Critique of UNIQUE GmbH's report "Greenhouse Gas Assessment of Bush Control and Biomass Utilization in Namibia":

Background:

Since 2013, the German government has been financing a development and climate finance project in Namibia called "Bush Control and Biomass Utilisation (BCBU)". It is managed by the German Development Corporation, GIZ. Since 2019, the project's focus has increasingly been on Namibia creating a future supply chain for woodchip and/or pellet exports to Europe.

As part of the project, GIZ commissioned the German consultancy company UNIQUE land use and forestry GmbH to assess the greenhouse gas emissions from large-scale debushing, i.e., removal of trees and bushes encroaching upon Namibian savanna rangelands. UNIQUE's report was published at the end of 2019.[1] Its most important conclusion is that large-scale debushing followed by so-called 'rangeland restoration' would increase Namibia's carbon sink and thus reduce the country's greenhouse gas emissions while, at the same time, allowing for a significant increase livestock numbers grazed on those rangelands.

Unreliable citations of scientific literature:

The first paragraph of the Executive Summary states:

"*Invasion and encroachment of woody plants into grassland is a global driver of land degradation and a widespread phenomenon in African savannas with significant negative economic and environmental impacts. It decreases landscape heterogeneity, alters vulnerable habitats, and reduces biodiversity (de Klerk, 2004; Sirami et al. 2009; Smit and Prins 2015), and it impacts carbon sequestration and water budgets (Woodward & Lomas 2004; Mitchard & Flintrop 2013). Changing the habitats towards more xerophytic, less productive, palatable, nutritious and resilient grass species, encroachment can reduce the "grazing capacity" to less than 10%*."

It is difficult to see how the authors justify basing those assertions on the studies they have cited:

- ***de Klerk, 2004***[2]: This study was commissioned by the Namibian government but not peer reviewed. Findings on biodiversity impacts of bush encroachment are summed up in the Executive Summary: "*A large number of mammals, bird species, reptiles and anthropoids are associated with problem bush species in one way or another and would be affected positively or negatively by bush control measures, depending on the method implemented. Bush thickening is seen as a major threat to the* *botanical diversity in Namibia and may even change the mammalian diversity, with the net effect likely to be negative. However, with the right densities and a sound mix of trees, bushes and shrubs, a more favourable sub-habitat is established, resulting in a greater variety of herbaceous species*".

The "rangeland restoration" scenario assessed as beneficial by UNIQUE foresees the removal of 78% of the volume of total average wood biomass. No evidence is cited that this would create the "right densities and a sound mix of trees, bushes and shrubs" which, according to the study by de Klerk, is most favourable for biodiversity.

- ***Sirami et.al., 2009***[3]: This study focussed on: "*the potential response of bird species to shrub encroachment in a South African savanna*". It found that: "*At the local scale, species richness peaked at intermediate levels of shrub cover*." Of the 57 species monitored in a savanna area with bush encroachment, nine had increasing and five had declining populations. In order to conserve those specialist species that depend on open savanna, the authors suggest that removing bush around existing grassland patches to create sufficiently large habitat (8 hectares being cited as the minimum size). However, the authors warn: "*areas treated with arboricides seem to be associated with low bird diversities, even of grassland birds".*

  By comparison, the authors of the UNIQUE report support the use of arboricides to keep mechanically de-bushed land free from woody vegetation.

- ***Smit and Prins, 2015***[4]: This study assessed herbivore populations in Kruger National Park, South Africa along a gradient of woody biomass cover. It found: "*increased woody cover is associated with (i) changed herbivore assemblage composition, (ii) reduced grass biomass, and (iii) reduced fire frequency. Furthermore, although increased woody cover is associated with reduced livestock production, we found indigenous herbivore biomass (excluding elephants) remains unchanged between 20–65% woody cover*." As woody cover increased, populations of some herbivore species (including giraffes) increased, those of other species (including plains zebras) decreased and populations of some species (including the white rhinoceros) appeared unaffected. African elephant populations were higher in areas with greater woody cover; however, the authors could not establish any causative link between numbers of elephants and the degree of woody cover. In short, this study showed that some herbivore species benefit from and others are disadvantaged by high rates of bush encroachment, but it does not demonstrate an overall negative impact on biodiversity.

