvesting. While moderate harvesting under certain conditions might have a positive effect on species richness, more intensive removal of woody plants would have strong negative impacts, both directly on woody plants and on tree-dwelling species and those organisms that require microhabitats and protection provided by woody plants. The importance of protection by shrubs for small mammals or reptiles, for example, could increase as climate change progresses.

UNIQUE study and corresponding ideas for woody plant biomass harvesting

There are two fundamental misconceptions that have the potential to cast the entire study into grave doubt. The first misconception arises from the choice of annual increment rates of woody vegetation. The authors base their assumptions on a master's thesis that determined an annual bush encroachment rate of 3.18% per year. Compared to more recent and peer-reviewed studies that use high-resolution satellite imagery to measure the extent of woody plants, the estimated growth rate seems much too high. For example, a study on the proliferation of woody plants in South African grasslands between 1990 and 2013 recorded an annual increase of 0.22%. The results of this study also showed that the changes varied greatly across the country; areas with more than 500 mm mean annual precipitation showed higher rates of woody plant spread than regions with less than 500 mm (0.31 % per year and 0.11 % per year, respectively). The carbon sink effect from woody plant removal expected in the UNIQUE study will probably turn negative if the realistic growth rates of 0.5 % to 1.0 % are used. Effects of climate change could even exacerbate the problem.

The second misjudgement of the UNIQUE study concerns the expected spatial extent of so-called "bush encroachment". Recent studies using high-resolution satellite imagery have shown that the areas that experienced significant vegetation changes in Namibia between 2000 and 2013 were spatially quite

limited (especially in northern Namibia, where annual rainfall is highest). The Seebauer et al. (2019) study assumes widespread increases in woody plants throughout Namibia, based on crude maps that are not supported by recent, high-quality data.

As the UNIQUE study is based on false assumptions and outdated scientific knowledge, and consequently grossly overestimates the area and extent of woody plant expansion, it seems futile to elaborate on other arguments put forward to justify the project.

The extensive international literature shows that the ecohydrological and biodiversity-relevant consequences of woody plant expansion need to be discussed in a much more differentiated way than UNIQUE does.

Our results seriously call into question the carbon balances and sustainability assessments of bush harvesting.

1. Introduction and aim of the analysis

The potential use of Namibian biomass as fuel in a German power plant has brought the problem of "bush encroachment" to the attention of a wider public unfamiliar with the ecological background of the issue.

The aim of this document is to provide an overview of relevant results published in the international literature on the causes and consequences of vegetational changes in Namibia and elsewhere.

The results will be discussed with respect to management options proposed in the context of a German-Namibian development cooperation project. This will include a critical evaluation of the UNIQUE study *Greenhouse Gas Assessment of Bush Control and Biomass Utilization in Namibia*, which provides the fundament for assessing the feasibility of bioenergetic use of bush biomass from Namibia (Seebauer et al. 2019).

2. Conceptual and terminological fundamentals

Woody plant proliferation has been documented and discussed for a long time, and it has been indicated that - especially in times of accelerating climate change - it is important to look at the phenomenon from a dynamic perspective (Archer et al., 2017). The interaction between grasses and woody vegetation is highly dynamic and their relative abundance changes frequently at timescales ranging from decades to centuries to millennia. Over the past 100 years, there has been a directional shift toward increased abundance of woody vegetation worldwide (Sala and Maestre 2014). However, this shift is not unidirectional, many (potentially) greening ecosystems also suffer from both deforestation and tree dieback. The displacements of grasses by woody plants have taken place around the globe and across bioclimatic zones. While trees proliferate in humid regions, unpalatable shrubs replace grasses in more arid regions. The proliferating woody plants can either be non-native species that were introduced purposely or accidentally or native species that have either increased in abundance within their historic ranges or expanded their geographic range (Archer et al., 2017).

Within the scientific community, woody plant proliferation has often been viewed as being associated with declining ecosystem functioning, landscape degradation or desertification (Van Auken, 2000). Many assessments that treat woody plant proliferation as ‘*bush encroachment*’ derive from rangeland-focused studies that highlight its negative effects on forage production. However, woody plant proliferation is a complex and multifaceted phenomenon, and understanding its ecological consequences requires that we adopt a more holistic view, acknowledging the multiplicity of organisms and ecosystem processes/services it affects (Maestre et al., 2016).

The phenomenon of “bush encroachment” was first described after the exploitation of drylands by European settlers led to their transformation. The exact dates vary between regions and continents, but normally range from 100 to 150 years. Exploitation was followed by the development of steady-state management that was based on the assumptions of equilibrium ecology. This type of management attempts to maximize sustainable yield of specific goods that are most highly valued, mainly fodder, by actively controlling ecosystem variation through fire suppression, predator control, and fencing. Hence, “bush encroachment” not only represents a colloquial term, but implies a normative statement.

‘An encroachment is something that intrudes and has the power to influence whatever it encounters. Some might consider text messaging to be an encroachment of impersonal technology on true, heartfelt interactions. Encroachment carries the sense of something slowly creeping into something else’s space, either literally or figuratively. An encroachment can be of the physical variety, such as the encroachment of new development into a beautiful coastal area. Encroachment typically has a slightly negative meaning, hinting at something that intrudes on something and then spoils it in some way’(Vocabulary.com; last access 16 March 2021).

‘Bush encroachment’ suggests that a negative driver (woody plant proliferation) has to be controlled to be benefit of a positive state of the system that provides the desired good (such as forage). From a land use perspective this may represent a relatively legitimate approach, but it cannot be considered as a neutral ecological view. From a neutral ecological perspective, this document considers the term “bush encroachment” to be prejudiced and not sufficiently result-open. Therefore, it will be avoided and woody plant proliferation or vegetation change will be used instead.

It has been long suggested that the woody plant proliferation and the measurable vegetation greening may be seen as a natural process involving the interaction of counteracting functional types, the tree and grass component of savannahs, where there is an ongoing switching and intermingling of relatively stable or unstable ecosystem states (Fowler 1982; Davis et al. 1998, Walker et al. 1981; Frost et al. 1985).

It is notable that much of the discussion on vegetational change in drylands and elsewhere is driven by both empirical data on vegetation changes and land use interests. Nevertheless, the perspective of modern (eco)system ecology in many assessments is largely missing. In this context, ecosystem change is a dynamic and fundamentally open-ended process that by no means stops at a supposed climax or ‘climax’, but rather progresses steadily. Ecosystems are complex systems whose development is driven, among other things, by the need to husband with scarce resources and, above all, energy (Fath, 2017). Ecosystems are energy-utilizing

bioreactors whose evolution is accompanied, within the limits of what is physically possible, by increases in biomass, information content (genetic information), and network (between components) (e.g., Fath et al., 2004; Jørgensen, 2007).

Nevertheless, systemic perspectives on vegetational change have become more important. Rangeland sciences themselves have undergone substantial transformations within the past 25 years. The introduction of resilience theory and state-and-transition models have provided a conceptual framework for the development of an alternative assessment procedure and have led to the recognition of nonlinear vegetation dynamics, as well as the adoption of ecological principles (Briske, 2017). Indeed, the understanding of woody plant proliferation and vegetation greening can also benefit from looking at the theory of ecosystem regime shifts (see Scheffer and Carpenter, 2003).

3. Vegetational change and global dryland greening as dynamic, systemic process

Very recently, Wei et al. (2021) provide an insightful review of systemic responses and feedbacks of African dryland ecosystems to environmental changes. The assessment that it is based on remote sensing tries to get to grips with the dryland ecosystem dynamics and the various interacting drivers of vegetational change. Wei et al. (2021) note that global CO₂ enrichment, changes in precipitation regimes, and a decline in fire activity have collectively driven vegetation greening, increases in woody plants, and carbon dynamics in African drylands in recent decades. This would challenge the long-held narrative of desertification. Most importantly, the authors also highlight the importance of systemic feedback loops between rainfall, vegetation, and fire in enhancing the resilience of dryland ecosystems. They provide a Resource-Ecosystem-Disturbance framework that highlights the inter-linkages between rainfall, soil, vegetation, fire, and human management and helps to understand how dryland ecosystems' structure and functioning respond to global environmental changes (Fig. 1).

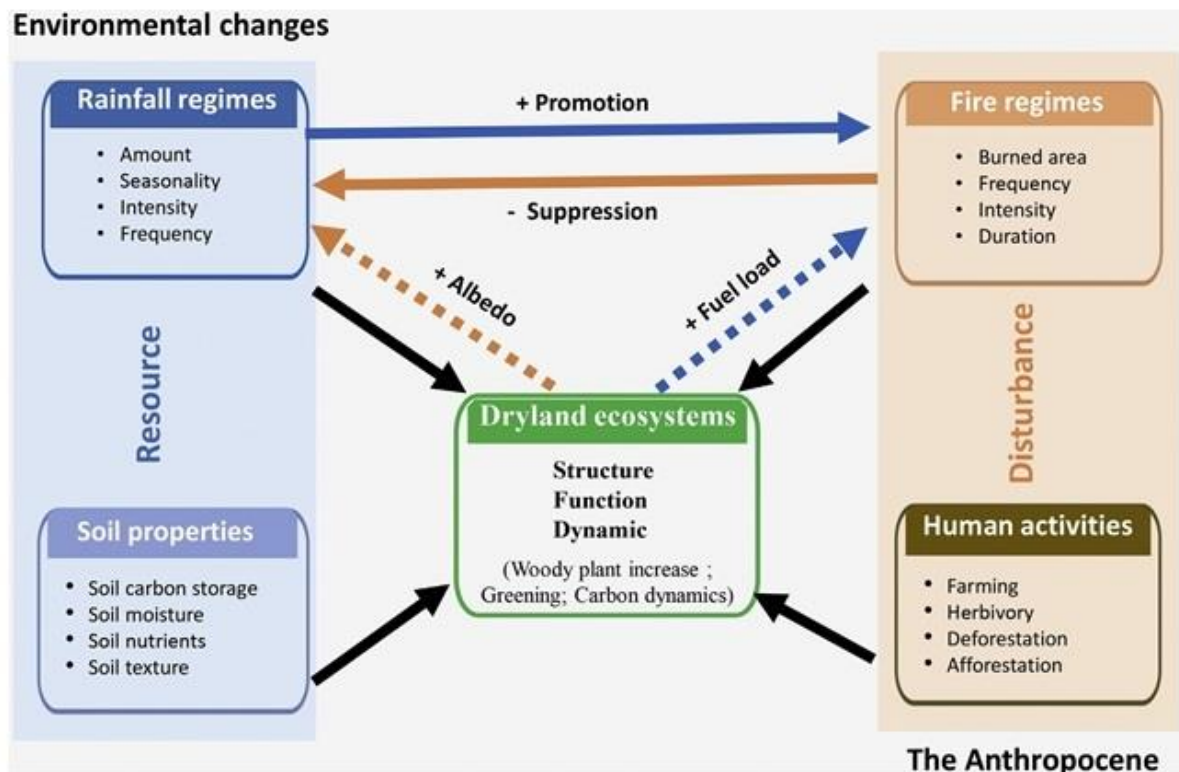


Figure 1 Wei et al. (2021): “A conceptual framework of drivers-responses-feedbacks in African dryland ecosystems. Here we present the driving mechanism of dryland ecosystems (center) from the perspective of resource availability (left side) and disturbance (right side). Specifically, rainfall regimes (dark blue box), soil properties (light blue box), fire regimes (orange box), and human activities (brown box) together drive ecosystem structural and functional dynamics (green box) in African drylands. We also highlight the rainfall–vegetation–fire feedback loops in drylands where rainfall promotes fire through fuel load (blue arrow) while fire suppresses rainfall by increasing surface albedo (orange arrow).” (Figure and caption adopted from Wei et al 2021).

Based on multiple sources, the authors conclude that changes in rainfall regimes (i.e., amount, frequency, intensity, and seasonality) are an important determinant of structural and functional changes in African dryland ecosystems. Changes toward more intense and less evenly distributed rainfall events - often attributed to climate change globally - would have promoted woody over herbaceous vegetation in recent decades. Similarly, soil nutrient availability may interact with precipitation to influence tree-grass dynamics in ecosystems where fire and herbivory also influence vegetation dynamics. The role of these disturbances, which are fundamental to nutrient recycling and niche partitioning, is to promote alternative biome states (e.g., forest-savanna-grass mosaic) through stabilizing feedbacks. Fire (compare photograph 2) can be viewed as a self-reinforcing disturbance that allows for dominance of shade-intolerant, flammable grasses, leading to higher frequency, while in more closed systems woody plants shade the grasses, which in turn reduces dry fuel loads and fire frequency and promotes woody plant proliferation.

When vegetational changes such as drylands greening or woody plant proliferation are understood as manifestation of complex ecosystemic changes, it is not surprising to observe non-linear dynamics such as decrease–increase, decrease–increase–decrease, and increase–decrease–increase (compare Ding et al., 2020). Clearly, ‘*vegetation greening or browning is often a matter of observation period and associated interpretations of such changes to represent ‘recovery’ or ‘degradation’ are not always appropriate and oversimplified*’ (Wei et al. 2021, based on Kusserow, 2017).



Photo 1 In the less arid regions of Namibia the vegetation is heavily influenced by historical and current landuse, including agriculture, grazing or fencing (photo P.L. Ibisch; Kavango, Namibia, 20 March 2015).



Photo 2 Post-fire situation of managed Kalahari landscape in northern Namibia (Kavango; photo: P.L. Ibisch, 21 March 2015).

An Australian study indicates that short-term, small-scale, local observations and experiments are rarely tested over larger scales and longer time frame; interactions between rainfall fluctuations and density dependence as determinants of large-scale, long-term woody plant cover dynamics in savannahs would be subject to large rainfall excess and deficit over multi-year time-scales (Fensham et al., 2005). The authors showed that the interaction between rainfall and initial woody cover was significant; increases in woody cover coincided with low initial cover when rainfall was higher than average, whereas loss in woody cover occurred with high initial cover, regardless of rainfall.

The logical conclusions from non-linear performance of climate-vegetation interactions for future projections of woody plant expansion in drylands is that they are highly unreliable. In this context, it is noteworthy that a slowing of the greening trend in natural vegetation in many ecosystems is not only plausible, but also increasingly recognized: New results do not support previously published accounts of dominant global-scale effects of CO₂ fertilization; *'Earth's greening trend is weakening and clusters of browning are beginning to emerge, and importantly, expanding during the last two decades'* (Winkler et al., 2021). While a greening cluster is still evident in southern Africa (Winkler et al., 2021), the trend can by no means be extrapolated into the distant future.

4. Extent and patterns of current dryland greening in Africa

Woody plant proliferation has been identified as a concern for rangeland management since the early 20th century, but, until recently, the causes and consequences have only been described at local to regional scale. The increasing availability of high quality remote sensing data and artificial intelligence technologies have substantially improved our understanding and our capacities for data-informed modelling.

Venter et al. (2018) used high-resolution satellite imagery to assess the drivers and the extent of woody vegetation cover in sub-Saharan Africa. Their findings showed a 0.27 % year⁻¹ increase of woody vegetation cover, confirming global greening trends and challenging the widely held theories about declining terrestrial carbon balances and desertification. Over the past three decades, 7.5 million km² (55%) of non-forest biomes in sub-Saharan Africa underwent significant net gains in woody plant cover (Fig. 2), while 2.2 million km² (16%) experienced significant decrease in woody plant cover. Venter et al. (2018) describe their findings as follows: *“Woody cover loss was prevalent in parts of the Sahel, East Africa and much of Madagascar, but WPE (in this document referred to as woody plant proliferation; note of the author) dominated the central-interior of Africa. Countries exhibiting a mean fractional increase >30% were Cameroon, Central African Republic, South Sudan, and Uganda. Almost all other counties experienced net greening, with only Congo, Kenya, Madagascar, Niger and Somalia undergoing a net decline in woody cover. (...). Areas with more than 75% initial cover experienced highest rates of loss, probably due to human-induced clearing. There was little difference between WPE (woody plant proliferation) inside (13.9%) and outside of (12.5%) protected areas. Proliferation trends were lowest in shrublands (3.5 ± 0.4% increase) and highest in Caesalpinoid savannahs (20 ± 0.4% increase), but were pronounced across all vegetation types, indicating that the drivers of this change are globally available, but act regionally allowing woody plant proliferation in some areas and deforestation in others.”*

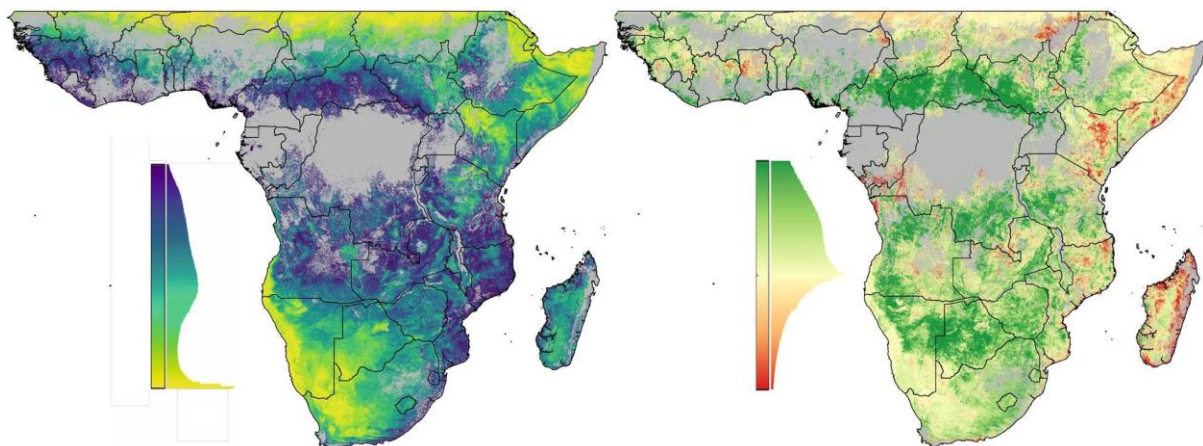


Figure 2 Venter et al 2018: *“Woody plant cover dynamics over sub-Saharan Africa. Satellite observations of 30 years of fractional woody plant cover (a) reveal a dominant increasing trend (derived from the slope of the linear trend line between 1986 and 2016) (b). Histograms alongside colour scales indicate data distributions. Grey areas were masked from the analysis and represent urban surfaces, wetland, cropland, and forest (areas >40% cover by trees >5 m). Maps were constructed in Google Earth Engine.”* (Figure and caption adopted from Venter et al 2018)

These trends have been confirmed by a global assessment by Tian et al. (2017) who mapped the gains and losses in woody vegetation across global tropical drylands. They identified large

coherent areas of pronounced increasing trends of vegetation optical depth (VOD) in woody vegetation in the Sahel, Namibia and South Africa. Contrastingly, areas of significant decreasing VOD trends in woody vegetation were found in eastern Africa and the eastern part of southern Africa. The extensive woody plant proliferation in the drylands of Namibia and South Africa (Buitenwerf et al., 2012, O'Connor et al., 2014) was supported by the significant positive trends in both the leaf and woody components. However, the VOD of woody vegetation showed much larger areas of positive trends as compared to VOD of leave components, indicating a potential underestimation of the spatial extent of woody plant proliferation based on optical remote sensing data in this region (Saha et al., 2015). The authors also discussed the effects of manmade fires through a case study from Botswana and Zimbabwe, where fires are used for controlling woody plant proliferation (Gandiwa, 2011, Mudongo et al., 2016). Their findings showed that even though fires rarely killed trees, woody plant proliferation was suppressed, which was expected to lead ultimately to a reduction in the size of woody plants (Higgins et al., 2007). The authors argue that the observed intensification of fire events during the study period (Andela and van der Werf 2014) would be a plausible explanation for the overall decreasing VOD trends of woody vegetation in Botswana and Zimbabwe.

