Chapter

Vegetation Dynamics. Natural versus Cultural and the Regeneration Potential. The Example of Sahara-Sahel

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Abstract

There is a principal and controversial debate on the so-called 'Greening-Regreening' of the Sahel. There still is the old philosophy of an expanding/shrinking ecosystem Sahara versus Sahel. In some concepts, it is presented as annual. Another concept is based on a general degradation of the Sahelian savannas – in some cases with a decline to a lower state of ecological equilibrium after a short period of resilience. Anyhow, there are also signs of still ongoing regeneration processes of vegetation and soil. The main problem, however, lies in the principal lack of terrestrial observation and in the confusion of terms. This mostly concern on vegetation units and their dynamics. The goal of this article is to explain the general nature of the Sahara and the Sahel based on maps and graphs. We try to analyse the dynamics of boundaries during the last 200 years. The main results are the tripartite nature of the Sahara, divided into semidesert, desert and Saharan savanna with relatively stable boundaries. A reconstruction of the vegetation for the last 200 years confirmed the position of these borderlines even under different states of the plant cover. It also revealed the nature of Sahelian savannas as cultural landscapes – in higher diversity and density. It is also possible that the North Sahelian savannas had been for long times under the dynamics of elephant landscapes. A high-resolution sediment and pollen record from the Middle Sahel of Niger evidenced the high diversity and resilience up to the severe drought of the 1970s. It was a definite stroke from which these savannas never reached again their former diversity despite a slide recovery named 'Regreening'. The various projects for regeneration or conservation in Sahara or Sahel differ in two types of projects. The one is the installation of Nature Reserves/National Parks with special reserves for emblematic animals as keystone organisms and an auto-regeneration of vegetation and soil. The other type consists of pasture rotation projects such as in the Malian Gourma or in the Central Air Mts. The first initiative resulted in the decade-long protection against the severe degradations, which were typical for the surrounding regions. The rotation system was based on timewise open wells and of observed pasture status. It was conceived together with the local populations and has been respected until the invasion of northern cattle keepers during the peak of drought in 1984. After severe quarrels, the system collapsed and the savannas degraded heavily. A comparable project worked in the central Air Mts. for 5 years. Remarkable results have been, but the rebellion of the 1990s, put a sudden end on it. The general insecurity of the last decades caused by civil war and/or various terrrorist groups led to a re-evaluation of a great number of regeneration initiatives including the pharaonic 'Great Green Wall', a continent wide forest belt. However, smaller projects on the village level may better develop as they are under the responsability of local population, which can reactivate their long experience. The 'regreening' might be restricted to the region of the southern Sahara and the northern Sahel as well as to the traditional park systems. Anyhow, even if a long-time amelioration of production systems will happen, the former must be regarded on the background of a rapidly increasing demography.

Keywords: Sahara, Sahel, vegetation, landscape types, present situation, historical development, stability of limits, cultural, landscapes, degradation, regeneration potential

1. Introduction

In the last years, a 'Greening' or 'Regreening' of the Sahel was a most disputed topic. It mutated to a general discussion of regeneration potential of the ecosystems and the possibilities to find production modes for the necessary food production. Moreover, conservation and nature protection were discussed and great projects were initiated [1–13].

On the other side, the general political insecurity of the last 15 years supressed fieldwork and made an end to several initiatives. Many of the conservation projects are now classified as 'in suspense.' This stands especially for the big National Natural Parks in the Sahara of Niger and Chad [14–16] and more or less for the 'Great Green Wall' too [17, 18].

Thus, the reasoning on degradation or regeneration is often based on pure remote sensing without the necessary ground check or field work. In addition, for the case of Sahara-Sahel-complex, there is still a deep confusion on the nature and dynamics of ecosystems and landscapes as well as on their definitions. Limits and boundaries seem to be free floating – sometimes on an annual scale.

On this background, we will characterise the main ecosystems – landscapes of Sahara-Sahel by a general vegetation map in order to avoid further confusions. This should also work as a base to interpret palaeorecords. Furtheron, we will try to reconstruct the landscape evolution during the last 200 years. Finally, we will discuss the chances of measures of regeneration and conservation.