- ***Woodward and Lomas, 2004***[5]*:* This study is based on modelling of global vegetation responses to climate change and increasing CO_2

concentrations in the atmosphere. It does not discuss impacts of woody biomass growth in savannas.

- ***Mitchard & Flintrop, 2013*[6]**: This is a literature review which assessed 16 studies that looked at woody encroachment across African savannas and woodlands together with long-term remote sensing data. It found that woody encroachment was widespread in sub-Saharan Africa. The authors state that they did not directly look at impacts on carbon balances, although "*forest regrowth must form part of the land-surface carbon sink*". Nor did they look at impacts on water budgets.

In summary, neither of the two studies cited as having shown that bush encroachment has significant impacts on carbon and water budgets addressed those impacts at all.

Of the three studies cited as a source for UNIQUE's claims that woody encroachment harmed ecosystems and biodiversity, one study revealed changes to herbivore population compositions that benefitted some species at the expense of others but did not reveal overall harm to biodiversity. The other two studies suggest positive impacts of woody biomass growth on species diversity up to a certain level of bush encroachment and negative impacts thereafter. The authors of one of those two studies suggest recreating some areas of open grassland by removing bushes around existing grass patches in order to maintain habitat for specialist savanna bird species. It is not obvious that this literature supports the UNIQUE study's recommendations of a very aggressive bush removal approach (78% of average woody biomass to be removed).

Other unreliable literature citations have been found elsewhere in the report.

UNIQUE describes a protected tree species as a high-biomass encroacher bush:

UNIQUE's report lists four dominant tree/bush species in its study area, all of which are described as belonging to "*high biomass encroacher bush systems*". This is in the context of a report that supports removal of an average of 78% of such trees and bushes. One of the species listed is *Colophospermum mopane*.

This tree is listed as protected by Directory of Forestry of Namibia,[7] a fact not acknowledged by UNIQUE, who effectively propose the large-scale removal of this protected tree species.

Not one study cited backs up both of UNIQUE's claims that, following bush removal, soil organic carbon (SOC) recovers to original levels found in open grasslands AND that those SOC levels are higher than those under bushes:

One of the main conclusions from the UNIQUE study is that removing 78% of the average volume of woody biomass cover, followed by land management practices described as 'rangeland restoration', will positively impact on Namibia's greenhouse gas balance.

This conclusion is based on the assumption that SOC levels found in undisturbed open grasslands are fully restored following bush removal, and are higher than SOC levels under bushes – indeed so much higher that they more than offset the undisputed loss of carbon in vegetation resulting from bush removal.

The literature list presented by UNIQUE includes six relevant studies. Four of them are peer-reviewed studies that looked at SOC levels after grassland debushing. In addition, one peer-reviewed field study and one PhD thesis are presented, both of which involved field research on the impacts of debushing on soil fertility rather than on SOC.
However, SOC is a strong predictor of soil fertility.[8] Here is a brief summary of the results:

- Three field studies found that the removal of woody biomass leads to sustained losses of SOC/soil fertility. Two of those studies focussed on debushing in rangelands in South Africa and Namibia respectively.
- One field study, based in Namibia, found that grasslands could recover to a state resembling that of undisturbed open grasslands over a period of 3-9 years; however, it also found that SOC levels were significantly higher under woody vegetation compared to levels under grasses;
- One field study, based in Ethiopia, found higher SOC levels in bush encroached land compared to open grasslands, however, SOC levels were higher still in bush thinned grasslands. No information about the time elapsed between bush thinning and soil sampling was included, thus it is not clear whether the researchers found a long-term effect or merely a short-term SOC boost due to residues following bush removal;
- One study, based on a mixture of soil sampling and mapping, states that bush encroached land had lower SOC than grassland after bush removal, although the amount of SOC following bush removal was less than that on undisturbed open grasslands. As discussed below, no statistical analysis backing up such a correlation is provided, and the authors' stated findings are not obvious from looking at their published data showing bush density and SOC.