In the study of Venter et al. (2018), rainfall was identified as one of the main drivers of woody plant proliferation. Areas experiencing increases in rainfall underwent greater woody plant proliferation than those where rainfall has decreased, confirming findings of previous studies (Sankaran et al 2008, Staver et al 2011). At a local scale, rises in temperature have been shown to enhance woody plant proliferation through declines in frost-induced tree mortality. The enhancing effects of rising temperatures on woody plant cover were also confirmed by Venter et al.'s study at a regional-scale. Likewise, their analysis confirmed that local disturbance patterns by fire and herbivory can have continental consequences for woody plant proliferation and are of equal importance to edaphic and climatic variables in explaining the spatial variation in woody cover change. During the study period, Africa experienced large reductions in burned areas, which probably have driven larger woody plant proliferation rates. Venter et al. (2018) found that the *“bulk of the data for trends in herbivory suggest that increasing herbivore intensity exacerbates woody plant proliferation. Grazing herbivores, which dominate most African rangelands (Hempson et al 2015, Robinson et al 2014), reduced grass competition with woody plants and fuel loads for fires, thereby releasing woody plants from the fire trap (Roques et al., 2001). However, woody plant proliferation might also be facilitated in areas with large declines in herbivory.”*

Water availability was also found to be a principal driver of large-scale land cover spatial heterogeneity in sub-Saharan savannahs. Marston et al. (2019) analyzed satellite imagery to evaluate mosaic distributions and characteristics across sub-Saharan Africa, as well as the environmental drivers of mosaic formation. They found that mosaic habitats were abundant at the scale analysed (19.6 km²), although mosaic characteristics varied considerably. Precipitation was identified to be the most important factor influencing mosaic complexity, followed by evapotranspiration, temperature, lithology and distance to rivers. Fire and ecosystem engineer presence were of lesser importance at the scale of the study. This came to a surprise to the authors, since literature on African savannah vegetation provides extensive evidence for the importance of such disturbance in maintaining a mosaic vegetation that does not succeed to forest (e.g. Laws 1970; Dublin et al. 1990; Midgley et al. 2010; Pringle et al. 2014). The authors offered two likely explanations for the lower importance of disturbance in

their analysis. On the one hand it is possible that the datasets used in the analysis of herbivores effects were not detailed enough to pick up these effects. On the other hand it is possible that the disturbance effects of large mammals (especially elephants) and fire are of lesser importance at the scale of sub-Saharan Africa.

Wei et al 2019 (2019) discuss many factors as drivers for ecosystem changes in African drylands, including climate change, CO₂ fertilization, fire regime, grazing, and agriculture (Andela et al., 2013; Higgins & Scheiter, 2012; Liu et al., 2013; Muller et al., 2007; Wigley et al., 2010; Yu & D'Odorico, 2014), but conclude that vegetation changes in these areas are mainly controlled by water availability (Andela et al., 2013; Brandt et al., 2017; Liu et al., 2013; Wang et al., 2010).

In their study, the authors (Wei et al., 2019) assessed ecosystem changes in African drylands through the complementary use of optical and passive microwave satellite data—normalized difference vegetation index (NDVI) and vegetation optical depth (VOD). They found that 54% of African drylands experienced a significant increase of VOD, mainly located in southern Africa and west and central Africa, with an average rate of increase of $(0.0012 \pm 0.0027) \times \text{year}^{-1}$ during 1993–2012. At the same time, over 43% of the African drylands experienced a significant decrease in NDVI, in particular in western Niger and eastern Africa, with an average browning rate of $(-0.00013 \pm 0.0015) \times \text{year}^{-1}$. The contrasting vegetation trends (increasing VOD and decreasing NDVI) were largely caused by an increase in the relative proportion of the woody component of the vegetation, as a result of the prevailing woody plant proliferation in African drylands during the study period. Soil water emerged as the dominant driver of ecosystem changes in African drylands, in particular in arid and semiarid areas that accounted for about 48% of vegetation variations. The authors concluded that soil water, which is directly available to vegetation, should be a better indicator for vegetation dynamics than precipitation.

On a smaller scale, Saha et al. (2015) assessed the linkages between woody plant proliferation and greening in southern Africa. They found an underlying, overall greening in southern Africa, increasing 0.26% year⁻¹ over the 2000–2013 study period. Over 15% of the region underwent statistically significant change, strongly biased towards greening (Fig.3). The strongest greening was in a coherent band stretching from northern Namibia to Lesotho, an area that is also subject to woody plant proliferation. The authors suggested that the processes of greening and woody plant proliferation are linked. Shrublands and savannahs accounted for 78% of the study region. Savannahs did not change appreciably (-0.21% total change) from 2000–2013 while shrublands were greening faster than any other land cover type over the same period (+8.93%). Fast rates of greening in this biome may be indicative of woody plant proliferation.

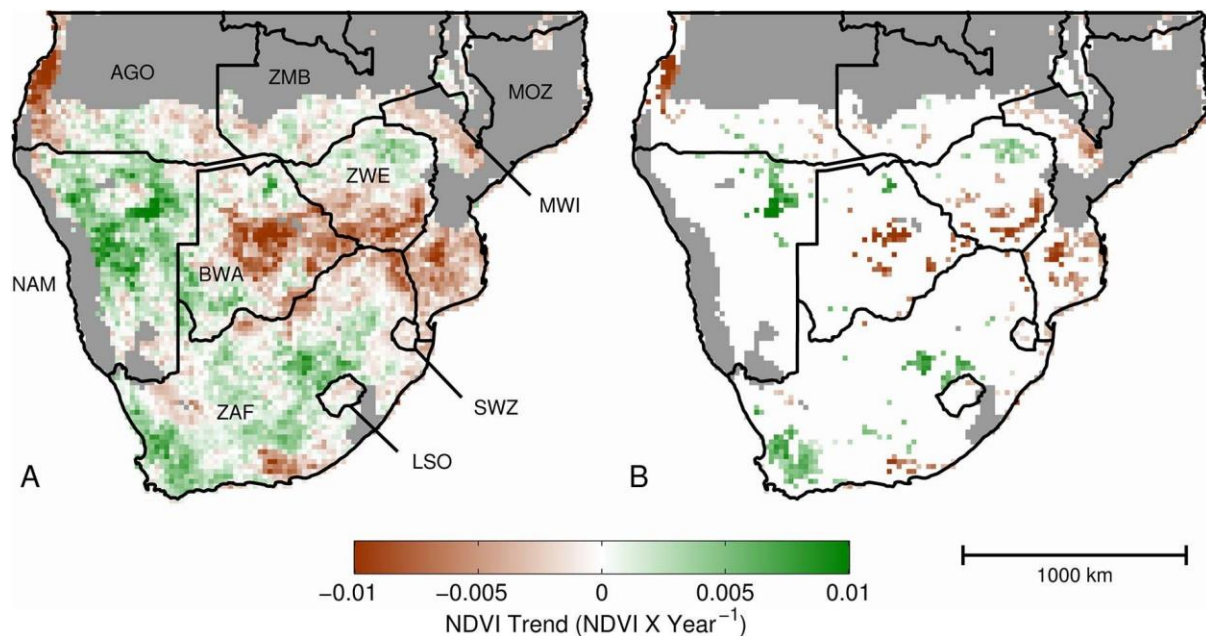


Figure 3 Saha et al 2015: “Observed trends in NDVI_{max} for (A) all pixels and (B) only pixels showing a significant ($p < 0.10$) change. Grey areas are regions that have been excluded from our study. Country abbreviations are as follows: AGO: Angola, ZMB: Zambia, MOZ: Mozambique, ZWE: Zimbabwe, MWI: Malawi, NAM: Namibia, BWA: Botswana, ZAF: South Africa, SWZ: Swaziland, and LSO: Lesotho.” (Figure and caption adopted from Saha et al. 2015).

Many sources of evidence suggest that landscapes of central and southern Namibia would have changed radically since the 19th century, but, as Rohde and Hoffmann (2012) underline, “there are no detailed documentary sources that authenticate the state of the pre-colonial environment and how it has changed since then, across such a large spatial scale. Understanding the extent and cause of change is important since degradation in Namibia is commonly blamed on inappropriate land use practices (local drivers) leading to woody plant proliferation, soil erosion, aridification and a decline in agrarian productivity (Eitel et al., 2002; de Klerk, 2004; Getzin, 2005; Dirkx et al., 2008). Furthermore, future climate change scenarios predict that these ecological processes will be exacerbated by the regional impact of global drivers in the form of anthropogenic global warming (Midgley et al., 2005; Haensler et al., 2011). Future projections based on bioclimatic envelope models suggest that desert and arid shrublands will expand into present grassland savannahs with a concomitant reduction in net primary productivity (Thuiller et al., 2006) and negative impacts on biodiversity, ecosystem services and livelihoods (Kruger, 1997; de Wit and Stankiewicz, 2006; Reid et al., 2007).”

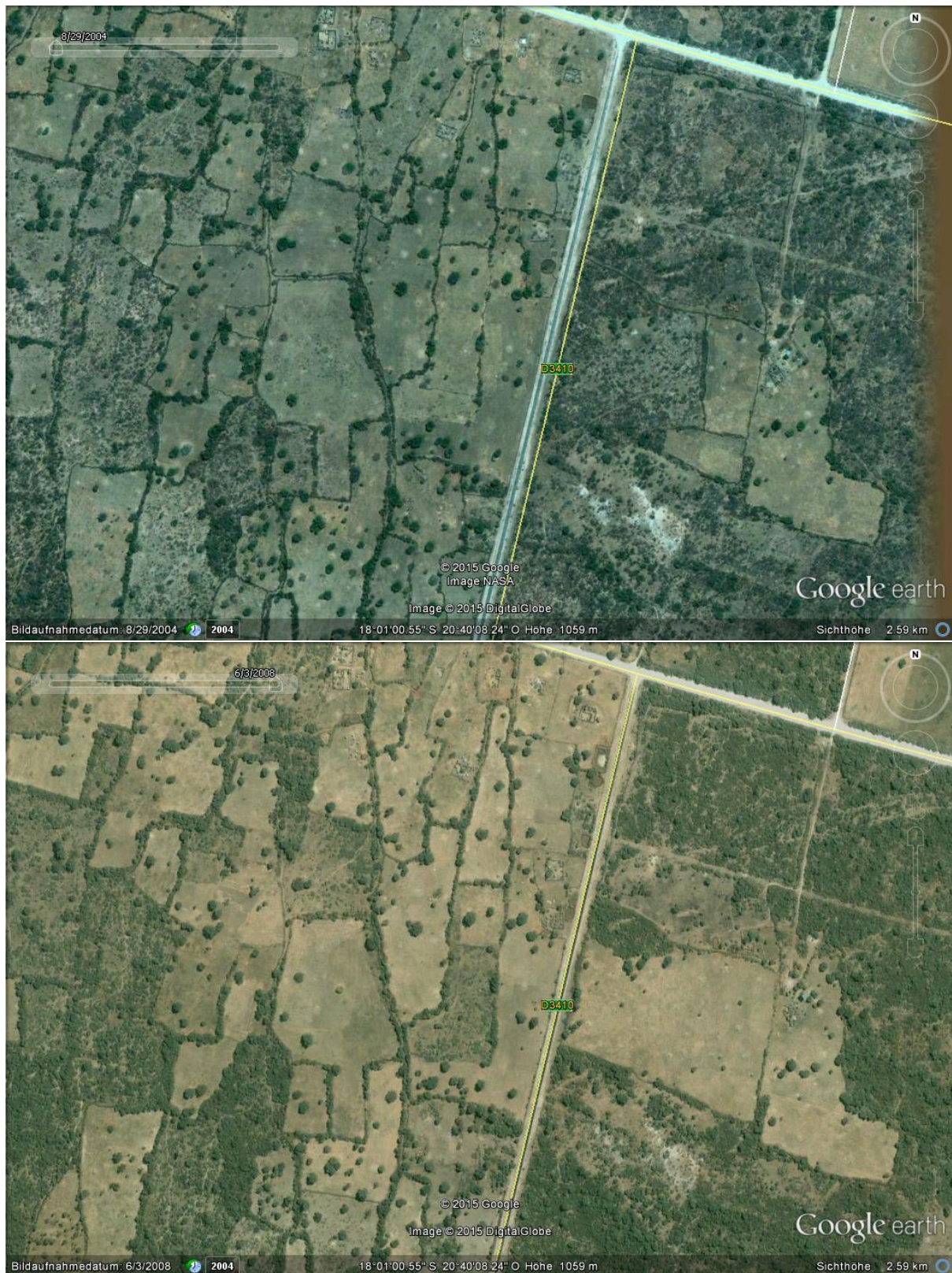


Photo 3 Exemplary GoogleEarth pictures from 2004 (top) and 2008 (bottom) depict that the increase or decrease of woody plant vegetation follow small-scale patterns strongly influenced by land use. Correspondingly, it is complicated to assess and interpret dominant trends.

In their excellent study from 2012, Rohde and Hoffmann (2012) give a detailed recount of the historical ecology of Namibian rangelands and test the influence of both local and global drivers on long-term changes in the vegetation of Namibia's extensive rangelands. For this

purpose fifty-two historical photographs of the Palgrave Expedition of 1876 were re-photographed and used to document changes over more than 130 years, in grass, shrub and tree cover within three major biomes along a 1200 km climatic gradient in central and southern Namibia. Their study showed that patterns of change correlated with mean annual precipitation (MAP) and that vegetation remained remarkably stable since 1876 below a threshold of around 250 mm, regardless of land-use or tenure regime. Above this threshold, an increase in tree cover was linked to the rainfall gradient, the legacies of historical events in the late 19th century, subsequent transformations in land-use and increased atmospheric CO₂. Their study showed that the *“onset of woody plant proliferation coincided with political events linked to colonialism, in conjunction with drought, epidemics and epizootics of the late 19th and early 20th centuries. Legacies of demographic collapse, land-use change and landscape fragmentation were evident in these more mesic Savannahs. (...) Local drivers (decimation of megaherbivores and wildlife browsers, fire suppression, cattle ranching) across a climatic gradient and the global driver of increased atmospheric CO₂, provided a parsimonious explanation for past and ongoing vegetation change (Archer et al., 1995).”* However, the authors did not find any evidence that savannah patch dynamics promoted the reversion from bush-encroached to open grassland over the timescale of their study. Nor did they see any evidence for the expansion of desert and arid shrublands into Tree and Shrub Savannah areas (Midgley et al., 2005; Woodward and Lomas, 2004), the predicted decrease in groundwater or increased evaporation as a result of global warming (Dirkx et al., 2008; Haensler et al., 2011).

5. Consequences of dryland greening in Southern Africa

Greening has multiple effects on soils, micro and meso climates, ecohydrology, carbon stocks and flows, as well as biodiversity, which we will discuss in the following. Contrary to prevailing views of rangeland managers, woody plant proliferation is not synonymous with land degradation.

In an extensive review of scientific evidence, Eldridge and Soliveres (2014) analysed the effects of woody plant proliferation on ecosystem structure and functioning in Australia, which should have some relevance to drylands on other continents where woody plant expansion occurs. The study summarizes the scientific evidence into two conceptual models in order to optimize landscape management that strives to maximize the services provided by shrub-encroached areas. The first model aimed to reconcile the apparent conflicts between the patch- and landscape-level effects of shrubs (Fig. 4).

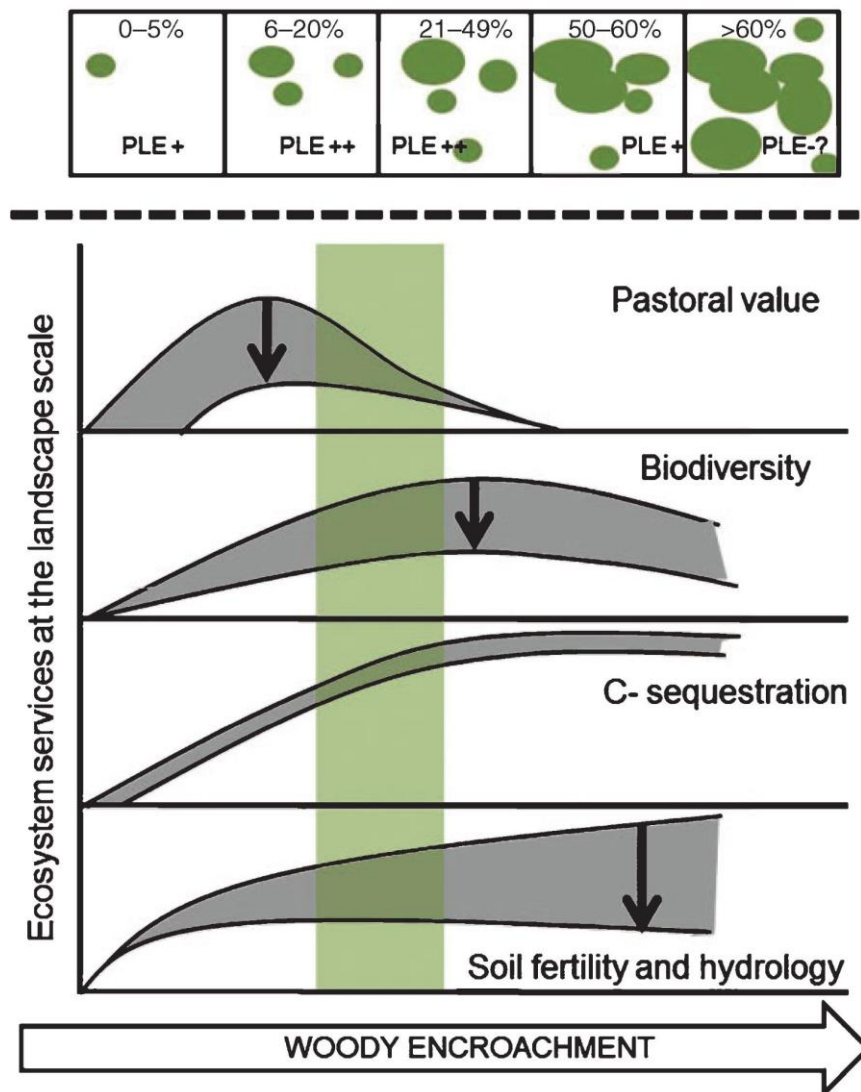


Figure 4 Eldridge & Soliveres (2014) ["Disentangling the myths and truths of woody encroachment in Australia"]: At the landscape level, the effects of individual woody plants (patch-level effect; PLE) change across the gradient in woody densities (uppermost panel). Here, the PLE of individual shrubs (the green ellipses) remains positive until woody cover reaches ~60%, which is close to the maximum cover found in eastern Australia (Soliveres and Eldridge 2014). In the lower panel, different ecosystem services that we have assessed (C sequestration, biodiversity conservation, hydrology, plant pastoral nutrients, pastoral production, soil fertility) are likely to respond differently to increasing woody densities (adapted from Blaum et al. 2007; Sirami et al. 2009; Eldridge et al. 2013). The grey-shaded envelope indicates the range of values that occur under varying levels of grazing, with downward arrows indicating increasing grazing pressure. The positive responses of plant biomass (the main component of the pastoral production score), plant richness (biodiversity), soil fertility and infiltration dampen under increasing grazing pressure (indicated by the downward arrows and the lower limits of the shaded envelopes; Eldridge et al. 2013). Grazing, however, has little effect on C sequestration, which stabilises at a maximum once woody cover reaches: 230% (Reich et al. 2001; Breshears 2006), at least in the short to medium term. The lack of grazing effect on C sequestration occurs because soil C is relatively slow to respond to increased grazing, and plant biomass makes up only a small proportion of total C compared with soil and woody C (Daryanto et al. 2013a). The green stripe indicates the range in woody cover that maximises the level of all ecosystem services simultaneously. (Figure and caption have been adopted from Eldridge & Soliveres 2014; see source for references).