2. The 'bandoneon desert'. Concepts and nature of the Sahara

It is fascinating to see that the old concept of an extension of one large ecosystem on the cost of another – here the advancing/encroaching desert into the savannas is still taken as valid. The alarm of Stebbing [19] of an advancing desert in the Niger-Nigeria border region was rapidly disproved by a common French-English – Forester expedition [20]. More than half a century later, Tucker et al. [21] presented the model of an expanding and retracting Sahara, which he considered as desert for the whole in the scale of years. Their conclusions were based on interpreted vegetation changes with help of satellite images; however, without any differentiation between permanent and short-time plant cover. Another less meaningful approach was presented by Thomas and Nigaru [22], who claimed a 10% expansion of the Sahara/desert since 1920 both to the North and to the South. The authors based

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their conclusion on changes in precipitation as they defined ecosystems/landscapes exclusively by mean annual precipitation.

Thus, we have to deal with a variety of methods and concepts in the analysis of landscapes/ecosystems in northern and western Africa. We take the term 'landscape' we take in a broad sense as a characteristic part of the earth's surface, which is defined by various features such as vegetation, relief or the intensive human impact, which developed in time, and which is visibly different from neighbouring regions.

A. Field observation and subsequent definition of landscape – or vegetation types. This was the procedure at the beginning of the twentieth century in the aftermath of the colonisation with Chevalier [23] as an example.

B. The characterisation of recognised landscapes and definition of leading features of their vegetation or geomorphology.

C. A difference in the concept of consistent or transition zones. 'Sahara' as the transition from the Mediterranean to the 'Sahel' [24] or the 'Sahel' as transition from the 'Sahara' to the (real) savannas [25].

D. Reduction of landscapes/ecosystem (and climate too) to a single feature such as rainfall. It is the main cause of confusion on the dynamics of the large ecosystems in northern and western Africa [26].

E. A main problem is the emotional component in the term 'desert', which impedes often a neutral recognition. Mostly, the terms 'Sahara' and 'desert' are used as synonyms – see [24].

Thus, it is necessary to explain clearly the terms in order to avoid confusion and to define them from direct observation in the field – or at least from clear descriptions.

3. What are we talking about?

A vegetation map of northern and western Africa was established in order to explain clearly the large vegetation types and their repartition. It is based on direct observation during several expeditions (see the small included map) and on published vegetation maps [27]. It deals with the physiognomic units such as forest, shrub-land or grass-land and gives the main floristic components. There is no differentiation between natural formation, near to nature formation or cultural units; however, their dynamics are shortly discussed. Here, we will concentrate on the South-Mediterranean steppe, on the Sahara and on the Sahel to give a background to the discussion about limits, their dynamics and their regeneration potential. Block diagrams and designs will support it. Thus, we will try to avoid the various confusions on terms such as 'steppe or prairie'. The map is to document visible units and their limits and to work as a modern model when reconstructing the past. The question of limits might be regarded as an academic one. However, it is an assessment of resource areas-mainly of pasture.

3.1 The southernmost formation of the Mediterranean realm is the 'steppe'

The term 'steppe' is freely used in literature – comparable to the term 'savanna'. For both the statement of Cole [28] is still valid: 'Most discussed and least understood' (see **Figure 1** nr. 10 and 2). Thus, 'steppe' is rarely referred to the original definition as a tussock-grassland of the genus *Stipa* under continental winter cold conditions [29, 30]. In this area, it is mainly characterised by *Stipa tenacissima* and *Lygeum spartium* on fine-grained substrates such as loess. It stretches over the plateaus of the Atlas Mts., and it is severely exploited for pasture, agriculture or paper production.