In short, not one study listed by UNIQUE backs up both their dual claims that a) debushing restores soil properties to their original state, comparable to soil properties found on un-encroached open grassland and, b) SOC levels following the restoration of open grassland oils exceed those under bushland.

Below is a more detailed summary of the six studies considered by UNIQUE.

- ***Buyer et.al., 2016***[9]: This field study, based in Namibia, focussed primarily on impacts of bush encroachment on soil microbial communities, although soil chemistry, including soil organic carbon content were also measured. It involved taking soil samples on land where bush had been thinned 3, 5 or 9 years prior. The authors found that: "*A major disturbance to the ecosystem, bush thinning, resulted in an altered microbial community structure compared to control plots, but the magnitude of this perturbation gradually declined with time*." After nine years, soil organic carbon levels under grasses were nearly identical to those on control plots, i.e., plots where bush had not been removed. The authors' conclusion was more optimistic than that from the two studies referred to above: "*We found that bush thinning initially perturbs the soil ecosystem, but over 3–9 years the system recovers to a state resembling that of undisturbed grass in a bush-encroached savanna*". However, the significantly higher levels of SOC under bush compared to those under grass identified by the authors means that the study does not support UNIQUE's assertion that debushing increases overall soil organic carbon. Furthermore, in the study, bush was thinned by up to 70% "almost entirely by manual cutting", with no subsequent bush removal. UNIQUE's preferred scenario involves removing 78% of bush via "*medium-scale mechanized harvesting with excavator*", followed by the application of arboricides. We would suggest that this approach may impact differently and possibly more severely on soils, especially if soil compaction by heavy machinery occurs.

  - ***Gobelle and Gure, 2018***[10]: This field study examined the impacts of bush encroachment on plant diversity and carbon stocks in rangelands in a region of Southern Ethiopia. The researchers looked at bush encroached, non-encroached and bush-thinned rangelands. Unfortunately, no information is given as to when the bush thinning occurred. The researchers found that soil organic carbon levels were higher in bush encroached than in open grasslands. However, they were higher still in bush-thinned grasslands. The authors discussed the possible reasons for this finding and suggested it could "*arise from high amounts of litter deposits and dead root addition to the soil from encroaching species, or the improvement of microclimate under bush encroached rangeland types. Alternatively, it might be due to the heavy grazing in non-encroached rangeland types."* Given that residues left behind after debushing are known to boost soil organic carbon, the lack of information about the time lag between debushing and soil sampling makes it impossible to know whether the findings represent any longer-term trend.

  - ***Elmarie Kotzé, 2015***[11]: This Ph.D. thesis involved field research in rangelands located around Thaba Nchu in South Africa. It addressed land degradation linked to inappropriate rangeland management, especially over-grazing. The author sampled rangeland management systems under communal, commercial and land reform, with different levels of grazing intensity. Soil carbon was assessed in relation to management and farming systems rather than the degree of woody encroachment. However, the author found: "*Soils in both ecosystems responded differently to increased* *rangeland degradation. In the grassland ecosystem bare patches and soil crusts lead to a degradation of the soils, whereas in the savanna ecosystem bush encroachment led to a temporary improvement of the soil quality*". Woody encroachment created "*islands of fertility*". Severe bush removal was found to lead to "*soil degradation rather than soil restoration*". The author pointed out that "*little is known on the early indicators, rates and threshold values that characterise changes in soil properties*", i.e., it was not clear what level of bush removal would lead to degradation of different soils.