The second model identified the ecosystem services derived from different stages of shrub encroachment (Fig. 5). In addition, they examined six ecosystem services provided by shrublands (biodiversity, soil C, hydrology, nutrient provision, grass growth and soil fertility) by using published and unpublished data. Their findings demonstrated that shrub effects on

ecosystems are strongly scale-, species- and environment-dependent and, therefore, no standardised management should be applied to every case. Overgrazing dampened the generally positive effect of shrubs, leading to the misleading relationship between woody plant proliferation and degradation. Woody plant proliferation per se did not hinder any of the functions or services described above, rather it enhanced many of them. Their findings also showed that no single shrub-encroachment state (including grasslands without shrubs) will maximise all services; rather, the provision of ecosystem goods and services by shrublands requires a mixture of different states. Finally, their analysis highlighted that rigorous assessments of the long-term effectiveness of woody plant removal were largely missing, as was evidence that this practice would improve land condition in most cases.

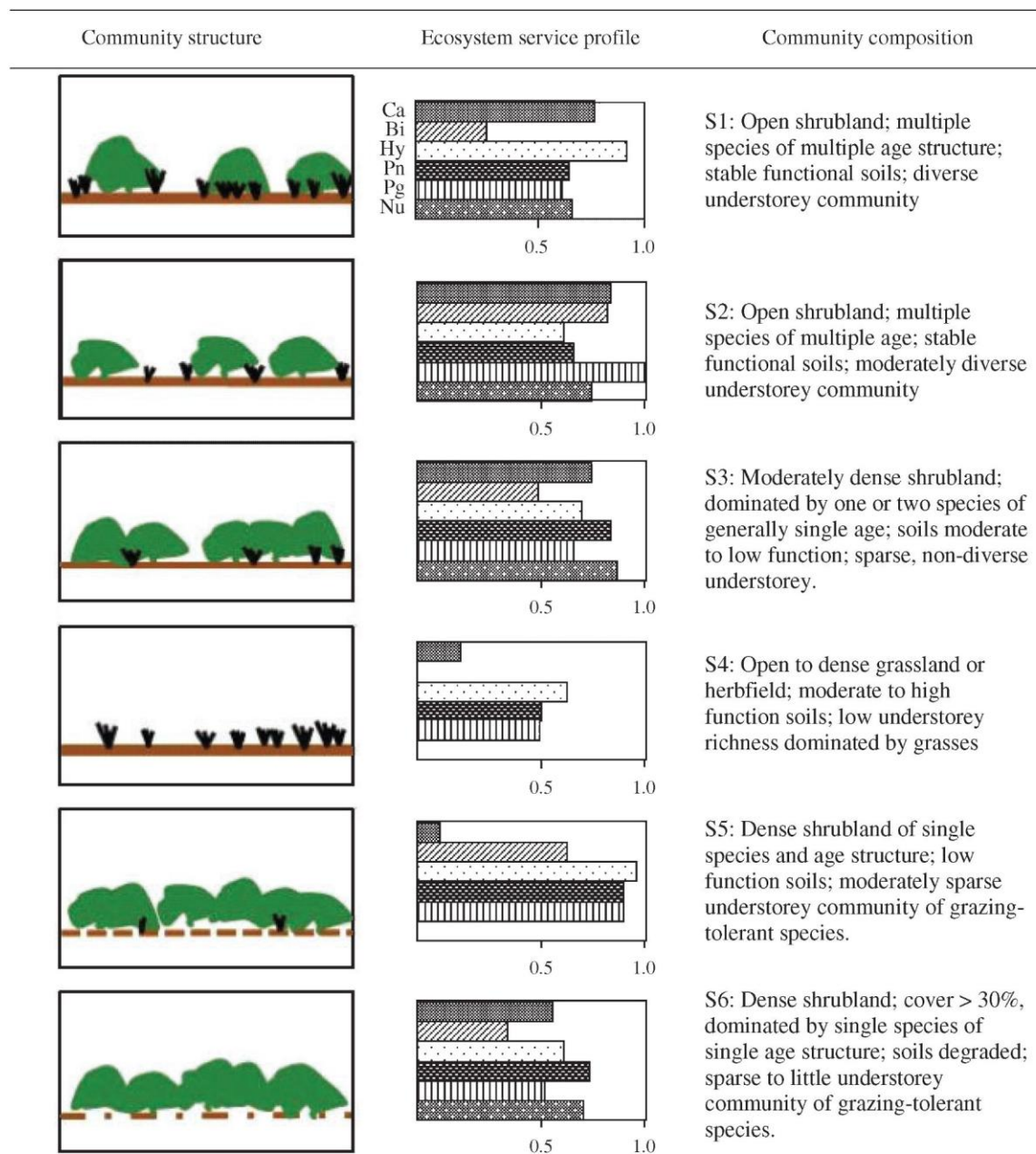


Figure 5 Eldridge & Soliveres 2014: "Schematic diagram showing the community structure of six contrasted states of shrub encroachment, a diagrammatic representation of the relative cover of woody and herbaceous plants, a description of the community composition, and relativised values for the six ecosystem services derived from each state. The six ecosystem services are C sequestration (Ca), biodiversity conservation (Bi), hydrology (e.g.

infiltration of water; Hy), plant pastoral nutrition (provision of nutrients N and P that are critical for pasture grass growth and nutrition, Pn), pastoral grass production (plant biomass; Pg), and soil fertility (i.e. organic matter content, soil nutrients; Nu). To derive an overall value for each of the six services, we searched the literature for studies reporting empirical data on various attributes related to the six services. First, we collected any data that allowed us to derive a value for any of the six attributes from a range of publications (see below). Each value was relativised by dividing it by the largest number. This has the effect of rescaling values to a maximum of 1 and improves the comparison among variables with different units and ranges. For each of the six services for each state, the relativised values are then averaged. Some data were unavailable (fertility for States 4 and 5, biodiversity for State 4), so these values have been left blank. Sequestration of C relates to the potential of a given state to fix and store atmospheric C and was calculated using measures of plant, litter and biological soil crust cover, plant biomass, total and labile soil C, and total ecosystem (above- and below-ground) pools of C (e.g. Burrows et al. 2002; Daryanto and Eldridge 2010; Stefani Daryanto, unpubl. data). Biodiversity relates to the capacity of a given state to provide habitat for plants and animals. We could find very little information on fauna from the six encroachment phases (apart from limited information in Ayres et al. 2001; and Doerr et al. 2009), so we based our assessment only on plant richness (e.g. Daryanto and Eldridge 2010; Daryanto et al. 2012, and unpublished material). Hydrology was related to the capacity of each state to conduct water through the soil profile and was assessed using various indices and empirical measures of infiltration capacity such as infiltrability (e.g. Daryanto et al. 2013a), sorptivity and steady-state infiltration under ponding and tension from different shrub states in western New South Wales (NSW) (Bowker et al. 2013; Eldridge et al. 2014; D. J. Eldridge, unpubl. data from Cobar and Griffith, NSW) and assorted soil infiltration indices relating to landscape-function analysis (LFA; Eldridge et al. 2013). Pastoral nutrients relate to the service provided by soil in supplying P and N to plants. These elements are critical components of grass biomass and essential for livestock growth and production (Belsky 1994; Treydte et al. 2011). Information was obtained on various forms of N and P, including organic, inorganic and mineralisable N, total soil N, net N mineralisation potential; Tighe et al. 2009; Eldridge et al. 2013). Pastoral grass production is the service most closely aligned to pastoralism, and is related directly to biomass production, particularly grasses. Even though this is not strictly an ecosystem service, we calculated its value because it is the attribute that is most valued by pastoralists and often the only attribute considered to have real utility. Data were obtained from a range of published and unpublished sources (e.g. Tothill 1971; Robson 1995; Snowdon and Ryan 2005, Thompson and Eldridge 2005). Soil fertility was derived from soil N, P and C, and specific nutrient indices (e.g. LFA nutrient index) using data from Eldridge (2011), Daryanto and Eldridge (2012), Daryanto et al. (2012, 2013a) and unpublished reports.” (Figure and caption have been adopted from Eldridge & Soliveres 2014, see source for references).

Soils

Global studies have shown that shrubs have substantial positive effects in drylands (Eldridge et al., 2012, 2011; Maestre et al., 2009). The soil beneath shrubs contains higher levels of potentially limiting resources such as water, organic matter, seed and nutrients than interspace soil (‘fertile island’ effect, e.g. Garner and Steinberger, 1989).

The effects of greening on grass production are fairly unequivocal, the general trend being an increase in grass production with a decrease in tree density and cover up to a limit. Yet, the converse seems to apply to grass quality. The higher nutrient status under trees (Scholes and Walker, 1993) is likely to lead to a higher nutrient quality of grasses under a tree canopy. While assessing the effect of *Acacia mellifera* on soil properties, Hagos and Smit (2005) found a gradient in soil nutrient status, which was highest near the stem of free standing trees, and decreased with increasing distance from the canopy in open ground. 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.

Blaser et al. (2014) studied the effects that the N-fixing shrub *Dichrostachys cinerea* had upon the pools and availabilities of N, P and C in soils of a mesic savannah in Zambia. They found that shrubs increased total N, P and C pools, and that the storage of soil C was not limited by shortages of either N or P, indicating that woody plant proliferation by this species in mesic savannahs could represent a C sink for several decades.

A study by Dlamini et al. (Dlamini et al., 2019) also showed that shrub encroached grassland exhibited a lower soil C:N ratio compared to the open grassland, indicating greater N

mineralisation. The soil C content and stocks were positively correlated with effective cation exchange capacity and exchangeable calcium, manganese and zinc, but negatively correlated with soil bulk density. These findings suggest that total C content and stocks in the surface plinthic soil of the studied shrub-encroached grassland are chemically stabilized via complexation interactions with polyvalent cations.

There is increasing evidence that overgrazing by livestock reduces ecosystem functions in shrublands, but that shrubs may buffer the negative effects of increased grazing. Eldridge et al. (Eldridge et al., 2015) examined changes in water infiltration and nutrient concentrations in soils under shrubs and in their interspaces in shrublands in eastern Australia that varied in the intensity of livestock grazing. Soils under shrubs and subject to low levels of grazing were more stable and had greater levels of soil nutrients. Shrubs had a direct positive effect on soil nutrients; but, grazing negatively affected nutrients by increasing soil bulk density. Their results indicate that shrubs may reduce the adverse effects of grazing on soil properties. Specifically, shrubs could restrict access to livestock and therefore protect soils and plants beneath their canopies. This is in line with findings by Sandhage-Hofmann et al. (2015), who found that soil fertility in continuously grazed communal land increased with the distance from water points.

Further analyses of their study confirmed that the soils of the communal grazing systems benefited from the shift of grass-dominated to bush-dominated system with woody *Acacia* vegetation, while the rangeland had lost palatable grass species and degraded. Mills and Fey (2004) found poorer soil quality in areas of the Eastern Cape of South Africa, where heavy browsing by goats had led to the transformation of xeric succulent thicket to savanna. A study by Andrews (Andrews 2008) showed that the decline of topsoil fertility led to an increase in woody plant growth, which brings up minerals from the subsoil. The author hypothesized that if the established woody plants are given the opportunity to replenish soil fertility over decades, then grasses eventually might regain their competitive advantage and woody plants might decline once more. However, if woody plants are removed, then fertility declines further in a vicious circle as woody plants regrow with more vigour.

Micro and mesoclimate

Greening of drylands has usually a buffering effect of wood plants by shading during daytime and reduction of thermal radiation at night time, creating more favourable conditions for plant saplings. Thomas et al. (2018) analyzed the microclimates beneath trees, shrubs, and grasses in the Kalahari. They found that *“the air beneath tree (and to a lesser extent shrub) canopies was cooler than the soil boundary layer under grasses during the daytime, particularly in the hotter months. The closed canopy of shrubs also had a significant impact in reducing cooling and keeping the air beneath shrubs warmer than in grass areas during cold winter nights. This could lead to fewer winter ground frosts, which might contribute to shrub survival and provide a further competitive advantage to shrubs over grasses (D’Odorico et al., 2012; He et al., 2010). In addition, shading from tree and shrub canopies will reduce soil moisture evaporation. Wind permeability, air movement, and convection will also be reduced in shrub canopies compared with more open grass covered sites. There is likely to be a vertical shifting of the wind velocity profile around taller vegetation. Shrubs and trees typically have a lower albedo than grasses, particularly in the dry season when grass foliage is dead (Hayden, 1998), and this is likely to have an impact on regional heat balances. From a mesoclimatic perspective, because woody plants reduce temperature extremes experienced at the soil surface, an*

increase in their cover will homogenise temperatures across the landscape compared with areas with both grasses and woody plants. Whether or not this is favourable to the ecosystem remains questionable.”

However, studies from other parts of the world have documented different effects. For example, in the northern Chihuahuan Desert there are no differences in net short-wave radiation between the grassland and the shrubland because they tend to have about the same winter albedo (He et al., 2010). Shrub canopies are relatively sparse and each shrub is bordered by bare soil areas, while the adjacent grassland exhibits a relatively uniform grass cover (Schlesinger et al., 1990). Because of the larger bare soil fraction, the shrubland experiences higher soil heat fluxes during the day and reaches higher soil temperatures than the grassland (He et al., 2010). At night the energy stored in the ground is released in the form of long-wave radiation. The higher nocturnal upward radiation measured in the woodland causes the warming of the air beneath and around the shrub canopies (D’Odorico et al., 2010). Thus, this warming effect is not due to the retention of nocturnal long-wave radiation by the canopy but to a more intense nocturnal upwelling radiation emanating from the bare soil beneath and around shrubs (He et al., 2010).

Ecohydrology

A key issue in the discussion of woody plant proliferation is the role of water in controlling the process and the consequences of greening on water availability. Contradictory results have been published. According to Deng et al. (2020): *“vegetation greening increased evapotranspiration and resulted in excessive soil water consumption (Feng et al., 2016; Zeng et al., 2018), and severely, caused more ecological droughts (Tietjen et al., 2017); however, other studies have proposed that vegetation had the ecological function of water conservation and storage (Feng et al., 2018), and the growth of precipitation caused by increased vegetation can even compensate for soil moisture loss resulted from the enhanced surface evapotranspiration (Li et al., 2018).”* Amongst others, shrubs would enhance the infiltration of water in drylands (Dunkerley, 2000; Daryanto et al., 2013a). A more systemic view suggests that all of these observations are valid, but that the processes are so diverse, interconnected and context-dependent that they require appropriately systemic analysis. This is where the emerging discipline of ecohydrology comes in.

“The interdisciplinary science of ecohydrology explores interactions between the structure and function of ecological systems and the movement and quality of fresh water. While aspects of this science have been investigated for over a century (Mackay, 2019), the field has experienced significant growth over the past two decades” (Guswa et al., 2020). The ecohydrological view on water is a systemic one and has made hydrology more complex “Vegetation partitions soil- water into “green” water fluxes that sustain biomass and “blue” water fluxes that supply groundwater recharge and streamflow (Evaristo, et al. 2015). Both a changing climate and changing landscapes can affect this partitioning. These interactions between water and vegetation occur in a dynamic feedback system within the critical zone where vegetation is influenced by the zone’s structure and function, and, in turn, the critical zone is altered by the vegetation” (Guswa et al., 2020).

And green water is much more than just water stored or evaporated by plants. Actually, green water is ‘eco-water’ bound to all types of biotic interactions within ecosystems. Therefore, *“green water flow leading to transpiration is a complex process, firstly because of the small spatial scale involved, which requires indirect visualization techniques, and secondly because the near-root soil environment, the rhizosphere, is habitat for the soil microbiome, an*

extraordinarily diverse collection of microbial organisms that influence water uptake through their symbiotic relationship with plant roots. In particular, microbial polysaccharides endow rhizosphere soil with properties that enhance water uptake by plants under drying stress“ (Sposito, 2017).

Schwärzel et al., (2020) concluded that global long- term greening in drylands would require a careful ecohydrologic evaluation. They learned (in Chinese drylands) that at adjacent plantation and grassland sites afforested land removed significantly more water from soil to atmosphere than grassland, but, contrary to the general belief, it was the understory—instead of the overstory— that performed as main water consumer in plantations. They also observed that there is a strict physiological regulation of forest transpiration. For instance, in contrast to grassland, annual seepage under the forest was minor in years with an average rainfall.

Nevertheless, man-made plantations must be distinguished from the ecosystem process of spontaneous revegetation through woody plant expansion. Negative feedback loops should play a role in avoiding complete depletion of water resources at a given site. Additionally, recent ecohydrological studies suggest that greening and increased evaporation could amplify precipitation and therefore trigger changes of the local or regional climate as well as the enhancement of the ecosystem's productivity.

To quote Sheil & Bagues-Tobella (2020): *“The more-trees-means-less-water myth has been debunked many times.”* A study by Ilstedt et al. (2016) has shown that increased tree cover often improves water availability and that landscapes with some tree cover have the potential to capture several times more water than comparable treeless landscapes. The use of water by trees is not synonymous with its loss. For example, continental rains depend much more on moisture derived from trees and other deep rooted vegetation than was recognised until a few years ago. The presence of trees also intensifies water recycling processes, resulting in a higher frequency of rainfalls on land before the water departs back to the ocean. In addition, trees can boost rainfalls through the generation of condensation nuclei that promote cloud formation and rain (Sheil 2018).