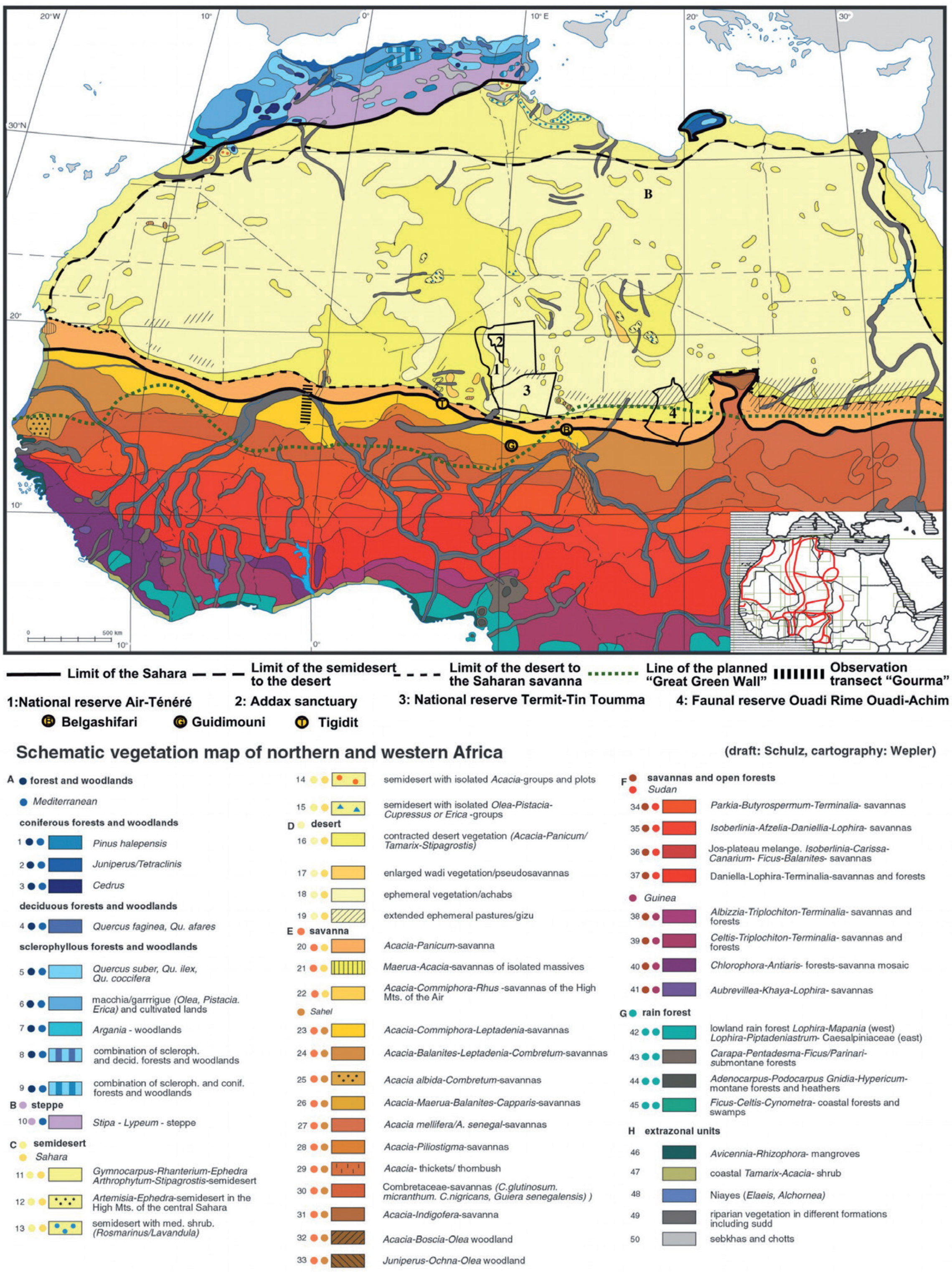

Figure 1.
Schematic presents vegetation map of northern and western Africa. Also shown are the national parks-national reserves in the Sahara of Niger and Chad and the location of the planned 'Great Green Wall'. From [27], modified and enlarged.