- ***Martinez-Mena et.al., 2002*[12]*:*** This was a field study carried out in Murcia, in the Southeast of Spain. It involved the removal of pine trees as well as shrubs from a plot of land which was compared with a control plot on which no vegetation was removed. Nine years after vegetation removal, soil organic carbon content had fallen by 30.7%. Most of the loss of carbon was due to oxidation (i.e., chemical reactions with oxygen), rather than soil erosion, with soil nitrogen levels broadly unaffected. The authors concluded: "*The effect of vegetation removal in a Mediterranean semiarid area leads to a rapid decline in the amount of organic carbon stored in the soil. Such perturbation is irreversible if left to nature*". The scenario differed from bush removal in Namibia in so far as trees and bushes had not recently grown on previously open grassland. However, the climate was broadly similar to that on Namibian rangelands, and the authors suggest that soil organic carbon loss after vegetation removal appears to be particularly concerning in arid and semi-arid regions.[13]

- ***Nijbroek et.al., 2017***.[14] This study involved a combination of mapping and soil sampling in order to develop and assess an optimal methodology for mapping SOC as part of a land degradation assessment. The authors of this study stated that an important approach to mapping land degradation "*was to show that areas that had converted from the more desirable grassland to bushland had lower SOC values…than either areas that converted from bushland to grassland…or areas that remained grassland…from 2000 to 2017*." They observed: "*that areas which are becoming bush encroached (measured by the density of small bushes less than 1.5m in height) are actively replacing grasslands and have a negative correlation with SOC. On the other hand, once land is encroached by mature bushes (greater than 1.5m), SOC tends to increase again probably due to density of the root system.*" This statement appears to imply that the authors calculated a correlation between the number of trees/bushes on the one hand and SOC on the other hand. However, the authors provide no information as to which statistical test they may have used, nor do they provide any of the essential details (e.g., slope of the relationship between small bushes and SOC, p-value) to show whether/how statistical significance was established. Nonetheless, it is clear that the study does not back up UNIQUE's assumption that clearing bush on encroached land will restore SOC levels to those found under non-encroached grassland.

- ***Zimmermann et.al., 2017*[15]*:*** This field study focussed on soil fertility, not directly measuring SOC. It involved sampling soils on 27 sites in central Namibia on which woody biomass had been left undisturbed, or partially cleared, or totally cleared. It was found that there was "*no evidence of restoration of soil fertility, even 13 years after debushing*". The authors state that "*it seems unlikely that the grass growing on debushed land will be very nutritious from the second year onwards, due to the lower soil fertility found even in sites debushed two years previously*" (following a short-lived boost to soil fertility in the first year due to residues and roots left behind after debushing). The authors suggested that farmers might be able to counter this loss of soil fertility by returning minerals to the land, however, this hypothesis was not tested.

UNIQUE study authors contradict themselves in relation to bush thinning intensity and soil organic carbon sequestration:

The UNIQUE study states: "*only under the assumption of aftercare and savanna restoration success SOC is increasing (sequestration), and the highest SOC increase is under a moderate harvesting of 50% bush biomass leading to 0.12 t C/ha/year or 0.44t CO2e/ha/year respectively*".

However, the 'optimal' scenario put forward as 'rangeland restoration' involves the removal of 78% of bush on average. According to a graphic for this scenario, this would lead to 9.9 tonnes of CO2e sequestration per hectare over a period of 20 years, which comes to 0.495 tCO2e/ha/year.

Clearly, those two statements cannot be reconciled.

The large majority of the literature cited by UNIQUE shows that bush encroachment generally leads to increases rather than decreases in soil organic carbon:

As shown in the paragraph above, UNIQUE's claim that debushing can benefit Namibia's greenhouse gas balance are not backed up by any of the field studies they cite. Here we shall look at whether UNIQUE's assertion that bush encroachment in Namibia reduces SOC is in fact supported by the literature they cite.

In order to assess this claim, we have summarised each study or report included in UNIQUE's literature list which compares either SOC or soil fertility (closely correlated with SOC) in open grasslands with those under woody encroached land anywhere in the world. This list includes those studies discussed above in relation to SOC and soil fertility following debushing.

UNIQUE's literature list contains 21 relevant entries of which 19 are peer-reviewed studies, one is a PhD thesis, and one is a non-peer reviewed report.