The diverse mechanisms by which trees influence water availability are detailed in Table 1, which has been extracted from Sheil & Bagues-Tobella (2020). According to Sheil & Bagues-Tobella (2020), *“these theories indicate that local climates switch from wetter to drier and vice versa with critical losses or gains in tree cover. If sufficient tree cover was established over broad dryland areas it seems that net rainfall would increase, with the wider benefits that that implies (Sheil 2018; Sheil et al. 2019).”*

An excellent overview over ecohydrologic studies that are relevant to understanding the positive impacts of woody plants and shrublands on landscape hydrology is presented by Wilcox et al. (2017).



Photo 4 Woodlands in Central Namibia (photo: P.L. Ibisch, Otjozondjupa, 21 April 2016).

Table 1. Mechanisms by which trees influence water availability. For additional reviews and references aimed at a non-technical audience, see Ellison et al. (2017) and Sheil (2018). (Table and caption adopted from Sheil & Bagues-Tobella 2020; see source for references).

Mechanism	Scale	Effect	Influences and management implications
Infiltration	Tree and stand	The entry of water into soil, controlling surface runoff generation and soil and groundwater recharge	Soil and rainfall properties; tree roots and litter; tree-associated soil fauna
Preferential flow	Tree and stand	The flow of infiltrating water along preferred pathways in the soil, including macropores formed by roots and soil fauna	Soil properties; tree roots, litter and tree-associated soil fauna
Transpiration	Tree and stand	The process by which trees extract water from the soil or groundwater and emit it to the atmosphere as vapour	Influenced by rooting depth and volume, leaf area and phenology; correlated to canopy cover; reduced by pruning/coppice
Interception	Tree and stand	Prevents some rain reaching the soil surface (evaporates back)	Leaf area and phenology; branch architecture; crown shape; leaf size and orientation; correlated to canopy cover; bark roughness; reduced by pruning/ coppicing
Soil evaporation	Tree and stand	Reduced sunlight and cooler understorey temperatures reduce evaporation from the soil surface	Leaf area and phenology; branch architecture; correlated to canopy cover; reduced by pruning/coppicing
Litter mulch	Tree and stand	Affects how much water enters the soil; reduces soil temperature, soil evaporation and surface runoff	Leaf area, lifetime and phenology
Soil water holding capacity	Stand to catchment	Trees often contribute to, and maintain, soils with comparatively good water storage capacity	Soil physical properties, some affected by trees through organic matter inputs and activity of roots and tree-associated soil fauna
Deep water uptake	Tree and stand	Some trees obtain water from much deeper in the soil profile (including groundwater) than other vegetation and can thus emit vapour over more extended periods, which influences atmospheric moisture	This is not the case for seedlings Rooting morphology, tree age/size
Hydraulic redistribution	Tree and stand	Deep-rooted trees, especially those with dimorphic root systems, passively redistribute water from moist to dry soil layers via their roots	Species choices and maturity

Mechanism	Scale	Effect	Influences and management implications
Stem water storage	Tree	Trees store water, allowing them to maintain high transpiration for some periods even when uptake from the soil is limited; this allows trees to emit vapour over more extended periods, thus influencing atmospheric moisture	Tree size and species choices; some species, such as baobabs (<i>Adansonia spp.</i>) show major adaptations to this strategy
Vapour capture	Leaf and tree (& soil)	Some plants extract water from humid air (some soils are also able to gain moisture directly)	Uncertain, but likely a minor effect in drylands
Dew capture	Tree and stand	Condensation of water vapour is promoted on cool surfaces (shaded places, transpiring stems and from radiative cooling at night); leaf surfaces have been shown to influence dew formation and its capture	Typically minor, but may be locally important; influenced by foliage, architecture and epiphyte load
Cloud capture	Tree and stand	Interception of fog and cloud provides significant amounts of moisture in certain locations/seasons	Locally important (e.g., on coasts and mountains); influenced by tree foliage, architecture and epiphyte load
Aerosols	Stand and region	Plants emit a range of particles and compounds into the atmosphere, which influence when and where water vapour condenses; emissions vary with species, physiology and specific triggers, e.g., heat stress causes some plants to emit isoprene, herbivory can also stimulate various emissions	Largely unknown but likely to be powerful at large scales
Rainfall recycling	Regional	An integrated property that results from many of the others but is also influenced by large-scale atmospheric flow	Increased tree cover typically leads to more effective recycling and a net increase in regional rainfall as water arriving from outside the continent is likely to fall more often before it is lost
Biotic pump	Regional	The theory that suggests that tree cover attracts atmospheric flows from elsewhere by favouring condensation to occur more frequently (a process that leads to lower air pressures)	Increased tree cover will typically increase and stabilise rainfall patterns at regional scales (decreased tree cover reduces rainfall and reliability)

Grazing and less shrubby vegetation reduce the water infiltrability of soils, run-off and can change ecohydrological landscape connections, which has important, but not always well understood, ecological consequences (Basant et al., 2020). Especially, when severe rainfall events are more common, woody plant coverage can improve water harvest and better prevent runoff and soil erosion. Eldridge et al. (Eldridge et al., 2015) analysed the effects of grazing on the ecohydrology of shrublands in eastern Australia. For this purpose, they examined changes in water infiltration and nutrient concentrations in soils under shrubs and in their interspaces in shrublands with varying intensity of livestock grazing. Through structural equation modelling the authors showed that shrubs had a direct positive effect on water flow under ponded conditions, but also enhanced water flow indirectly through increased litter cover. The positive effects of shrubs on water flow under low levels of grazing vanished at high levels of grazing. In contrast, shrubs had the potential to reduce the adverse effects of grazing on soil properties, especially by restricting the access of livestock and therefore protecting soils and plants beneath their canopies.

Carbon stocks and flows

Greening of drylands has resulted in a significant redistribution of carbon (C) among major terrestrial pools, yet we cannot confidently predict the magnitude or direction of change. Eldridge et al. (2011) found that the above ground net primary productivity (ANPP) scaled linearly with Mean Annual Precipitation (MAP) in landscapes where woody plants have displaced grasses. Their findings showed further that: *“at an MAP of ~340 mm the ANPP contribution to the C pool in woody plant dominated landscapes switches from being a net C source to a net C sink. Whereas grassland ANPP stabilizes at MAP > 500 mm, woody plant ANPP continues to increase linearly with increases in MAP.”* The authors argue that this: *“presumably reflects the ability of woody plants, with their more complex canopy architecture, to utilize greater leaf area than grasses (Knapp et al. 2008a)”*. The below ground soil organic carbon (SOC) pool typically dwarfs the above ground pool in drylands. However, the survey of studies quantifying changes in SOC with woody plant proliferation revealed no consistent patterns—it increased markedly in some cases, and remained unchanged, or decreased in others and had no correlation with MAP (Archer et al., 2017). This limits the potential to formulate robust generalizations about the C stock changes when grass communities are replaced by woody plant communities, since ANPP scales with MAP while SOC has no apparent relation to it.

Shrubs and trees are hotspots of biological activity, including carbon and nitrogen cycling (Tews et al 2004). A study by Thomas et al. (2018) in Kalahari rangelands showed that storage and concentrations of soil carbon and nitrogen, microbial activity, and CO₂ efflux were significantly higher under shrubs and trees compared with grasses. The authors argue that there are numerous pathways in which the soil is enriched under vegetation including hydrological (stemflow and throughfall), rhizospheric (root exudates and N- fixation by leguminous species such as *Acacia mellifera*), vegetation (primarily leaf litter), and animals (dung and urine). The productivity of shrubs and trees is underpinned by the moisture that is made available by deep roots, which allows the woody plants to generate more leaf litter, soil organic matter, and carbon and N than grasses (Su, et al., 2014). Another study in the Kalahari (Wang et al., 2009) found well- developed islands of fertility under plant canopies. Soils under plant canopies had consistently higher moisture and significantly larger carbon pools compared with open areas. Their work concluded that over regional scales, the availability of

moisture controls nutrient cycling rates, whereas at a local scale, vegetation patchiness is the key control.

Thomas et al. (2018) argue that the “*higher CO₂ efflux associated with soils under trees and shrubs was most likely due to a combination of factors including greater heterotrophic microbial and plant root respiration, higher concentrations of carbon, and more favorable conditions for microbial respiration (Tang & Baldocchi, 2005). Soil microbial populations, respired CO₂ and gas diffusion* will all be affected by changes to soil properties associated with vegetation change.” Woody plant proliferation can be driver of greater CO₂ efflux in dryland sand soils, yet this effect might be compensated by the associated increase in soil carbon contents and stocks. Dlamini et al. (2019) quantified and compared surface (0–5 cm) carbon stocks in shrub-encroached and open grassland savannah on similar plinthic soil and topographic position, and determined controlling edaphic factors. Soil carbon content and carbon stocks were on average 148% and 117% greater in shrub-encroached grassland soil, compared to open grassland soil, respectively.

Heavy grazing can alter the effects of woody plant proliferation on carbon stocks. Reda et al. (2020) assessed the effect of land exclusion and age of exclosure on herbaceous standing biomass, woody biomass, woody biomass carbon, soil organic carbon (SOC) and other soil properties in Northern Ethiopia. For this purpose, they selected exclosure plots in three age classes (5–7, 12–15 and >20 years) and adjacent free grazing areas as references. Their findings showed that exclusion of communal lands significantly improved herbaceous and woody biomass, woody biomass carbon, SOC, total nitrogen and total potassium. Woody biomass and woody biomass carbon were highest in the older exclosures. The content of SOC, total nitrogen and total potassium increased with age of the exclosure. Old-aged exclosures stored more biomass carbon (267 %) and SOC (37.66 %) than the young-aged exclosures.

In some areas, seeming woody plant proliferation could even represent a recovery of formerly degraded vegetation. In the northern Kalahari region, sometimes, old tree relicts indicate that the vegetation potential is different from the current situation (compare photograph 5).



Photo 5 Fallen remnant tree indicates (former) vegetation potential in degraded shrub-dominated landscape (photo: P.L. Ibisch, Kavango, 20 July 2015).

Species diversity

Flora

There is a large body of literature postulating negative effects of woody plant proliferation on herbaceous plant diversity and species richness (e.g. Gobelle and Gure, 2018). First, colonization of grasslands by woody plants introduces additional species that directly increase the biodiversity pool. Subsequently, changes in soil properties, vegetation structure, and microclimate can facilitate the establishment of other plant and animal species. Maximum species diversity in savanna-like systems often occurs where both woody and herbaceous plants are well represented, or where the increase in new woody and herbaceous species outweighs the loss of species originally associated with grasslands. As woody plants become more abundant, grassland components eventually decline and are replaced by species adapted to shrublands or woodlands (Archer et al., 2017).

In tropical and subtropical areas with large and diverse regional species pools, there may be a net increase in diversity along with changes in community structure. In other areas, there may be little or no net change in numerical diversity but profound changes in community structure. In environments where the number of woody species spreading is low, their increase may result in virtual monocultures with little or no understory, leading in turn to profound decreases in plant and animal diversity. Regardless of numerical changes in species diversity, plants and animals endemic to grassland and open savannah ecosystems are threatened. Some obligate grassland species will be lost immediately in the early stages of encroachment (e.g., Fuhlendorf et al. 2002; Lautenbach et al. 2016), while others may survive until woody plant cover reaches critical thresholds (Archer 2010). Yet, other studies have found high

resistance of plant biodiversity to moderate native woody proliferation (Teleki et al., 2020). Despite these negative effects, some studies argued that, at low densities, the competitive effects of trees are more than compensated for by their facilitative effects. In their study of *Acacia karoo* trees in the Eastern Cape, South Africa, Stuart-Hill & Tainton (1987) showed that trees facilitate the growth of grass, due to increased shade and leaf litter.

Grazing can significantly alter the effects of woody plant proliferation on biodiversity. Reda et al. (2020), also assessed in their study the effect of land exclusion and age of enclosure on plant species richness, diversity, density and dominance were assessed, among other parameters. Their results indicate that exclusion in communal lands significantly improves species richness and diversity. The density of perennial species and the density of grass species increased with the age of enclosure. Herbaceous species richness, diversity and annual species density were higher in the young-aged enclosures than in the older enclosures. Woody species richness, diversity and density were highest in the older enclosures.

Fauna

In a global meta-analysis, Stanton et al. (2018) examined the effects of woody plant expansion on vertebrate diversity. To do so, they estimated relationships between the percentage of shrub cover and the structure of terrestrial vertebrate communities (species richness, Shannon diversity, and community abundance) in experimentally thinned and unmanipulated areas of woody vegetation within grassland-dominated biomes described in 43 studies published from 1978 to 2016. They evaluated influences by parameters such as continent, biome, mean annual precipitation, net primary productivity, and the normalized difference vegetation index (NDVI) on the relationship between woody vegetation cover and vertebrate community structure.

Their results showed that species richness, Shannon diversity, and total abundance had no consistent relationship with woody plant cover and that experimental thinning did not reverse revegetation effects on vertebrate communities. However, some effects of woody plant cover on vertebrate communities differed with net primary productivity, among vertebrate groups, and among continents. Woody plant proliferation had negative effects on vertebrate diversity when net primary productivity was low. Mammal and herpetofauna diversity decreased with woody plant expansion. Woody plant proliferation also had negative effects on species richness and overall abundance in Africa in some cases, but positive effects in North America. It should be noted that the coverage of the vertebrate groups studied varied across continents. Impact studies were collected for all groups in North America, for birds and mammals in Africa, for birds only in Europe and Australia, and for herpetofauna alone in South America. The number of studies considered also varied among biomes. In total, the researchers collected studies from eight biomes. Five biomes were the subject of one or two articles and the remaining three biomes were the subject of five or more articles.

Arthropods

In a study from 2009, Blaum et al. (2009) investigated the effects of woody plant proliferation on the abundance and diversity of different wingless arthropods. Abundance of ants (Formicidae), scorpions (Scorpiones) and dung beetles (Scarabaeidae) increased with shrub cover, whereas grasshopper (Orthoptera) and solifuge (Solifugae) abundance declined. Spider (Araneae) and beetle (Coleoptera) abundance, in particular, ground beetles

(Carabidae), darkling beetles (Tenebrionidae) and carcass beetles (Trogidae), exhibited bell-shaped responses to shrub cover with abundance maxima at shrub cover values between 15 and 18%. The authors did not detect a clear trend for termites (Isoptera) and stick insects (Phasmatodea).

Another study by Blaum's workgroup further strengthens the case that the increase of shrub cover is not always synonymous with land degradation (Hering et al., 2019). In this study, Hering et al. analysed the consequences of shrub encroachment for ground-dwelling beetles in a semi-arid Namibian savannah rangeland along a shrub cover gradient (<1% to >30%). They focused on species niche breadths and optima and identified two crucial shrub cover thresholds (2.9% and 10.0%), at which major changes in the beetle communities were observed with implications for savannah ecosystem functioning. Their findings showed that the niche optima of most species were between the first and second thresholds. Beyond the second threshold, numbers and diversity of saprophagous, coprophagous, and rare predatory beetles declined, which might have negative impacts on important ecosystem functions, such as decomposition and nutrient cycling. However, their findings also showed that certain species were adapted to high shrub cover, and that shrubs, especially in their early life stages, provided essential structures, which enhanced habitat quality for these ground-dwelling beetles.

Marquart et al. (2020) studied the drivers of invertebrate-derived macropore density in a semi-arid Namibian savanna. They found that individual shrubs and the amount of large scale grass cover increased macropore densities, which were highest at the beginning of the rainy season. They argue that ecosystem functioning is greatest when vegetation is very heterogeneous due to invertebrate diversity and activity.

Birds

Results on the impacts of woody plant proliferation on grassland and savannah bird diversity have been mixed. Species richness of birds has been found to increase (Pidgeon and Mathews 2001), peak at intermediate levels (Sirami et al., 2009), or remain unchanged (Kaphengst and Ward 2008). However, the effects of woody plant proliferation on grassland specialists is usually negative (Anderson and Steidl 2019).

The study by Sirami et al. (2009) found that bird species composition showed high turnover along the gradient of shrub cover, suggesting that widespread woody plant proliferation is likely to lead to the loss of certain species with a concomitant decline in bird species richness at the landscape scale. Finally, savannah bird species responded to changes in vegetation structure rather than vegetation species composition: bird assemblages were very similar in shrublands dominated by *Acacia mellifera* and those dominated by *Tarchonanthus camphoratus*. Hence, woody plant proliferation might have a bigger impact on bird diversity in grassland than in open woodland, regardless of the shrub species. These findings are in line with Skowno & Bond (2003), who also confirmed the importance of vegetation structure and vegetation composition on bird community composition.

The changes in vegetation structure can also have effects on the behavior of birds. A study by Bamford et al. (2009) found that African white-backed vultures *Gyps africanus* were reluctant to land at carcasses from which the angle required to pass over the surrounding vegetation on take-off was greater than 6°, while Cape vultures *Gyps coprotheres* were not observed on carcasses from which the required angle of take-off was greater than 4°. Hence,

high vegetation densities of woody plants might constrain the carcass utilisation by vultures since it may leave insufficient space for the vultures to take-off.

Mammals

It is a common assumption that increased woody plant cover will lead to a decrease in mammalian diversity in African savannahs. Two recent studies have tested this hypothesis with mixed outcomes. Soto-Shoender et al. (2018) analyzed the importance of grass cover for mammalian diversity and habitat associations across a gradient of bush encroached sites. They examined the fine-scale response of mammals using camera traps and a Bayesian hierarchical multi-species abundance model to estimate local relative abundance and species richness while accounting for imperfect detection. Contrary to their expectations, the relative abundance of only one species showed a negative relationship to shrub cover and another to tree cover. Nonetheless, the relative abundance of eight out of twenty-one species showed a positive association with grass cover. Mammal species richness increased with grass cover, decreased with shrub cover, and showed no clear pattern with increasing tree cover.

Schwarz et al. (2018) studied the influence of woody plant cover on the distribution of large herbivores in the Namibian Savannah. While one of the studied grazers (warthog) favoured sites with high grass cover, the distribution of the other grazer species (oryx), correlated positively with the presence of shrubs with a height of 80–150 cm. For the studied browser (kudu), only the interaction of site and grass cover was significant in their models, even though this was related to the occurrence of shrubs of 80–150 cm height. They concluded that the differences in vegetation cover did not influence herbivore distribution as expected and that other factors, such as human impact might be important drivers of habitat use.

Reptiles

Studies on the richness of reptiles and tortoises showed no significant trend in relation to increasing shrub cover at sites in the Kalahari (Blaum et al. 2007), Arizona (Castellano & Valone 2006) and Texas (Kazmaier et al. 2001). A study by Meik et al. (2002) found mixed responses of lizards to woody plant proliferation in central Namibia. During their survey, three arboreal (*Mabuya varia*, *M. striata*, and *Lygodactylus bradfieldi*) and one terrestrial species (*Pedioplanis undata*) accounted for 97,5% of all observations. One of the arboreal species (*Mabuya varia*) was only observed in savannah plots. The abundance of two species (*P. undata* and *L. bradfieldi*) decreased with increasing shrub cover, while the abundance of one species (*M. striata*) increased. Their findings also showed that arboreal lizards demonstrated an avoidance to invasive woody plant species. The authors concluded that the decreased diversity of habitat structure in bush-encroached habitats appears to influence native savannah lizard assemblages.