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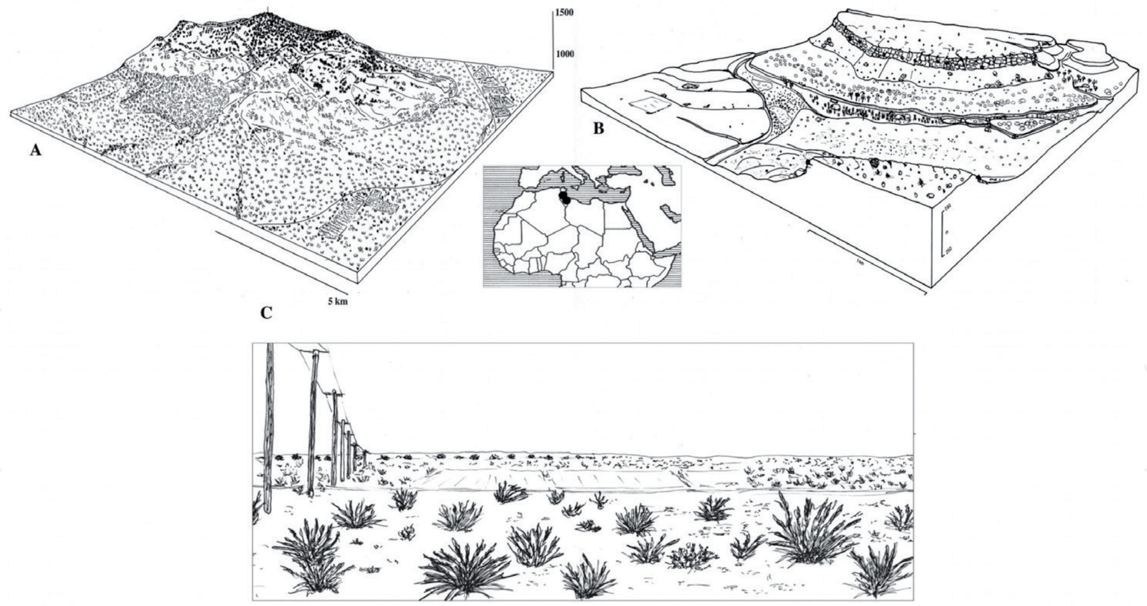

Figure 2.
Aspects of the steppe (cf. **Figure 1***, 10). (A) Block diagram of Djebel Chaambi in Central Tunisia. In the upper part, the southernmost stand of* Quercus*-forests, in the lower part the* Juniperus-Rosmarinus*-shrubs and on the plain the* Stipa-Lygeum Artemisia*-steppe. (B) Djebel Dahar, Southeast Tunisia. The southernmost outpost of steppe on the loess plateaus. (C) Aspects of the* Stipa-Lygeum*-steppe near Kasserine, Central Tunisia. Drawing Schulz.*

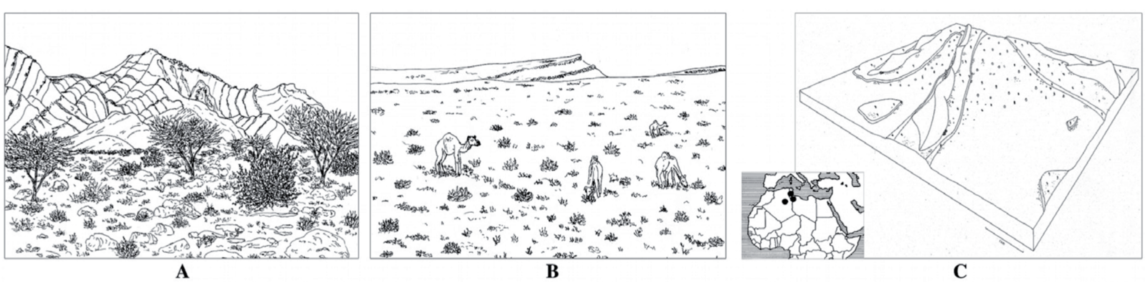

Figure 3.
Aspects of the semidesert. (A) Acacia-Rhantherium*-stands in the Bou Hedma, southern Tunisia. (B)* Rhantherium*-semidesert South of Remada, southern Tunisia. (C) The southern limit of semi desert with* Calligonum-Ephedra *at 30°N, South of El Golea, Algeria. Drawing Schulz.*

To the North, the steppe interfingers with Mediterranean *Rosmarinus-Juniperus* formations and a clear limit is hardly visible. However, at the southern part of the Sahara-Atlas, it ends with the loess cover. But there is an outpost of steppe on the loess plateaus of the Dahar Mts. in southeast Tunisia.