The non-peer reviewed report includes a short discussion of a peer-reviewed study from 1992 which, according to the report authors shows that "*the soil beneath a canopy generally has a higher nutrient status than the soil in open areas. Trees, therefore, effectively recycle plant nutrients and thus maintain a high soil fertility.*"

Of the 20 peer reviewed studies, including the PhD thesis, 12 are based on field research, four are based on literature reviews, one is a simulation study (based on a biogeochemistry model), one is based on remote sensing, and one on a combination of mapping and soil sampling and analysis.

Of the 12 studies involving field research:

- 3 studies found that bush encroachment was associated with increased SOC compared to open grasslands, and two other studies found that it was associated with increased soil fertility;
- A further two studies found that the removal of woody vegetation led to a decline in SOC and soil fertility respectively;
- One study found considerable carbon additions from leaf litter under bushes which contributed to SOC and soil nutrients, however SOC and nutrient levels under grasses were not measured;
- One study looked at three different sites in southern USA rangelands. At two sites, shrubs had encroached on grasslands and, at those sites, SOC was significantly higher under bushes than under grasses. At a third site, grasses had encroached into shrubland, and at that site, there was no significant difference in total SOC under shrubs and grasses;
- One study looked at four different soil types in a semi-arid savanna in South Africa. It found that surface soil carbon under woody plants was higher than that under grasses on three soil types. On a fourth soil type – which had the densest bushland cover of all four – it was lower than surface soil carbon under grasses;
- One study looked at field data from six sites in the Southwestern USA, each of them with open grasslands as well as bush encroached land. It found that sites with higher rainfall saw SOC losses following bush encroachment, whereas sites with lower rainfall saw SOC gains;
- One study, which did not involve SOC measurements, found that plant litter took twice as long to decay in bush encroached land compared to open savanna in a game reserve in South Africa. The authors suggest that this is an important finding related to carbon cycling, but provide no details as to what those implications are likely to be;
- One study found higher levels of SOC under bush encroached land than under open grassland, but higher levels still under bush-thinned land. As referred to above, the study does not give sufficient information to judge whether this may have been a short-term impact, caused by decomposing residues after bush removal;
- One study based on a mixture of soil sampling and mapping, states that bush encroached land is associated with lower SOC than open grassland, although

once the bushes/trees grow in height, the soil underneath them starts accumulating more SOC. However, no statistical analysis is presented to show in how far those are indeed statistically significant correlations.
- One study found higher SOC stocks in an open grassland in a desert area of Northwest China compared to adjacent bushland.

Of the four studies based on literature reviews:

- One study combined an analysis of a total of 241 scientific publications looking at soil carbon responses to various changes in grassland management worldwide. Of those studies which looked at conversions from native vegetation to grassland, 46.2% found that this led to increased SOC; however, all 52 newer studies reviewed found that such land conversion led to SOC losses;
- One review of 244 case studies found that field studies consistently showed bush encroachment to result in increased SOC.
- One study involved a literature review of studies providing data on carbon flows and carbon stocks related to tropical savanna (both woody and open savanna). The authors found that SOC can be high in tropical savannas, although it tends to be lower in arid and semi-arid compared to humid savanna ecosystems. They did not compare SOC in bush encroached versus open savanna.
- One meta-analysis using data from 142 studies found that the main effect of shrub encroachment was to increase topsoil organic carbon content, and that shrub encroachment had a mostly positive impact on total SOC.

The results of all four literature reviews thus contradict UNIQUE's assertion that bush encroachment generally reduces SOC.

The simulation study included in UNIQUE's literature list concluded that bush encroachment increased SOC.

The study based on remote sensing did not measure SOC content but found that soil erosion through water runoff on hill slopes on a site in South Africa correlated with dense bush encroachment. Soil erosion is associated with loss of SOC.

As discussed above, the study based on mapping and SOC measurements, which set out to develop and assess mapping tools for land degradation assessments, suggest that SOC under small bushes is lower than that under grasses, but that it increases as bushes and trees grow in size. However, no information as to whether or how statistical significance was measured in order to establish such ccorrelations.