6. Plausible scenarios and risks under climate change

Dryland climatology is primarily controlled by interactions between general atmospheric circulation and regional topography (Nicholson, 2011) that affect atmospheric fluxes of precipitation and potential evapotranspiration. Besides these large scale processes, aridity is influenced by soil moisture feedbacks and plant physiological response to increasing CO₂ (Berg et al., 2016; Huang et al 2016).

In a recent study, Koutroulis (2019) tested the response of global drylands to different levels of global warming. For this purpose the transient response of aridity from the recent past until the end of the 21st century was examined as well as the expansion of global drylands under specific levels of global warming (1.5 °C, 2 °C and 4 °C). His findings showed that southern Africa is moving to drier states in all three tested scenarios, along with other dryland regions in western North America, the northern borders of western and eastern Asia drylands, Mediterranean and Australia.

Long-term temperature records from weather stations in Namibia and the Northern Cape show a mean decadal temperature increase of 0.2°C., roughly three times the global mean temperature increase reported for the 20th century (Midgley et al. 2005). This trend is expected to continue leading to a significant increase of mean temperatures, as well as extreme hot days until the end of the century.

Within Namibia, rainfall reductions are expected to be greatest in the northwest and central regions. Particularly strong reductions are expected in the central areas around Windhoek and surrounding highlands (Midgley et al. 2005). Projections range from small increases of less than 30mm per year to severe decreases of 200mm per year compared to current averages (Government of Namibia, 2002). Both rainfall and temperature in Namibia are sensitive to the El Niño-Southern Oscillation (ENSO), usually resulting in rainfalls below average during El Niño conditions. In the future, rainfall is expected to become even more variable than at present (Government of Namibia 2002).

Even if rainfall changes little from present levels, the water balance in Namibia is expected to become drier due to temperature increases, which will lead to an increase in evaporation rates. Government reports expect an increase in evaporation of about 5 percent per degree of warming (Government of Namibia 2002). If the projected decreases in rainfalls manifest themselves, Namibia is likely to face severe water shortages. More recent studies confirm that *“in southwestern Africa, the shift toward more arid conditions due to a decline in rainfall is exacerbated by temperature-driven increases in evapotranspiration”* (Fig. 6; (Serdeczny et al., 2017)).

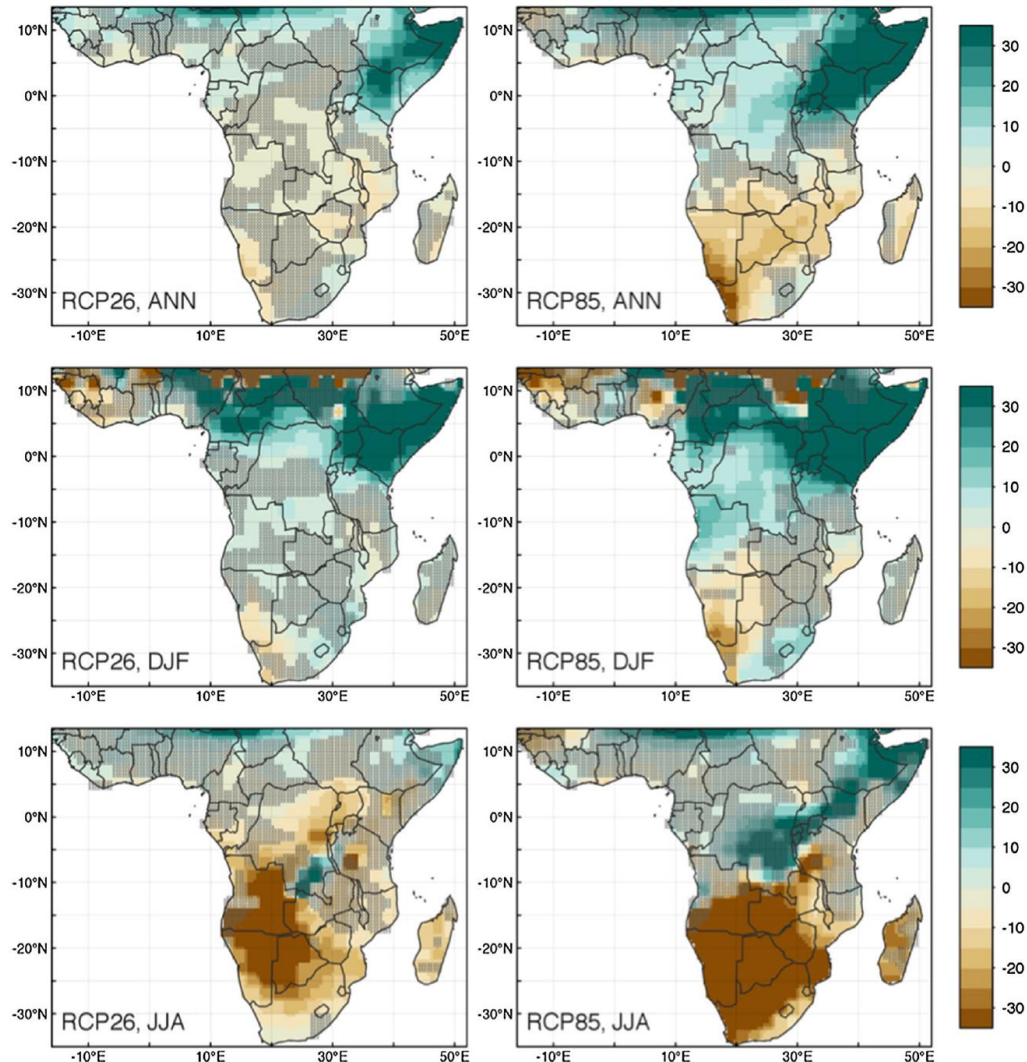


Figure 6 Serdeczny et al. 2017: “Multi-model mean of the percentage change in annual (top), austral summer (DJF—middle) and austral winter (JJA—bottom) precipitation for RCP2.6 (left) and RCP8.5 (right) for Sub-Saharan Africa by 2071–2099 relative to 1951–1980. Hatched areas indicate uncertainty regions with two out of five models disagreeing on the direction of change compared to the remaining three models” (Figure and caption have been adopted from Serdeczny et al. 2017).

Dixon et al. (2003) suggest that South African savannah and nama-karoo biomes will advance at the expense of the grasslands. Midgley et al. (2005) suggest that Namibia’s dominant vegetation type, grassy savannah, will lose its dominance to desert and arid shrubland vegetation types. They predict that vegetation cover will be reduced along with net primary productivity throughout much of Namibia by 2050. In models where savannah converts to grassland, four out of five savannah systems showed a 10 percent rainfall reduction, suggesting the presence of positive feedback from climate change (Hoffmann and Jackson 2000). Other models show that the tree-grass balance in savannahs may shift towards trees due to rising atmospheric CO₂ concentrations, and the resulting reduced ability of grasses to suppress rapidly growing tree saplings in grass fires (Bond and Midgley 2000; Bond et al. 2003). Midgley et al. (2005) predict that elevated CO₂ levels will further reduce the dominance of grassy savannah by 2080.

Future scenarios cannot be derived from past climate trends, yet, the findings of Rohde & Hoffmann (2012) on vegetation changes in Namibia since 1876, which are coinciding with the

onset of anthropogenic greenhouse gas emissions, are inconsistent with predictions of aridification resulting from global warming. While predictions of bush encroachment due to atmospheric CO₂ fertilisation could be corroborated by their findings, the relative influences of local (land-use) and global (atmospheric CO₂) drivers could not be disentangled.

Given the global scale of climate change, the changes of grassland-dominated biomes and the resulting threats to their endemic biodiversity should be treated as a global scale problem, and detailed prioritization schemes should be developed based on the available evidence. There remains a high degree of uncertainty regarding the future development of global drylands. In the following we try to summarize some of the likely effects of climate change on soils, micro and mesoclimates, ecohydrology, carbon stocks and flows, as well as biodiversity.

Soils

Climate change has the potential to affect dryland soils through various factors, including elevated levels of atmospheric carbon dioxide; elevated temperature; increased drought; increased precipitation and/or flooding; and increased fire frequency (Jansson and Hofmockel, 2020; Fig. 7). Although each factor can appear independently, it has to be emphasized that in most cases a combination of factors will interact; for example, heat waves can include both increases in CO₂ and temperature (Berard et al 2014) and there can be combined effects of drought and warming (Sheik et al 2011). This makes it difficult to predict if dryland soils will become a source or sink of greenhouse gases under future climate scenarios, due to unknown changes in soil carbon and nitrogen pools, and differences in microbial responses between soil locations.

Jansson and Hofmockel (2020) summarise the various responses of soil microorganisms to climate change as follows: *“Elevated CO₂ can result in an increase in carbon below ground due to increases in plant growth, with corresponding increases in soil microbial biomass and shifts in community composition. (...) in the long term, soil organic carbon (SOC) may decompose at a faster rate than it is formed. (...) Increased temperature can result in loss of SOC, shifts in bacterial and/or archaeal compositions and decreases in fungal abundance. (...) Drought can result in less decomposition of SOC, lower microbial biomass and less CO₂ production. Surviving bacteria may produce molecules to retain cell turgor (osmolytes) and/or enter a dormant physiological state (...). Under drought, fungal hyphae can be better suited to bridge disconnected soil pores and serve as a fungal highway for other microbial cells. Increased precipitation can increase water saturation and anaerobic soil zones. (...) sudden increase in water and nutrient availability in dry soils may cause some cells to burst and serve as a substrate for other cells to become more active (...), respire and produce CO₂ (Birch effect); there can also be some community shifts. (...). Fire results in a turnover of soil carbon and nitrogen stocks, reduction in microbial biomass, depletion of fungi and some community shifts.”*

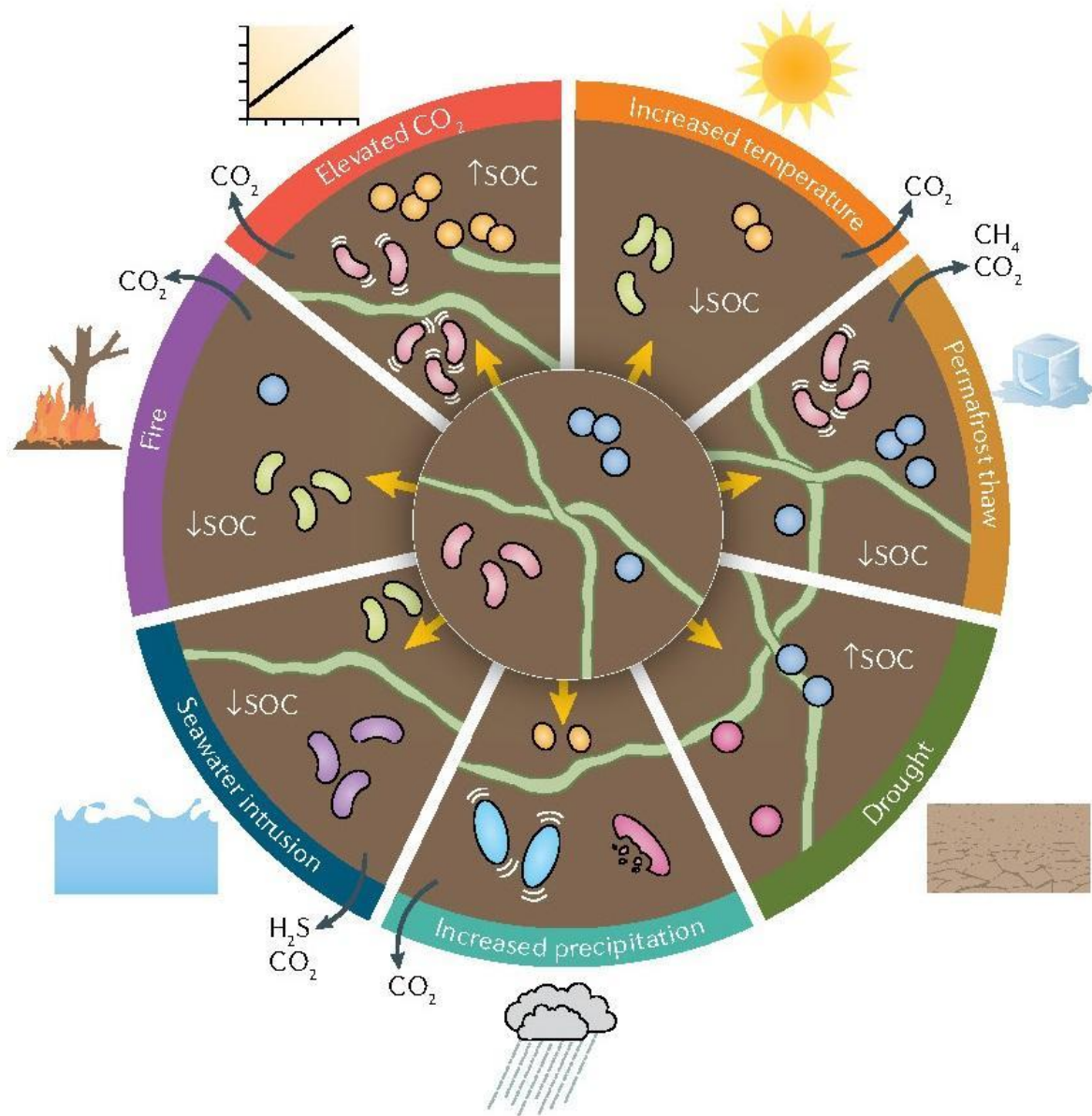


Figure 7 Jansson & Hofmockel 2020: “**Soil microbial responses to climate change**. A soil microbial community of bacteria, archaea (red and blue) and fungal hyphae (green) in the absence of climate change pressures is depicted in the centre. Examples of climate responses are shown at the periphery (note that changes in cell colour to orange, green or purple indicate a community shift). Increases or decreases in soil organic carbon (SOC) are indicated by up and down white arrows, respectively. White lines indicate increased microbial activity.(...)” (Figure and caption have been adopted from Jansson & Hofmockel 2020).

Micro and mesoclimate

The biophysical characteristics of drylands make them highly vulnerable to global change drivers, and to climate change in particular. Two components of climate change are of particular interest for drylands: the expected increase in temperature and the predicted changes in precipitation patterns. Climate change is expected to exacerbate the aridity of most drylands in southern Africa (Haensler et al 2011) and to lead to a decrease of water resources because of increases in the variability of rainfall and in the frequency and duration of droughts.

A study by Strydom et al. (2019) investigated the microclimatic trends of the semi-arid/arid environment of the Northern Cape Province, South Africa by analysing long-term (1982–2016)

historical daily meteorological data. Their findings indicate an overall warming of the study sites, with rates of change varying between 1 and 4 °C century⁻¹. The overall increase in annual average air temperature observed at the three studied sites was linked to daytime warming trends. Total annual rainfall, as well as atmospheric water vapour, was found to be decreasing at significant rates across the sites, with serious implications for livestock farming in the region. Model outputs of normalized difference vegetation index (NDVI), 0–100-mm soil water and the reflection coefficient, indicated that observed changes in the microclimate were not a consequence of terrestrial factors. The results of the study indicate that the microclimate of the dryland Northern Cape environment is changing, but at rates that are different to global and continental estimates.

These findings underline the high degree of uncertainty that still persists in predictions of micro and meso climate changes. Part of this uncertainty derives from the complex interactions of different components of the ecosystem. Shifts in biocrust community states have the potential to cause rapid alteration of dryland albedo and energy balance by returning energy to the atmosphere that was once absorbed by the dark biocrust surfaces (Matthias et al 2000).

Ecohydrology

Worldwide, drylands are threatened by decreasing mean annual precipitation (MAP) (Dore, 2005). Generally, the frequency of precipitation events decreases; however, the number of extreme events increases (Easterling et al., 2000). Moreover, higher temperatures are likely to intensify water stress through increased evapotranspiration (Hughes, 2003) and percolating rainwater will have to penetrate deeper before it is below evaporation depths (Ward et al 2013).

Woody plant cover can have a strong influence on soil and groundwater recharge through the alteration of various components of the hydrological cycle, including interception, transpiration, soil infiltration, and preferential flow (Brauman et al., 2012; Fan et al., 2014; Le Maitre et al., 1999). A recent study conducted in semiarid West Africa showed that moderate tree cover enhanced soil and groundwater recharge (Ilstedt et al., 2016). This effect has been attributed to the critical role trees play in improving soil infiltrability and preferential flow, mainly by enhancing macroporosity through root and faunal activity (Bargués Tobella et al., 2014).

A study in the Kalahari, Botswana (Thomas et al., 2018) showed that the most frequently occurring rainfall event at the study site was <5 mm, which infiltrated to relatively shallow depths of approximately 0.1 m. Deep soil moisture recharge was only observed after successive, large (> 20 mm) rainfall events, which are reported to occur much less frequent. A shift to more intense rainfall events would lead to greater soil moisture recharge accompanied by increased microbial activity, and potentially, the ability of plant roots currently only extending into dry subsoil zones to access new sources of moisture. Conversely, more rain days, with fewer large events, could favour grasses (and biocrusts), delivering water to only shallow depths.

Previous studies have shown that in arid and semiarid environments, only heavy rainfall events contribute significantly to the recharge of soil and groundwater, whereas small rainfall events result in no or little percolation (Owor et al., 2009; Taylor et al., 2013). However, the degree of preferential flow seems to decrease with increasing distance to the nearest tree stem and was found to be higher in small compared with large open areas (Bargués-Tobella et al., 2014). This suggests that, in small open areas, higher rainfall intensities lead to enhanced recharge of soil water. In contrast, increasing rainfall intensities in large open areas

did not result in higher soil water recharge but likely led to more infiltration- excess overland flow (Bargués-Tobella et al., 2020). Especially if evaporation increases as a result of global warming.

At the same time, increased atmospheric CO₂ could mitigate these effects directly by higher photosynthetic rates of plants, and indirectly by enhancing the water use efficiency (Bazzaz 1990; Drake et al., 1997). However, the relative magnitude of this effect varies among plant types, so that species composition can shift considerably. These potential changes in vegetation cover and species composition will in turn strongly feedback on the water balance. Plants may facilitate their own growth by promoting infiltration, by decreasing run-off water as a result of higher surface roughness, and by preventing nutrient losses due to erosion of the topsoil (van de Koppel et al., 2000). Additionally, shading by plants leads to reduced evaporation and thereby improves the storage efficiency of shallow soils.