This follows the basic 'law of relative constancy' [30]. It means that plants or animals change the type of their habitat in the border region of their main area in order to guarantee the basic needs of the respective organism. Finally, it fits well to the original definition as a grassland under continental and wintercold conditions (**Figures 2, 3**).

4. The landscape system of the Sahara

Descriptions and characterisations of the Sahara are manyfold, see [31, 32]. Mostly it is taken as the greatest desert on earth with an extension of about 2000 × 5000 km. The area is structured by a system of wide basins and ridges often topped by mountains of more than 4000 m. Climatically, it is characterised by the interaction of the Westafrican monsoon and the tradewinds – see below. However, the most important feature is the general lack of water – a fact, which all living organisms have to cope with.

For a useful partition of the Saharan area, we need criteria, which are applicable to the whole area. Moreover, they must summarise the ecological effects of the respective region and in principle it must be visible and recognisable even in a reduced form, and it is not useful to choose volatile elements. In that way, the vegetation is the most appropriate way to characterise the whole region and to divide it in several parts. Thus, it has an indicator function. On a second level, the plant cover shall be described by its floristic content. In addition, the plant cover can be understood from detailed descriptions – even by non-specialists. And we should not forget that vegetation is the most important resource for various organisms. In that way, we will describe and divide the Sahara in units, which are easy to recognise – also from ancient descriptions.

Sahara est. omnis divisa in partes tres.......

4.1 The semidesert

South of Atlas Mts. there is a double change in landscape. It is from grassland (steppe) to shrub land and from the Mediterranean realm to the Saharan one (see **Figure 1**, 11–15). Vegetation is still diffuse, but rarely exceeds 30% of soil cover, and the greater part of biomass is below the surface. Saharan floristic elements like *Fagonia arabica, Rhantherium suaveolens, Gymnocarpus decander* or *Stipagrostis pungen*s on dunes dominate in the small- or dwarf shrub lands. It is the northern part of the Saharan landscapes – the semidesert.

The authors [33–37] claimed that the double stress by frost and drought impedes a tree development. However, the double strategy of life in the Sahara is already visible. Only a restricted number of organisms are equipped against drought and frost. On the other hand, there is the strategy of mass and accident. Aleatoric rainfall may activate the seed bank of herbs and grasses. These therophytes must fulfil their lifecycle in the short time of limited rainfall.

These accidental floras are an important resource for nomadic animal keeping.

Anyway, we must not forget that *Acacia raddiana*-stands still exist in southern Tunisia (Dj. Bou Hedma) or in southwestern Morocco. Perhaps, future records will convince us to rethink the dynamic of the northern Sahara [38–42].

The southern limit of semidesert is easy to recognise. Around 30°N (31° N in the East or along the Atlantic coast of Morocco), it changes from diffuse stands of *Calligonum* or *Ephedra* to another mode, (conracted or linear) of the *Acacia-Panicum*-type. This characterises the change from semidesert to desert.

4.2 The desert

The desert is extremely difficult to define because of the emotional component of the term (see **Figure 1**, 16-19, **Figures 4, 5**). Here, we follow the definition of Monod [44]. He stressed the difference of diffuse modes of semidesert or savanna to the contracted one – the desert. The desert is the region where permanent life is only possible in favourable places such as wadis (dry valleys) or depressions where groundwater and run off are available. Thus, permanent vegetation is contracted or linear.