The studies are summarised in more detail below:

- ***Archer et.al., 2000[16]:*** This was a simulation study using a biogeochemistry model, with data inputs from results of previous field research in La Copita, in southern Texas. La Copita is located in a semi-arid subtropical area in which shrubs and small trees have been progressively replacing large areas of grasslands since the 1800s. Vegetation on the site ranged from closed-canopy woodlands to open savanna parklands. It found: "*soil and plant C mass has increased 10% and 10-fold, respectively, with succession from pre-settlement savanna grassland to present-day savanna woodland over the past 100 years*." Bush encroachment, thus increased SOC.

- ***Buyer et.al., 2016[17]***: As discussed above, this field study conducted in Namibia found that nine years after bush thinning, SOC levels under grasses recovered, but soil under bushes contained significantly more SOC than soil under grass. Again, bush encroachment was associated with increased SOC;

- ***Conant et.al., 2017[18]***: This study involved a literature review of 126 papers and compared the results with those from a previous literature of 115 scientific publications, all which looked at soil carbon responses to changes in grassland management worldwide. According to the authors "*the majority of studies (68.2%) examining changes in soil C stocks with management improvements found increased soil C… the two exceptions being conversion from native vegetation (soil C increased for just 46.2% of studies) and grazing management (48.9%)*." Although older studies had suggested SOC increases from converting native vegetation to grasslands, 52 newer studies all found that that such land conversion led to SOC losses.

- ***de Klerk, 2004[19]***: This report published by the Namibian government is not peer reviewed. Soil carbon and soil fertility impacts of bush encroachment are not a focus of this report; however, it does cite relevant (older) literature in relation to soil fertility rather than SOC:

  "*Teague and Smit (1992:63) explain that…The soil beneath a canopy generally has a higher nutrient status than the soil in open areas, often considerably so. This includes most of the mineral elements and carbon (Bosch & Van Wyk 1970; Kennard & Walker 1973; Smith & Goodman 1987; Belsky et al. 1989), which are present mostly because of the leachate [throughfall] and litter enrichment…*"

  De Klerk et.al. sums up the findings from that study as including: "*The soil beneath a canopy generally has a higher nutrient status than the soil in open areas. Trees, therefore, effectively recycle plant nutrients and thus maintain a high soil fertility.*"

- ***Dunham, 1989[20]***: In this field study, the researchers looked at litterfall in an *Acacia albida* woodland in Zimbabwe. They focussed on above-ground rather than below-ground productivity, including carbon in vegetation, which was significantly higher in the woodland than in areas with herbaceous vegetation.

It found considerable amounts of carbon as well as nutrient contained in leaf litter fall. Leaf litter fall contributes to SOC and soil nutrients. However, no comparison with open grasslands was made.

- ***Eldridge et.al., 2011***[21]: The authors of this literature review and meta-analysis found that field studies considered consistently show that shrub or bush encroachment into ecosystems increases SOC and soil nitrogen. It states: "*analyses of 43 ecosystem attributes from 244 case studies worldwide showed that some attributes consistently increased with encroachment (e.g., soil C, N), and others declined (e.g., grass cover, pH), but most exhibited variable responses*."

- ***Feral et.al., 2003***[22]: The authors of this field study examined relationships between vegetation and soil nutrients along rainfall and land use gradients in the Kalahari. They found that SOC was significantly lower in areas with grazing and with reduced rainfall, and that soil organic nitrogen was significantly lower at the driest site but higher at grazed sites. It also found that: "*Woody plant canopies alone showed elevated SOC at three sites and SON [soil organic nitrogen] at one site*". Elevated SOC was attributed to litterfall under trees and bushes.