Tietjen et al. (2009) developed a coupled water-vegetation model for drylands to explore the effects of climate change on soil moisture and vegetation cover. Their model combined an ecohydrological approach that accounts for the intensity and duration of single precipitation events, as well as the resulting dynamics of grasses and shrubs and allowed to evaluate separate and combined effects of increased temperature and atmospheric CO₂ on water and vegetation. They applied this model to a Namibian thorn bush savannah and tested different climate change scenarios. The response of the vegetation to the different parameters varied. A decrease in MAP and an increase in temperatures led to lower vegetation cover (Figure 8). More variable and extreme precipitation within 1 year had little effect on soil moisture in the upper layer, or grass cover, but a positive effect on shrub cover. The combined effects of an elevated atmospheric CO₂ level, i.e. higher transpiration efficiency and increased growth rates, were ambiguous. Soil moisture was unaffected, grass cover declined and shrub cover increased.

The combined effects of the four possible climatic changes are given in Figure 9. Simulation results showed decreasing soil moisture in both layers. Especially, the upper 20 cm of the soil desiccated, but also the deeper soil was considerably drier. Even in the wet season, mean soil moisture remained at the critical plant specific wilting points, i.e. plants close their stomata in response to water stress. The response of the two plant types to this increased stress was diametrical: while grass cover strongly declined, shrubs benefited from the reduced competitive situation. This can even shift the savannah from a grass dominated ecosystem to a shrub-dominated system. If only transpiration efficiency was increased and growth rates of shrubs and grasses remained constant, this effect was mitigated: the decrease in grass cover is reduced, and shrubs lose their competitive advantage. In case of an additional increase in shrub growth without an increase in grass growth, the effects of climate change are exacerbated and grasses are reduced to a cover of less than 10%.

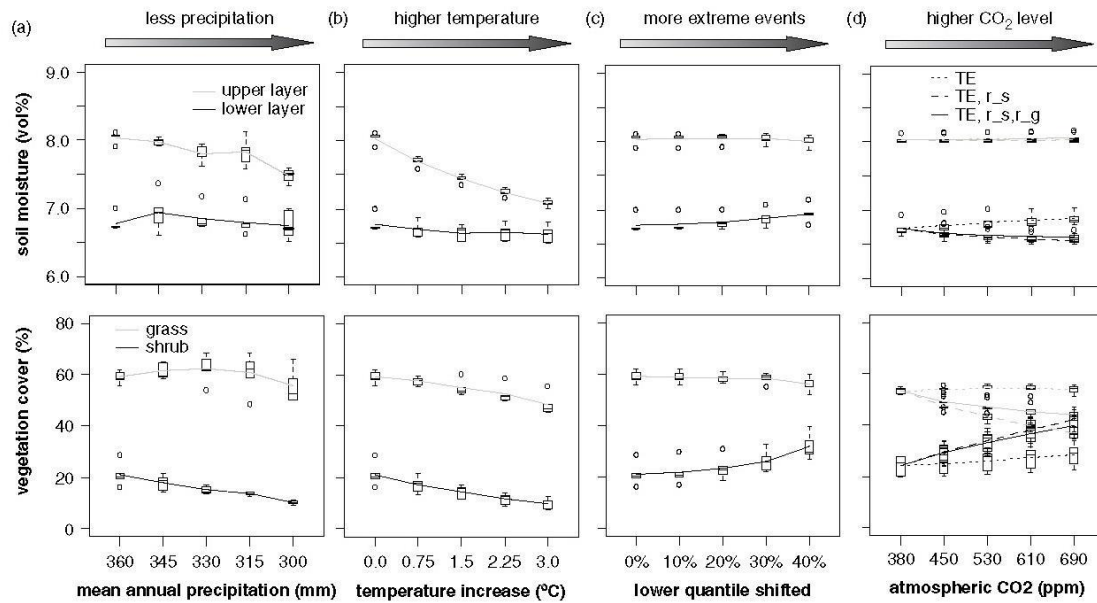


Figure 8 Tietjen et al 2009: “Effects of climatic change parameters on soil moisture and vegetation cover (box plots on simulated years 81– 100). Effects of (a) decrease in precipitation, (b) increase in temperature, (c) increase in extreme events, and (d) increase in atmospheric CO₂, with abbreviations TE: increased transpiration efficiency, r s: increased growth rates of shrubs, r g: increased growth rates of grasses.” (Figure and caption adopted from Tietjen et al 2009).

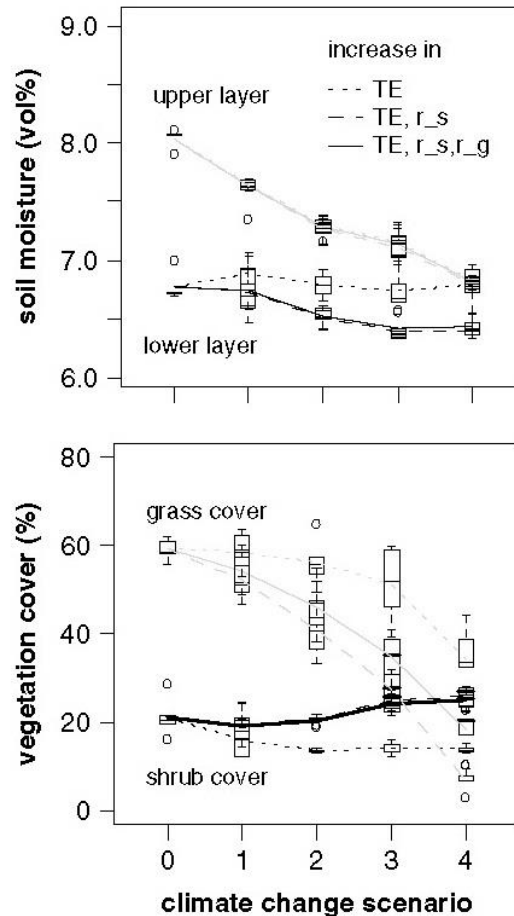


Figure 9 Tietjen et al 2009: “Combined effects of climate change on soil moisture and vegetation cover (scenarios see Tab. 3: 0 no change, and 4: the strongest change). Abbreviations: TE: increased transpiration efficiency, r s: increased growth rates of shrubs, r g: increased growth rates of grasses.” (Figure and caption adopted from Tietjen et al 2009).

These findings show that there remains a high degree of uncertainty on how the dryland ecosystems will respond to climate change; nevertheless, it is sufficiently clear that conditions for ecosystem functionality and usability will dramatically change.

Carbon stocks and flows

Recent studies have shown that dryland ecosystems dominate the global terrestrial carbon sequestration trend and largely contribute to the interannual variability in atmospheric CO₂ concentrations over the past decades (Smith et al., 2019, Yao et al., 2020). Several studies have also suggested that dryland ecosystems have strong C sequestration potential (Tagesson et al 2016, Kou et al 2018, Abdi et al 2019). However, the lack of systematic field inventories have led to considerable uncertainty in documenting patterns of carbon stocks, and their long-term change over the African continent (Ciais et al 2011, Williams et al 2007).

The African continent is facing one of the driest periods in the past three decades as well as continued deforestation, with large impacts on vegetation carbon (C) stocks. A study by Brandt et al. (2018) documented the recent climate-induced carbon losses in African drylands by using a satellite dataset based on vegetation optical depth derived from low-frequency passive microwaves (L-VOD) to quantify annual aboveground biomass-carbon changes in sub-

Saharan Africa between 2010 and 2016 (Fig. 10). The overall net change in drylands (53% of the land area) was -0.05 petagrams of C per year (Pg C yr^{-1}) associated with drying trends, and a net change of -0.02 Pg C yr^{-1} was observed in humid areas (Fig. 11). These trends reflect a high inter-annual variability with a very dry year in 2015 (net change, -0.69 Pg C) with about half of the gross losses occurring in drylands and the highly dynamic and vulnerable carbon pool of dryland savannahs for the global carbon balance, despite the relatively low carbon stock per unit area.

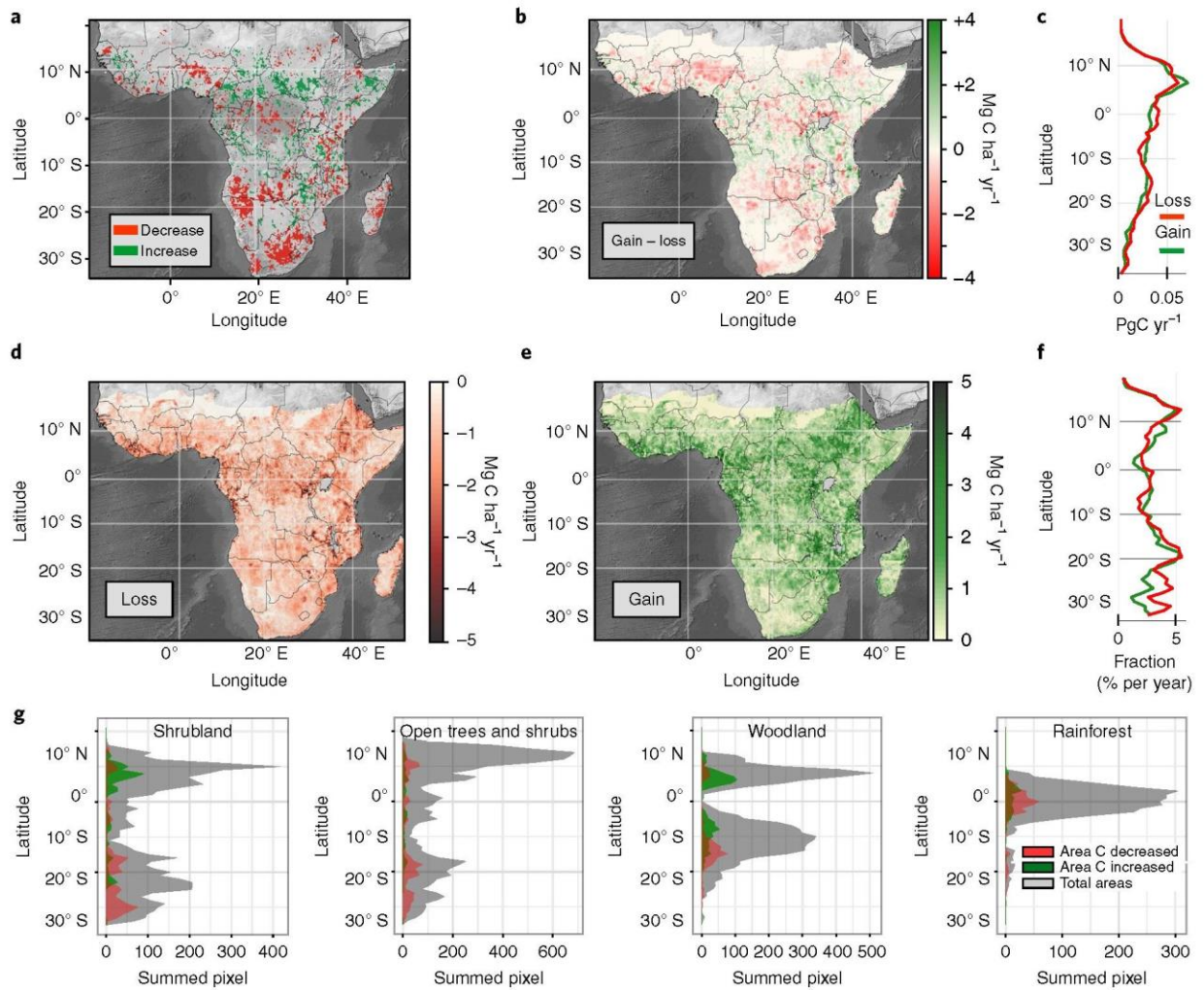


Figure 10 Brandt et al 2018: “**Changes in carbon stocks for 2010–2016.**a, Pixels with significant ($P < 0.05$) positive (green) and negative (red) changes (linear trend; $P < 0.05$) in L-VOD as a proxy for aboveground carbon density for the 2010–2016 period. b, Net changes in carbon density ($n = 26,711$) between 2010 and 2016. c, latitudinal sums of gross losses and gains. d, Cumulative gross losses (time integral of losses) in carbon density. e, Cumulative gross gains in carbon density (time interval of gains). f, Fractional gross losses and gains per year in the L-VOD data averaged per latitude. g, Areas affected by significant ($P < 0.05$) positive (green) and negative (red) changes in L-VOD carbon density 2010–2016 summed per latitude band.” (Figure adopted from Brandt et al 2018).

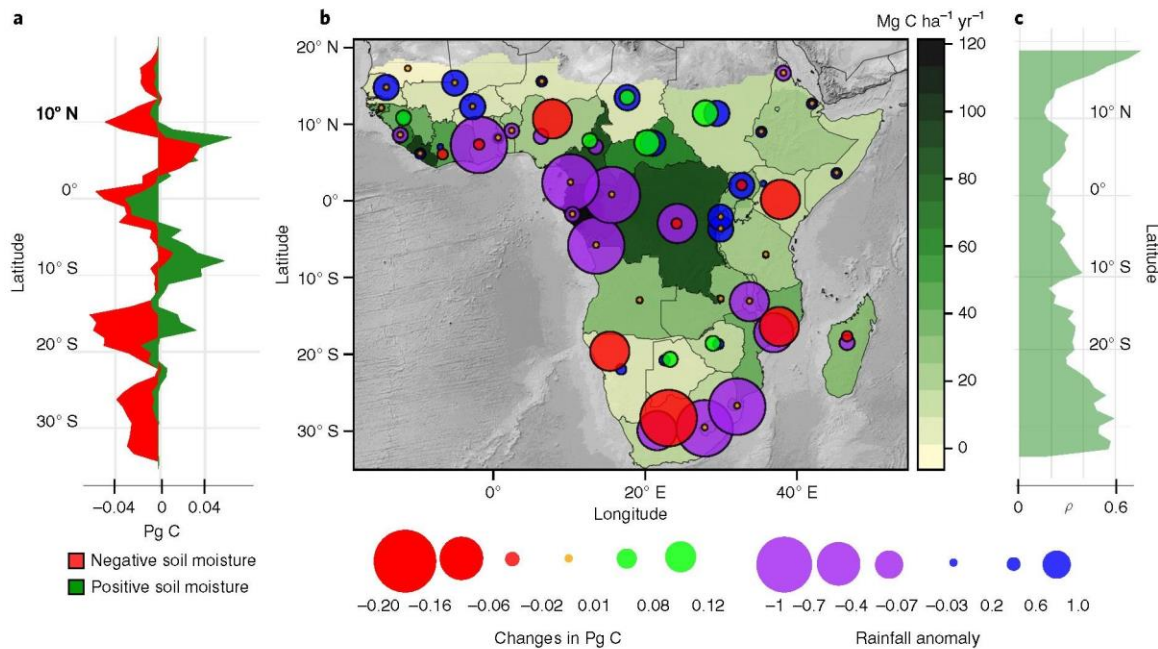


Figure 11 Brandt et al 2018: “**Climate as a driver of carbon stock dynamics.** a, Direction and magnitude of net carbon change for 2010–2016 (summed per latitude) are shown for areas with positive (green) and negative (red) linear trends in soil moisture (2010–2016). b, Average carbon density (in Mg C ha⁻¹) and net carbon change for 2010–2016 summed for each country (in Pg C). Anomalies in annual rainfall (2010–2016 compared to 1981–2016) averaged for each country are shown as purple (negative anomaly) and blue (positive anomaly) circles. c, Correlations between annual carbon stocks and annual soil moisture (shown as Spearman's ρ , $n = 26,711$) averaged along the latitudes.” (Figure adopted from Brandt et al 2018).

These findings are in line with a recent study by Dintwe and Okin (2018), who predicted that soil organic carbon in the Kalahari savannahs will decrease with anthropogenic climate change. The authors used the Century model to analyse how net primary productivity (NPP), soil respiration and soil C sequestration would respond to an increase in atmospheric CO₂ and soil temperature. In addition, they assessed the coupled effects of precipitation and temperature change on C dynamics under future climatic conditions, as well as the decoupled effects of each of the climate variables under three IPCC climate scenarios. In their study, an increase in soil temperature resulted in loss of soil organic C (SOC), whereas doubling atmospheric CO₂ concentration caused an increase in SOC. The increase in air temperature caused soil respiration to increase, while causing a decrease in NPP. They calculated the total SOC in the Kalahari savannahs to be 0.9 Pg C (1 Pg = 10¹⁵ g) in the top meter, and the rate of SOC loss due to anthropogenic climate change to be ~ 1.1 Tg C yr⁻¹ (1 Tg = 10¹² g) and ~ 2.0 Tg C yr⁻¹ under RCP2.6 and RCP8.5, respectively until the end of this century. The authors concluded that the rapid loss of C from dryland soils predicted by Century could accelerate global warming and strengthen positive feedback mechanisms between climate change and processes controlling SOC. Such positive feedbacks, like the one between the SOC and atmospheric carbon cycles, are currently not adequately accounted for in existing Earth System Models (ESM).

Species diversity

Dryland plants live on the brink of their physiological limits for water and temperature stress. Consequently, any alteration of the climate will impact the abundance of species substantially (Munson et al., 2011; Archer & Predick, 2008, Ulrich et al., 2014).

Yet, elevated levels of atmospheric CO₂ could mitigate the effects of projected climate aridification by increasing water use efficiency, especially in C3 plants (Ward, 2010). In their analysis of potential drivers of woody plant proliferation, Archer et al. (2017) provide a detailed review of the potential effects of climate change on this phenomenon: *“Atmospheric CO₂ concentrations have increased substantially during the twentieth century, from ~290 ppm at the beginning to ~380 at the end. Within this range, photosynthesis in C3 plants is CO₂ limited, hence, it is possible that rising atmospheric CO₂ has benefited C3 woody plants more than C4 grasses. A doubling of atmospheric CO₂ from 350 to 700 ppm typically results in a 30–50 % increase in the carbon assimilation rate of C3 plants under optimal conditions. In contrast, C4 plants are not affected directly by atmospheric CO₂ because they concentrate CO₂ at the carboxylation sites to substrate saturation. Still, C4 plants often receive a growth advantage through partial stomatal closure, which increases their water-use efficiency in water-limited environments. At the whole-plant level, elevated atmospheric CO₂ can elicit a wide range of growth responses depending on other co-limitations including other resource limitations (light, nitrogen, water), stress conditions (heat, frost), crowding, and species differences in growth and reproductive strategies (Körner 2006). As a result, a community may contain many species that show no response to elevated CO₂ at all.*

Therefore predictions about the effects of CO₂ enrichment should be made cautiously and in the context of other drivers and constraints. Woody (...) plants are composed overwhelmingly of C3 plants. By contrast, grasslands and savannahs in tropical, subtropical, and warm-temperate biomes often are dominated by C4 grasses. (...) Woody plants have other structural and functional advantages over herbaceous vegetation, which increase their ecological opportunities under accelerated growth conditions (Poorter and Navas 2003). Whereas herbaceous plants lose most annual biomass accumulation to herbivory, combustion, or decomposition, woody plants build up woody biomass and carbohydrate storage over decades, thereby strengthening their ability to persist in the face of stress and disturbance. Woody plants are most vulnerable to injury, physiological stress, and competition when they are small, and faster growth would expedite their transition to more resilient and competitive life stages. Global vegetation models have solidified support for the connection between atmospheric CO₂ and “woody thickening,” both within woodlands and forests and through the expansion of woodlands into grasslands.”