It follows the oasis system, as few places, where the basic needs are guaranteed. There are several modes to cope with the scarce water resources such as the Acacia-strategy. Aleatoric rainfalls may induce germination of the seeds – perhaps already prepared by the intestines of animals. After germination, all resources are mobilised to develop a tap root to reach ground water. In that case, the plant gets independent

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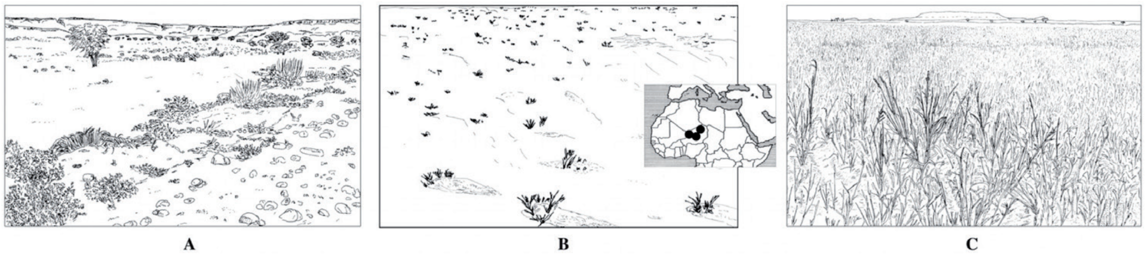


Figure 4.
Aspects of the desert. (A) Contracted vegetation in the Wadi Achelouma, northeastern Niger. (B) Achab in the Ténéré, northern Niger. (C) Wild cereal fields in the southwestern foreland of the Air Mts., N-Niger. From [27] modified.

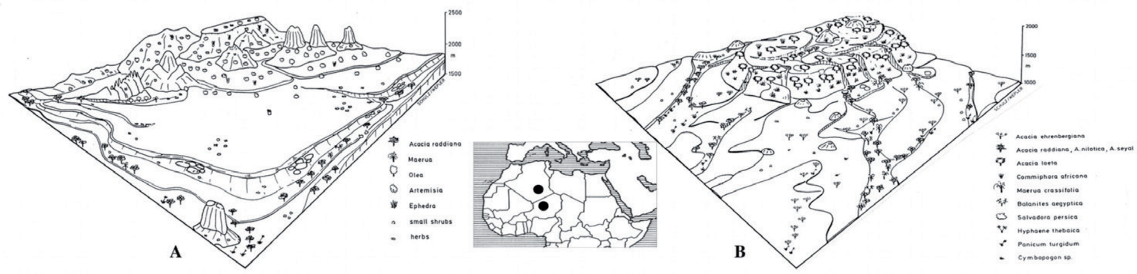


Figure 5.
The modes of altitudinal change in the Sahara. (A) From desert to semidesert (Ahaggar/Algeria and Tibesti/Chad) (B) From desert to savannah (Air Mts./Niger). From [43], modified.

from climate. However, there is the other strategy of life – that of achabs, already discussed in regard to the semidesert. The seed bank rapidly reacts on aleatoric rainfalls with a short time-flora. It may be the case once in 3 years or several times a year. There are also wild cereals as part of the achabs – an important resource for human food (see **Figure 4C**).

The contracted vegetation, mainly of the *Acacia-Panicum-* (tree-tussock grass) type, is typical for the wadis of mountain areas and their forelands (see **Figure 1**, 16, 17). Large wadis in the forelands – especially in the Southwest of Adrar des Iforas and Air Mts. might touch for a short distance but they separate afterwards. In that way the impression of a diffuse plant cover may exist. It is perfectly demonstrated by Voss et al. [45, 46] for the western forelands of the Adrar des Iforas in northern Mali.

4.3 Altitudinal change

As in other regions, the plant cover changes with altitude in the Sahara (see **Figure 1**, 12, 22, **Figures 5, 6**). There is an altitudinal change of vegetation in the High Mts. of the Sahara (**Figure 5**). In the Ahaggar Mts/South Algeria, the characteristic *Acacia-Panicum* vegetation of the desert wadis changes from about 2000 m into a diffuse *Artemisia*-shrub vegetation-a semidesert of a Mediterranean affiliation. In small gorges, some tree groups of *Olea lapperinii* or *Pistacia atlantica* exist. The Tibesti Mts. show similar features, however, on the highest peaks, some stands of *Erica arborea* survived (**Figure 7**). This is the Mediterranean type of altitudinal change [48].