- ***Gill and Burke, 1999***[23]: In this field study, the researchers assessed the amount, quality and distribution of SOC below woody vegetation and below grasses at three rangelands, located in Texas, New Mexico and Utah. At the sites in Texas and New Mexico, shrubs had encroached upon grasslands, and in Utah, grasses had encroached into shrublands. The site in Texas was the focus of Archer et.al.,2000 discussed above. At the Texas site, as shown above, soil carbon was significantly higher under bushes than under grasses. The same was found at the New Mexico site. At the site in Utah, there was no significant difference in total SOC beneath grasses and bushes, although significantly more soil carbon was found in the upper soil layers under shrubs than under grasses. The authors cautioned: "*The results from all three sites collectively demonstrate how difficult it is to define plant functional types in order to predict the influence of vegetation change on the distribution of soil C*".

- ***Gobelle and Gure, 2018***[24]: As discussed above, the authors of this field study found higher levels of SOC under bush encroached land than under open grassland in a region in Ethiopia, but higher levels still under bush thinned land. Unfortunately, it did not include enough information to judge whether this was a long-term effect or a short-term response to residues from debushing.

- ***Grace et.al., 2006***[25]: This study involved a literature review aimed at estimating carbon fluxes between tropical savanna ecosystems and the atmosphere, and to ascertain how significant such ecosystems are to the global carbon cycle. The savanna ecosystems considered included woody savanna as well as open grasslands. The authors found that tropical savannas can be highly productive, i.e., sequester significant quantities of carbon, although productivity was lower in arid and semi-arid savannas than in more humid ones. As a global average, savannas store at least as much carbon in soils as they do in above-ground biomass and account for 10-30% of global soil carbon. However, the authors did not set out to compare bush encroached with open savanna. They concluded: "*There is considerable scope for using many of the savannas as sites for carbon sequestration, by simply protecting them from burning and grazing, and permitting them to increase in stature and carbon content over periods of several decades*." Clearly, this study does not justify bush removal for increased grazing.

- ***Hibbard et.al., 2001***:[26] This is another study based on field research at the Mexican site discussed in Archer et.al., 2000 and in Gill and Burke, 1999 above. It compared ecosystem properties of the top 10cm of soils beneath herbaceous patches with ones beneath woody plants, in an area where woody encroachment had taken place over the past five to seven decades. The authors found that "*the rate and extent of soil C and N accumulation associated with this phenomenon [woody encroachment] can be rapid, substantial, and accompanied by increased N turnover*."

- ***Hudak et.al., 2008***[27]: This study is based on a field trial in two bush encroached semi-arid savanna systems in South Africa. It involved sampling soil and plant litter across four types of soil. Results showed that soil carbon and nitrogen were influenced by the texture of soils and by vegetation. Surface soil carbon beneath woody plants was higher compared to that under grasses on three soil types, and lower on a fourth. That fourth soil type was found on the most heavily bush encroached site. The authors suggest that this might be due to SOC generally increasing up to a certain degree of bush encroachment and then decreasing at high density, however, this hypothesis was not tested. Whether the degree of woody encroachment was responsible for lower SOC at one of the four soil types could not be established. The authors stated: "*Because our data were only sampled at one point in time, they are insufficient to confirm this speculation. Soil monitoring is needed to determine if rates of soil C sequestration are in equilibrium with rates of bush encroachment, and to what extent the soil C sequestration rate may lag behind*.

- ***Jackson et.al., 2002***[28]: This study is based on a field trial in which researchers compared carbon and nitrogen as well as soil carbon profiles across six pairs of adjacent grasslands, each made up of one encroached and one open grassland. All sites were located in the Southwestern USA. In relation to SOC, the key finding was: "*a clear negative relationship between precipitation and changes in soil organic carbon and nitrogen content when grasslands were invaded by woody vegetation, with drier sites gaining, and wetter sites losing, soil organic carbon*."

- ***Elmarie Kotzé, 2015***[29]:This PhD thesis involved field research in rangelands located around Thaba Nchu in South Africa. The study addressed land degradation linked to inappropriate rangeland management, especially over-grazing. The author sampled rangeland management systems under communal, commercial and land reform, with different levels of grazing intensity. Soil carbon was assessed in relation to management and farming systems rather than the degree of woody encroachment. However, the author found: "*Soils in both ecosystems responded differently to increased rangeland degradation. In the grassland ecosystem bare patches and soil crusts lead to a degradation of the soils, whereas in the savanna ecosystem bush encroachment led to a temporary improvement of the soil quality*". Woody encroachment created "*islands of fertility*". Severe bush removal was found to lead to "*soil degradation rather than soil restoration*". The author pointed out that "*little is known on the early indicators, rates and threshold values that characterise changes in soil properties*", i.e., it was not clear what level of bush removal would lead to degradation of different soils.