According to Marston et al. (2019), the predicted changes in precipitation patterns will have important implications for the future of savannah mosaics and their conservation importance in the context of climate change. They argue that the predicted precipitation reductions in southern Africa and increases in eastern Africa presented by Shongwe et al. (Shongwe et al., 2011, 2009) will likely result in increased homogeneity in southern African savannahs, with increased grassland dominance (Sankaran et al. 2005). In eastern African savannahs, heterogeneity is likely to be maintained at 600–1400 mm precipitation levels, but will decrease at >1400 mm, with increasing tree cover at these higher precipitation levels (Sankaran et al. 2005). Higher mean annual temperatures would also see increased savannah heterogeneity

between 18 and 23° C, while at extremes of >25° C the pattern will reverse, resulting in reduced heterogeneity. Consequently, savannahs at the upper extremes of the mean annual temperature range are likely to experience reductions in the number and types of patches in savannahs, and the surviving patches will be highly clumped.

7. Plausible scenarios and risks under climate change and biomass extraction

Woody plant proliferation has long been a problem for pastoralists where cattle and sheep grazing is the primary land use. More than half a billion people depend on livestock grazing for food (e.g. milk, meat, fuel), shelter and financial security, and therefore to sustain their livelihoods (Campos et al., 2018). Woody plant proliferation has the potential to threaten the social and ecological viability of pastoral enterprises and pastoral land management has aimed to maximize pastoral productivity, while maintaining a stable ecosystem (Blake et al., 2018). Where funds and equipment were available, management focused narrowly on reversing woody plant encroachment with the goal of increasing livestock production (Eldridge & Soliveres 2015).

Bush management has been applied aggressively since the 1940s, but results have been mixed, and its sustainability and cost-effectiveness questionable (Rango et al 2005). As we gain a broader understanding of how woody plant proliferation influences ecosystem processes and affects a broad portfolio of ecosystem services, we are better positioned to evaluate trade-offs that must be considered as their abundance changes. Increasing evidence suggests that the positive effects of woody plant proliferation might far outweigh the perceived negative effects (Maestre et al., 2016). More recent global-scale field studies (Soliveres et al. 2014) and regional syntheses (Eldridge & Soliveres 2015) indicate that plant diversity and multiple ecosystem functions are maximized under moderate levels of woody plant cover. There will likely also be co-benefits of thickening vegetation for flora and fauna (Dwyer et al. 2009).

In a recent global meta-analysis, Ding and Eldridge (2019) explored the effects of woody plant removal on ecosystems. Their analyses of 263 publications revealed that the overall effect of removal varied among different ecosystem response variables, with increases in composition (e.g., grass richness), reductions in structure (e.g., biocrust cover, woody plant cover and density), but no effects on function (e.g., increases in grass biomass, which compensated for reductions in soil roughness and shrub biomass). The outcomes of woody plant removal depended strongly on environmental context and woody plant traits, with removal more effective in mesic areas, but varied depending on both aboveground and belowground traits of the plants (e.g. plant shape, root types). Reports in the literature suggest a disconnect between effects on woody plants and ecosystem processes. While the effectiveness of woody plant removal was relatively short-lived (i.e. within 5 years), legacy effects on ecosystem function were generally large, negative, and lasted for up to 10 years (Archer et al 2011, Chief et al 2012). Their *“results highlight the wide disparity in removal outcomes, and reinforce the notion that the impacts of removal are strongly context dependent, vary with treatment methods, and generally ecologically undesirable in the long term. As climate changes, woody plant removal could become less effective due to drier climates and increased woody expansion. Treatment methods should be targeted to specific management goals (e.g.,*

pastoral production or ecosystem conservation), and particular ecosystem outcomes (e.g. ecosystem structure, or function or composition) to improve the efficiency of woody removal in global savannahs under the changing climate.”

There exist a variety of debushing and tree felling methods in Namibia (de Wet, 2015). Each method has its own specific impacts on soils, vegetation and animals. For the purpose of this study we concentrate on the method that is likely to be implemented for biomass harvest. Bush clearing for biomass harvest is a highly mechanised process that involves the use of heavy machinery such as skid steer harvesters, three wheel loaders, hydraulic grabs and shuttle buckets that can have significant impact on soils. The top soil layer is often damaged during the biomass removal and sometimes even removed completely. This has a negative impact on soil fertility and can increase soil erosion, especially during heavy rainfall events. The tools used for harvesting, such as horizontal rotary cutters, circular saw blades and grinders, generate high noises during their use, which are likely to have an impact on animals through noise pollution and human disturbance. Nonetheless, this process might be preferable to chemical debushing, which is currently the most common method used in Namibia with devastating effects on flora and fauna.

Soils

As mentioned in the previous section, the impact that debushing and bush thinning will have on soils depends on the specific method that is being implemented. Again, here we concentrate on the heavily mechanised process. This process is associated with the removal of the topsoil layer and usually soil compaction. This alone will have a negative impact on the soil health. Apart from the obvious damages to the soil structure there are two other aspects.

On the one hand, the removal of woody plants would result in a long term overall nutrient loss from the soil, since the nutrients locked up in the wood would be removed along with the wood plants. Scholes and Walker (1993) analysed the nutrient changes in soils after the removal of *Burkea africana* trees in a broadleaf savannah in South Africa. They found that harvesting and removal of the wood biomass led to a disruption of the nutrient cycle and a reduction of soil Nitrogen, Phosphorous, Sulphur, Calcium, Magnesium, Potassium and Sodium.

These negative effects were also reported by Zimmermann et al. (2017), who studied the effects of debushing on farms of the Cheetah Conservation Fund in central Namibia. They collected soil samples of uncleared, partially cleared and totally cleared land and conducted bioassays by growing barley (*Hordeum vulgare*) and *Moringa oleifera*. Their results demonstrated that the 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. They did not find any evidence of restoration of soil fertility, even 13 years after debushing and concluded that nutritious grass is unlikely to grow well after debushing. The spectacular flush of grass that often follows debushing is usually short-lived, probably declining as organic material from dead leaves and twigs become depleted, as demonstrated by the lower soil fertility found even in sites that had been debushed only two years earlier.

On the other hand, debushing is likely to increase erosion, especially if the number of heavy rainfall events will increase, as projected by future climate scenarios. If rainfall occurs in a bush cleared area soon after harvest, soil capping is likely to result, especially in heavier textured soils, since there is no protection from rain-splash impact. This would not only result

in soil erosion and also lower grass yields, since less water is penetrating the soil (Joubert and Zimmermann, 2002). Some of the negative effects on soils could be reduced by adapting the harvesting methods to the soil conditions. For example, during partial debushing in very sandy soils, the remaining strips could be aligned at right angles, to reduce evaporation and wind 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).

The removal of woody vegetation also affects soil microbial communities. Buyer et al. (2016) found that soil under bush had higher pH, Carbon, Nitrogen, and microbial biomass than under grass, and the microbial community structure was also altered under bush compared to grass. The removal of the woody vegetation presented a major disturbance to the ecosystem and resulted in an altered microbial community structure compared to control plots. However, the magnitude of this perturbation gradually declined with time and after 3–9 years the system recovered to a state resembling that of undisturbed grass in a bush-encroached savannah.

Micro and mesoclimate

The multiple effects of woody plants on micro and mesoclimate have been described in detail in previous chapters. Trees and shrubs often function as temperature buffers within the landscape, with cooling effects during daytime and warming effects at night. Woody plants are likely to have an impact on regional heat balances, due to their lower albedo, compared to grasses. In addition, shading from tree and shrub canopies usually leads to a reduction of soil moisture evaporation, wind permeability, air movement, and convection, which effects ecohydrology and erosion processes.

As has been mentioned before, the biophysical characteristics of drylands make them highly vulnerable to climate change. Increasing temperatures and variability in precipitation are likely to have significant impact on drylands in the future.

The removal of woody plants has the potential to further exacerbate the temperature extremes in the landscape. Whether the removal of woody vegetation has an effect on local and regional rainfalls, and if so to what degree, has been the subject to debate. Less debate exists regarding the changes in dryland albedo and energy balances, where the removal of woody plants will most likely causes an increased absorption of dark biocrust surfaces (Matthias et al 2000).

Ecohydrology

A meta-analysis by Ding and Eldridge (2019) did not find a significant response of soil hydrology to woody plant removal. This finding is contrary to the prevailing notion that removal of high water consuming plants will result in greater infiltration (Eldridge et al., 2015). The most parsimonious explanation is that removal disrupts the hydrological connectivity created by shrub islands (mosaics), leading to greater water loss (Okin et al., 2015).

Woody plant removal reduced ecosystem function (e.g., reduced hydrological function) for up to 10 years, particularly after browsing or the use of multiple methods. For example, a study

in the Chihuahuan Desert (Perkins and McDaniel, 2005) showed that soil infiltration declined 15–18 years after removal.

Carbon stocks and flows

Global drivers such as elevated atmospheric CO₂ favour woody thickening in grassy savannahs regardless of land-use (Wigley et al 2010). The carbon stocks of savanna-like landscapes are composed by the biomass of grasses, woody plants, litter, organic soil carbon and soil microorganisms. The removal of woody plants will lead to a decrease in woody biomass and an increase in grass biomass (Fig. 12). Litter biomass and organic soil carbon showed mixed outcomes in a global meta-analysis (Ding and Eldridge 2019). The effects woody plant removal on the overall carbon stocks are dependent on a variety of local factors, hence generalizations should be avoided. Although woody plants are crucial sinks for carbon and nitrogen (de Graaff et al., 2014), Eldridge and Ding (Eldridge and Ding, 2021) did not find evidence of a consistent effect on biotically-derived nutrients after removal. This may relate to the fact that the fertile island effect is known to persist for many years after removal of woody plants (Bechtold and Inouye, 2007).

Species diversity

The effects of bush extraction and climate change will depend on the extent of the bush harvest. While moderate harvest might have a positive effect on biodiversity, large scale removal of woody plants would have strong negative effects, directly on the woody plants, as well as on arboreal species, including cavity users and species that require micro habitats and shelter provided by woody plants. Hence, large scale removal might lead to local extinctions of species.

A global synthesis by Ding and Eldridge (2019) showed that woody plant removal resulted in a net increase in composition, reduction in structure, but an equivocal effect on function (Fig. 12). The authors state their findings as follows: *“Ecological attributes also exhibited a range of different responses. For ecosystem structure, woody plant removal resulted in substantial declines in biocrust (66%) and woody plant cover (55%) cover, and woody plant density (43%). Herbaceous plant cover (19%) and density (35%) increased with woody plant removal. Most functional attributes (e.g., soil functions) showed non-significant responses, though soil roughness (47%) and shrub biomass (29%) declined markedly, while grass biomass (30%) and runoff (56%) increased. The positive response of ecosystem composition to woody plant removal resulted mainly from increases in tree (14%) and grass (23%) richness. Woody plant removal had no significant effect on shrub species richness nor animal richness, but a net positive effect on ecosystem composition by increasing plant species richness.”*

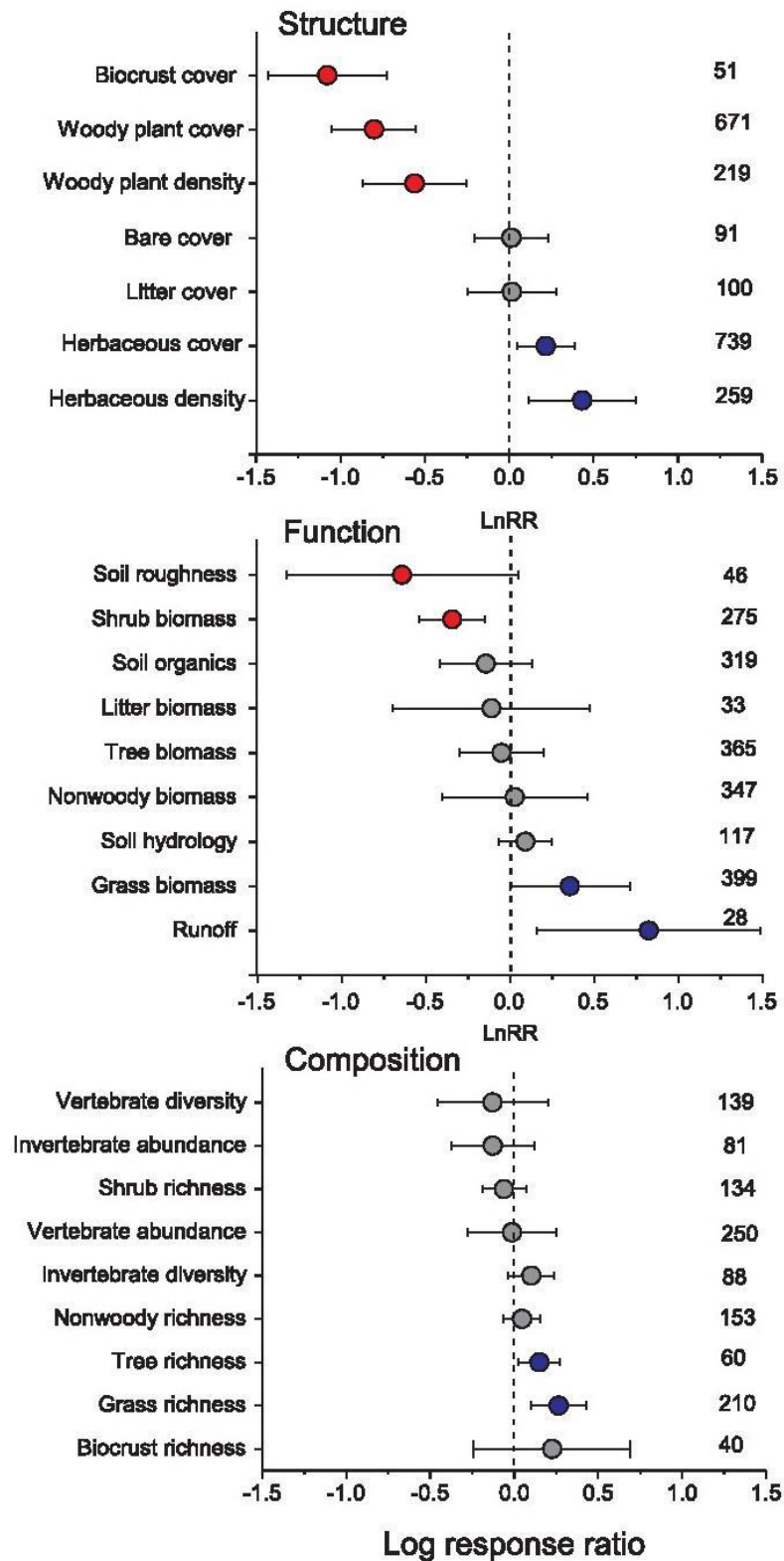


Figure 12 Ding & Eldridge 2019: "Response of ecological attributes in ecosystem structure, function and composition. Numbers indicate the number of studies. Significant results are shown in red (negative) and blue (positive), and error bars represent 95% confidence intervals. Sample sizes are indicated." (Figure and caption adopted from Ding & Eldridge 2019).

Woody plant removal generated pronounced and consistent ecosystem effects (i.e. decline in structure, increase in composition), but only in mesic areas, reinforcing the notion that removal is less effective in arid environments due to less reliable rainfall, lower ecosystem resilience and a generally more protracted recovery from disturbance (Maestre et al., 2016).

Ding & Eldridge (2019) describe their findings as follows: ... *“the effectiveness of woody plant removal was relatively short-lived, with either reductions in structure (e.g., reduced woody cover and density) or increases in composition (e.g., increased tree and grass richness) generally diminishing within 5 years of treatment, extending the narrow scope of Archer et al. (2011) to the global scale. At the same time woody plant removal has the potential to induce long-term legacy effects by altering ecological processes that are irreversible in the long run.*

First, removing woody plants could alter the succession process by changing plant composition (e.g. the proportion of C3/C4 species or palatable species), which directly affecting ecosystem productivity and resilience (Van Auken, 2000). Second, woody plant removal could alter hydrological processes by changing soil properties (Redmond et al., 2013), for example, by reducing water-stable aggregation or destroying soil structure due to removal disturbance (e.g. browser trampling) (Perkins and McDaniel, 2005; Daryanto and Eldridge, 2010). Third, removal could alter landscape connectivity by changing the distribution of resource shedding and resource accumulating patches (Schlesinger et al., 1990). For example, Nolte et al. (1994) showed that spatial heterogeneity declined when shrubs were physically removed by root ploughing, resulting in reductions in β -diversity. Ecosystem composition (e.g., plant richness, fauna diversity) can also be negatively affected by burning in the long-term (> 10 years). For example, Killgore et al. (2009) showed that invertebrate and vertebrate diversity (e.g., spider, termite, burrows) declined in burned areas with rapidly regenerated shrubs in an arid area of New Mexico. Fire can promote shrub regeneration by enhancing the dispersal of shrub seeds or reducing reestablishment of herbaceous species, and alter habitat quality by reducing soil organic matter weakening biological activity (Armas-Herrera et al., 2018).”

A study by Stanton et al. (Stanton et al., 2018) indicates that reducing factors that facilitate shrub encroachment, such as overgrazing, would be most effective in maintaining historic vertebrate diversity in desert grasslands and semi-arid savannahs. Their findings also indicated that shrub thinning has been ineffective in reversing shrub encroachment effects on vertebrate communities, at least at the spatial and temporal scales studied to date. Therefore, prevention and mitigation measures may be more effective than restoration.

Effects of debushing and bush thinning on mammals

According to Joubert & Zimmermann (2002), the thinning of bush thickened areas is very likely to result in a shift in the proportions of game species. They expected that *“populations of browsers or species that require dense cover for predator evasion (kudu, giraffe, eland, Damara dik-dik, duiker and steenbok) are likely to decline, unless some dense patches are maintained. Plains species and grazers (e.g. blue wildebeest, zebra, warthog, oryx and red hartebeest), which rely on fleet footedness in evading predators, may be favoured (DFN, 1997). Complete, or almost complete removal of trees will effectively reduce the carrying capacity of the area in question, since the browse component will be absent.”* Excessive bush thinning denudes landscapes from vegetation; thus, ungulate abundances may decline (Isaacs et al., 2013).

Yet, recent field studies analyzing the animal distribution of cleared and uncleared sites did not always match these expectations. In a study from 2018, Stolter et al. (2018) analyzed the impact of bush encroachment management on plant response and animal distribution. They hypothesized that the grass distribution would drive the animal distribution and that typical grazers (e.g., warthog and gemsbok) would be found at open cleared sites, while typical browsers (greater kudu) would be found in encroached regions. While warthog and cattle shared open bush-cleared sites, they found gemsbok utilizing non-cleared sites with high thornbush cover of medium height, which was similar to patterns shown by greater kudu. Apparently, other factors such competition, risk avoidance and habitat heterogeneity played an important role in animal distribution.