The Air Mountains are different. Above 1800 m the contracted *Acacia-Panicum-* plant cover changes to a diffuse *Acacia-Commiphora-Rhus*-savanna (savanna seen as a tree grass – vegetation under a tropical climate). Thus, it is a Sahelian type of altitudinal change. **Figure 6** gives a general overview of the Air Mts. (A) with the locations of the change to High-Mts.-savannas and the upper catchment of the wadi Anou Mekkerene (**Figure 8** see below, see also [49]).

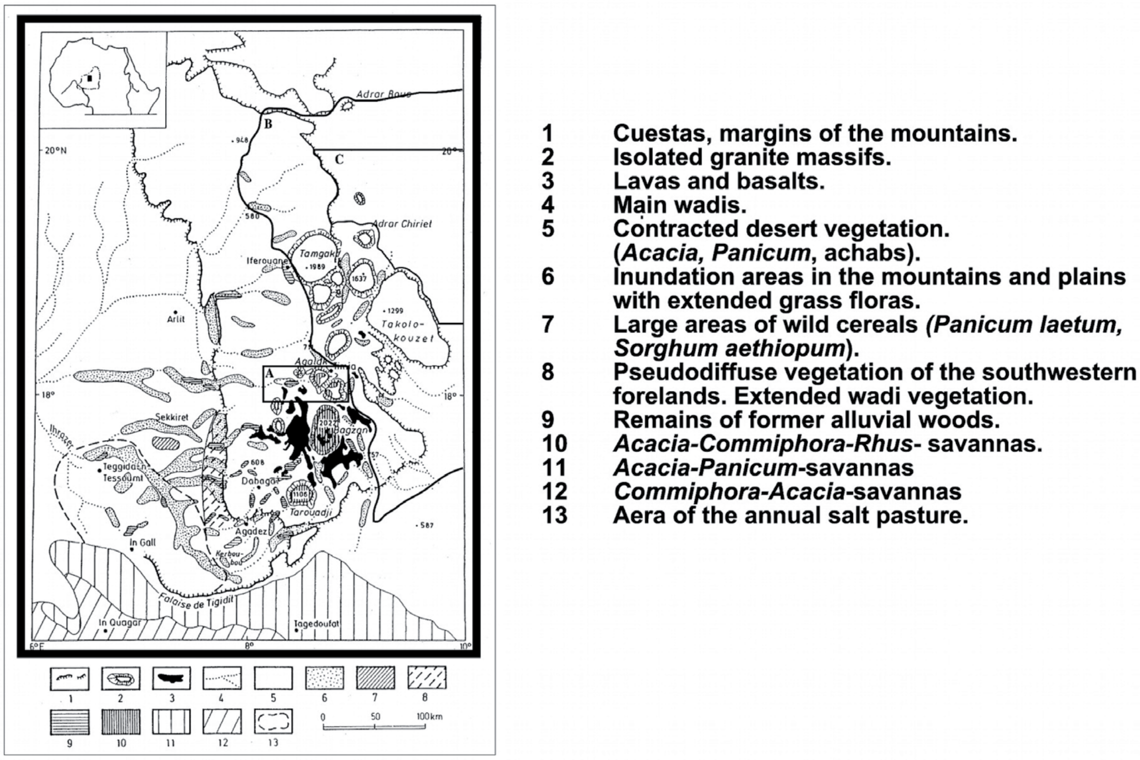


Figure 6.
Vegetation of the Air Mts./Niger and the limits of the desert as an example for the southern Sahara. Also shown are Upper Wadi Anou Mekkerene (A, see also **Figure 8***) and the Air-Ténéré-National Park (B) with its Addax sanctuary (C). From [47], modified.*