- ***Leitner et*.al., 2018[30]**: This study is based on field research at the Madikwe Game Reserve, South Africa, with 20 experimental sites each on encroached and open savanna. Instead of measuring SOC, the researchers assessed the decomposition of plant litter and the effects of woody encroachment on termite activity, important for plant decomposition. They found that plant litter took twice as long to decay in encroached compared to open savanna areas and that bush encroachment reduced the activity of termites. The authors state: "These findings have important and broadly applicable implications for ecosystem functioning given the vast expanse of savannas across Africa (> 13 million square kilometres (Riggio et al., 2013), the importance of decomposition for biogeochemical cycling and the global carbon budget (Raich & Schlesinger, 1992), as well as termites being a keystone taxon increasing soil productivity and landscape heterogeneity (Jouquet et al., 2005; Sileshi et al., 2010).". However, the authors do not conclude what the implications for the carbon budget are, i.e., whether more or less carbon will be sequestered in encroached soils.

- **Li et.al., 2016[31]**: This is a meta-analysis based on paired data from grassland with woody encroachment versus open grassland, based on 142 studies worldwide. It found that SOC contents changed in response to woody encroachment, and that those changes ranged from 50% reductions to 300% increases. SOC increased in semi-arid and humid regions, especially if grasslands were encroached by leguminous shrubs. SOC tended to decrease with woody encroachment in silty and clay soils, but increased in sand, sandy loam and sandy clay loam. The authors concluded that "*the main effects [sic] of shrub encroachment would be to increase topsoil organic carbon content*" and they refer elsewhere to "*the mainly positive effect of shrub encroachment on SOC content*". Based on this meta-analysis, the region considered in the UNIQUE study could be expected to have increased SOC associated with bush encroachment.

- ***Martinez-Mena et.al., 2002***[32]: This field study in Southeastern Spain is summarised above. It showed that vegetation removal in a semiarid area led to a rapid fall in SOC.

- **Manjoro et.al, 2012***:*[33] This study is based on remote sensing to investigate patterns of soil erosion as well as bush encroachment in a catchment area based in Eastern Cape Province, South Africa. It did not directly look at soil organic carbon contents, however, soil erosion is associated with a loss of soil carbon. The authors found that on hill slopes, high levels of soil erosion correlated with dense woody encroachment.

- ***Nijbroek et.al., 2017***[34]: This study has been discussed in detail above. The authors stated that "*areas which are becoming bush encroached (measured by the density of small bushes less than 1.5m in height) are actively replacing grasslands and have a negative correlation with SOC. On the other hand, once land is encroached by mature bushes (greater than 1.5m), SOC tends to increase again probably due to density of the root system*." However, there are unanswered questions regarding the authors' statistical analysis and whether the authors have established any statistically significant correlation.

- ***Zhou et.al., 2012***[35]: This study involved a field trial comparing SOC dynamics on an open grassland with those in adjacent bushland. The study area was located in an arid region of Northwestern China. The authors found higher SOC stocks in the open grassland than in the bushland. They suggested that this could be due to litter input from bushes being more resistant to decay and less available to decomposition by microorganisms. Unlike the Namibian rangelands considered in the UNIQUE study, the area studied in Northwestern China has a desert climate, with just over one-third the average rainfall in UNIQUE's study region. With a different climate and different tree, bush and grass species, it seems uncertain to us whether one can extrapolate from those findings to semi-arid rangelands in southern Africa

- ***Zimmermann et.al., 2017***[36]***:*** This field trial, discussed above showed that soil fertility was not restored even 13 years after debushing. SOC was not measured.

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