In an analysis by Nghikembua et al. (2020), the response of small, medium and large ungulates, as well as meso and large predators to bush thinning operations on three freehold farms in Namibia were assessed. Bush thinning only had a significant effect on the presence of large predators. The capture rates of small, medium, and large ungulates and meso predators were not significantly different between treatments.

Joubert & Zimmermann (2002) assumed that the negative effects might also apply to many small mammals that use woody plants for shelter and breeding, such as small spotted genets, Egyptian free tailed bats, Cape serotine bats, South African lesser bushbabies and black-tailed tree rats and woodland mice (Skinner and Smithers, 1990). The importance of woody plant understory for small mammals may increase as climate change progresses.

The purpose of the woody plant removal would be to increase the carrying capacity of the grasslands, hence the process will most likely lead to an intensification of the land use. Starik et al. (2020) analyzed the effects of land use intensification on small mammals in North-Central Namibia. They found that the reduction in the structural complexity (decrease in the degree of vegetation cover, soil compaction) accompanied by an increased grazing pressure reduced the quality of the small mammal habitat and led to a decrease in species richness. A phenomenon that has been described in several previous studies (Hauptfleisch et al 2017, Muck & Zeller 2004, Erckie 2007). In addition, they discovered that land use intensification led to an imbalance within the mammal community and a dramatic increase in a few pest species has the potential to threaten human livelihoods (e.g., crop damage, disease vectors).

Effects of debushing and bush thinning on bird species

Joubert and Zimmermann (2002) analyzed the effects of wood harvesting and greening on bird species, which have been recorded for the area around Otjiwarongo, Namibia by Gibbons and Maclean (Gibbons and Maclean 1997). 141 of the described bird species of this area nest in forks of branches, while approximately 44 species nest in cavities in trees (Gibbons and Maclean, 1997). Excessive removal of trees would reduce nesting space for both branch fork and cavity nesters and negatively impact bird species diversity. The authors also analyzed the effects on six game bird species, namely francolin (Crested, Coqui, Swainson's, Orange River, Hartlaub's and Red-billed) and one species of Guinea Fowl (Helmeted). They concluded that only the Orange River Francolin might be favoured by the complete, or almost complete, removal of woody plants. The others, including the endemic Hartlaub's Francolin, all require either some tree cover or patches of dense bush for cover from predators. While wood plant harvest, with the inclusion of patches of dense bush, should maintain healthy populations of these species, excessive, or complete, removal of bush will lead to the local extinction of these

species. This would also reduce the potential for game bird hunting, an economically important form of tourism that can contribute to the diversification of agricultural economies.

Effects of debushing and bush thinning on reptiles and invertebrates

The trends for reptiles and invertebrates are likely to be the same as for small mammals and birds. Arboreal reptiles, e.g. some *Mabuya* and many lacertid genera such as *Nucras* and *Ichnotropis*, depend upon woody plants for cover from predators, thermoregulation, as well as microclimatic conditions and litter beneath trees and shrubs. Complete thinning will eliminate the arboreal niches, whilst thinning, pruning and the maintenance of patches will increase habitat heterogeneity and thus might have a positive effect on species diversity (Joubert and Zimmermann 2002). Given the numerous species- (or genus-) specific associations, such as the dependency of the larva of the Western Marbled Emperor moth (*Heniocha dyops*) upon *Acacia mellifera*, *Acacia erubescens* and *Acacia hereroensis* (Oberprieler, 1995), it can be assumed that species diversity will be highest, when representatives of all woody species are preserved.

8. Discussion of findings and conclusions

8.1. Critical analysis of the 'UNIQUE study' underlying the project ideas for energetic use of Namibian bushes

Seebauer et al. (2019) analyzed and quantified the mitigation impacts of large-scale bush thinning on Namibian farmland, expected land use or productivity changes after bush thinning, and the utilization of the resulting bush biomass. They defined five harvesting and utilization scenarios that reflected existing and future bush value chains. For each scenario they calculated all emissions in the value chain as footprint (at the time of bush extraction and utilization) and as a long-term impact over a period of 20 years. Their findings showed that the GHG balances of one of the five tested scenarios presented potential mitigation options, namely Scenario 1: Rangeland restoration & bushblok, bush-to-feed or pellet production.

Although the study appears to be well-crafted, in our view there are two fundamental misconceptions that have the potential to cast the entire study into gravest doubt.

The first misconception arises from the **selection of annual rates of woody plant increment**. The authors reference the master thesis of Honsbein (2016) as source for their annual bush encroachment rate. Honsbein (2016) derived on the coefficient of 3.18% year⁻¹ for the country wide bush encroachment rate, by applying a linear regression to a series of data sets that were available for Namibia (Curtis & Mannheimer 2005; de Klerk, 2004; Joubert and Zimmermann, 2002; Ridgway 2009; Zimmermann & Joubert 2002). Most of the sources used by Honsbein are based on the 'Bester map'. This map was elaborated by the renowned botanist and bush encroachment expert Bester, who roughly estimated the extent of bush encroachment and then freely plotted it on a map of the country (Bester, 1999). Unfortunately, because adequate remote sensing data and methods were not available at the time of publication to quantify and locate the proliferation of woody plants, and the analysis also covers a period of more than 20 years ago, this map can no longer be considered an acceptable source.

Compared to more recent and peer-reviewed studies that used high resolution satellite imagery to assess the extent of woody vegetation cover in the region, the estimated encroachment rate of 3.18% year⁻¹ appears far too high. Wei et al (2019) calculated an average greening rate of $(0.0012 \pm 0.0027) \times \text{year}^{-1}$ for African drylands for the period between 1993–2012, with an average browning rate of $(-0.00013 \pm 0.0015) \times \text{year}^{-1}$. Venter et al. (2018) calculated a 0.27 % year⁻¹ increase of woody vegetation cover in sub-Saharan Africa. Saha et al. (2015) found an overall greening in southern Africa, increasing 0.26% year⁻¹ over the 2000–2013 study period. Skowno et al. (2017) assessed the woodland expansion in South African grassy biomes between 1990 and 2013. During the 23 year study period woodlands replaced grasslands over ~57,000 km² and conversely that grassland replaced woodlands over ~30,000 km², leading to a net increase in the extent of woodland of ~27,000 km² and an annual increase of 0.22%. The findings of this study showed also that changes varied markedly across the country. Areas that received over 500 mm mean annual precipitation showed higher rates of woodland expansion than regions receiving less than 500 mm (0.31% year⁻¹ & 0.11% year⁻¹ respectively).

Studies from Africa usually give values in the range of 0.1-1.25% cover per year⁻¹ as the annual growth rate (e.g. O’Conner et al 2014; Stevens et al. 2016). These values are comparable to those from Australia, North and South America (Archer et al 2017). Even if an outlier from North America is added (Barger et al. 2011; values in the range between 1.1 - 2.3% cover per year⁻¹), the estimated 3.18% appear to be unrealistic.

A change in the annual rate of woody plant growth from 3% to only 0.5 % or 1% has huge implications on the overall carbon balance and the sustainability of the bush harvest. The authors used the encroachment rate of Honsbein (2016) in their baseline scenario (Seebauer et al 2019; Table 17) and applied it to the estimated implemented area per year (433,333 ha), resulting in a total of -84.81 Total Emissions/ removals after 20 years (Mio tCO₂e) or -4.2 Mio tCO₂e on an annual basis. Only one of the five tested scenarios had a negative carbon balance (scenario 1). However, the expected sink effect is likely to be reversed if the realistic growth rates of 0.5 % or 1.0 % are used.

The second misconception concerns the **expected extent of the so-called bush encroachment**. As it has been described in previous chapters, the extent of bush encroachment is much more limited than previously expected. Recent studies using high resolution satellite imagery have shown that the areas experiencing *significant* changes in Namibia between 2000 and 2013 were spatially quite limited (especially in northern Namibia, where annual precipitation is highest, see Fig. 13; Saha et al. 2015; Fig. 3). The study by Seebauer et al (2019) assumes a widespread increase of woody plants across Namibia, based on a map elaborated by Southern African Institute for Environmental Assessment (SAIEA, 2015) (Fig. 14).

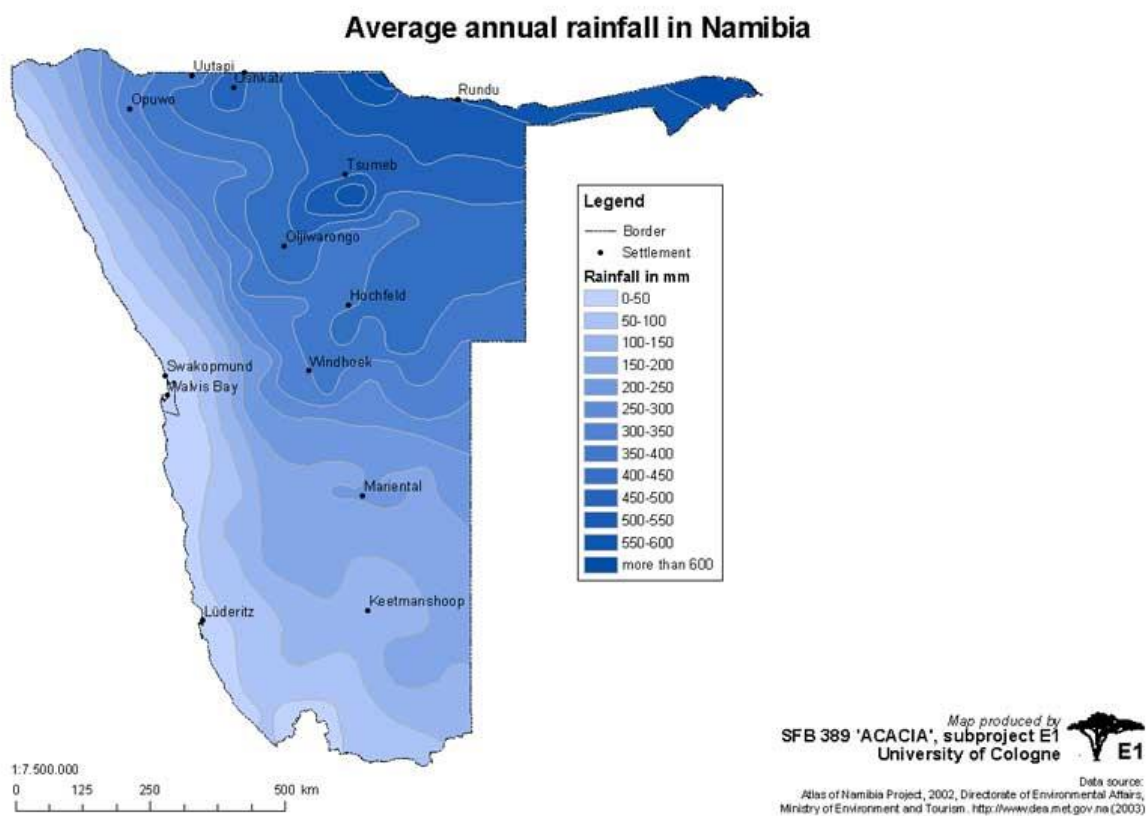


Figure 13 Average annual rainfall in Namibia. (Figure adopted from MET 2002).

Total Extent of Bush Encroachment

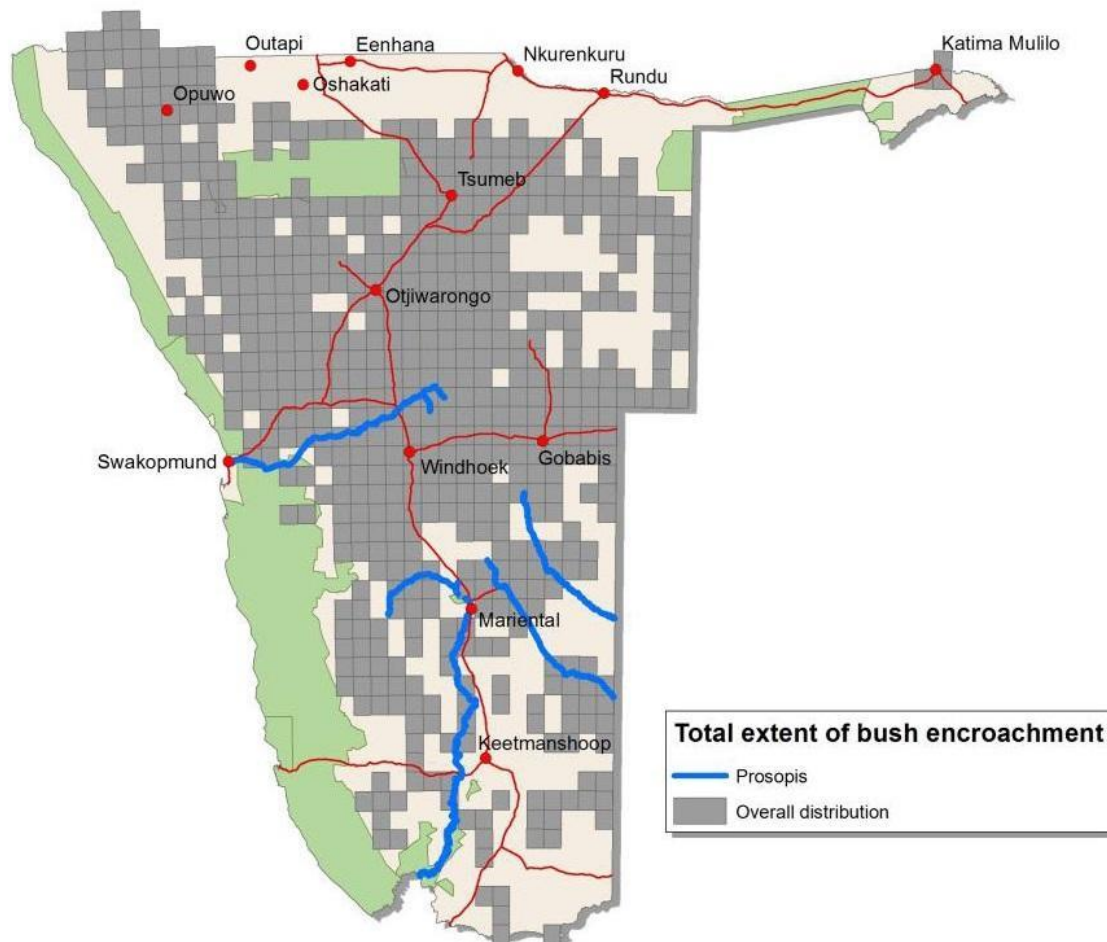


Figure 14 Map of total extent of bush encroachment in Namibia according to SAIEA (2015).

For example, the map of SAIEA indicates the widespread increase of the unpalatable shrub *Rhigozum trichotomum* in southern Namibia. In their analysis of historical photos, Rohde and Hoffmann (2012) found that 9 out of 16 photo site locations in the Nama-karoo biome had one or more landform units with *R. trichotomum* cover >5%. The cover of *R. trichotomum* ranged between 10% and 20%, however, these landform units often represented only a small proportion of the total landscape, suggesting that the proliferation of *R. trichotomum* has not been a widespread occurrence across the region. Furthermore, the findings of Rohde & Hoffmann (2012) showed that the vegetation in areas with < 250 MAP remained remarkably stable in the last 130 years. Translated to a map of the average annual rainfall in Namibia (MET 2002), these findings indicate that vast parts of western and southern Namibia will most likely not experience any increase in woody plant cover.

Nonetheless, projections of future climates suggest that annual precipitation will decrease, which will most likely lead to changes in the distribution of grasslands and shrublands. If the

climate becomes warmer and drier or if the frequency, magnitude, and duration of drought increase, present-day grasslands in some areas may become desert shrublands (Archer et al. 2017). However, woodlands and forests could also shift to savannah or grassland (Allen et al. 2010), and increases in woody cover of recent decades may be reduced by a higher frequency of “hot droughts” (Bowers 2005; Breshears et al. 2005; Twidwell et al. 2014). There remains a high degree of uncertainty how the vegetation will respond to the predicted changes in future climates.

These results also seriously call into question the carbon balances and sustainability assessment of bush harvesting.

Since the UNIQUE study appears to be based on false assumptions and outdated scientific knowledge, and consequently grossly overestimates the area and extent of woody plant expansion, it seems idle to go into further analysis of other arguments put forward to justify the project. The extensive literature that shows that the ecohydrological and biodiversity consequences of woody plant expansion need to be discussed in a much more nuanced way than UNIQUE provides. In fact, the study also fails to consider the rich current ecological literature presented in previous sections of this document.

8.2. Conclusions and recommendations

1. Bush encroachment is a normative and prejudicing term for vegetational change that is caused by complexly interacting drivers such as land use and climatic changes. The body of knowledge on the phenomenon has grown substantially requiring a careful reflection of its implications. The current state of knowledge in no way supports the assumption that a sustainable export of bush biomass from Namibia is possible and reasonable - certainly not if the aim is to contribute to climate protection.
2. The assessment of relevant and recent studies on the greening of drylands in the context of ongoing environmental changes and taking into account reliable sources on woody plant proliferation in Namibia it is concluded that both the problem of 'bush encroachment' and the corresponding potential of harvestable bush biomass have been overstated.
3. Before directing further investments into the development of strategies and projects for combating 'bush encroachment' and even using the woody material for energetic purposes, it would be absolutely necessary to provide a solid quantification of woody plant proliferation. This must be based on current data and methods, not questionable sources.
4. In addition, there are a number of critical issues that need to be addressed considering existing studies on bush encroachment and bush harvesting:
 - Vegetational changes such as greening and woody plant proliferation in drylands are systemic, non-linearly unfolding processes, where future scenarios cannot be derived from past trends, certainly not in times of rapidly accelerating climate change.
 - Woody plant proliferation can potentially lead to further enhancement of ecosystem functionality, e.g., in terms of improving certain ecohydrological conditions, rather than leading to ecosystem degradation. In fact, woody plant expansion can potentially even benefit regions in Namibia by cooling the landscape and generating precipitation - relevant aspects of ecosystem-based adaptation to climate change. Shading and cooling properties of woody plants might become even more relevant to animals and entire ecosystems as climate changes progress.
 - Ecosystem change inevitably leads to changes in species composition, but it is difficult to find a unanimous negative signal when analysing different taxa and accepting that ecological evolution permanently brings challenges to individual taxa and their specific functions, which tend to be temporal in nature anyway.
 - Scrub vegetation removal practices appear to have limited effectiveness - in the medium term - but create long-lasting ecological knock-on effects.
5. There are overarching doubts about the energy use of woody biomass as a contribution to climate change mitigation. This is related to the emission factors of different fuels, where wood has unfavourable values, and generally overestimated substitution effects (Leturcq 2020), but also to the fact that massive harvesting of woody biomass can lead to ecosystem changes that hinder future vegetation development under climate change. It is not valid to infer possible future carbon sequestration from past plant growth data, as environmental conditions have changed significantly and further dramatic changes are imminent.

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