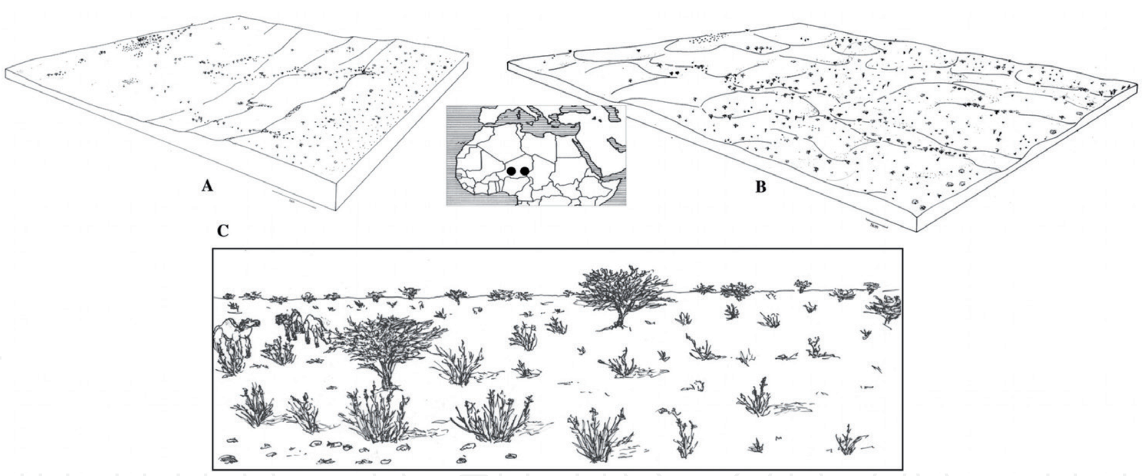
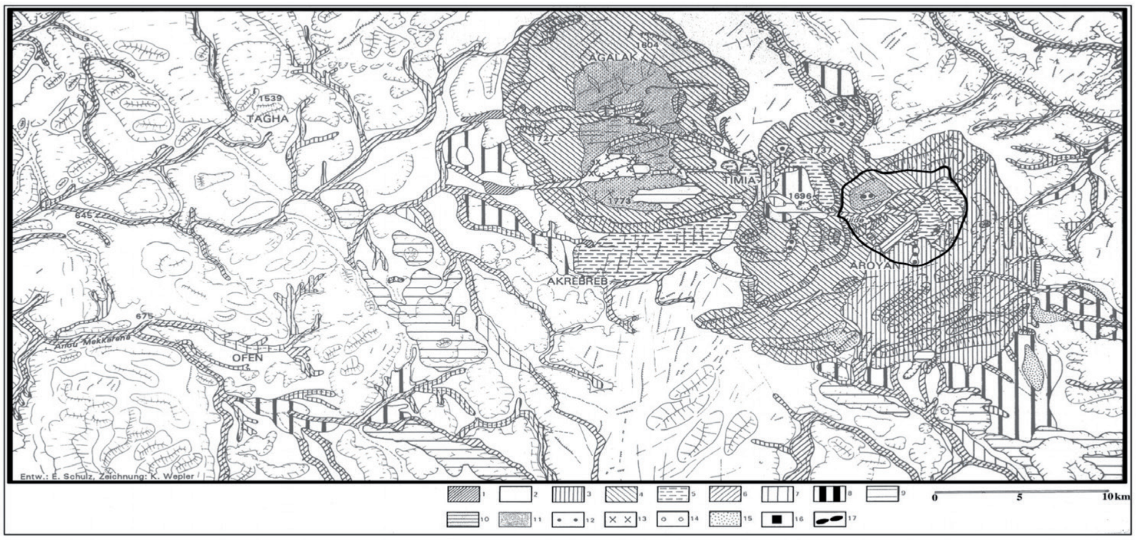


Figure 7.
*The southern limit of the desert and the Saharan savanna. (A) The passage from desert to (Saharan) savanna at the Tigidit escarpment, northern Niger. (B) The change from the linear desert vegetation to the savanna a the Belgaschifari well NE-Niger. (C) The general aspect of the Saharan Acacia-*Panicum savanna. *From [13], modified and complemented.*

4.4 The southern limit of the Sahara

In the southern forelands of the Air Mts. around 16°N/16°30′N, the aspect changes again in two steps. The first step is visible by a diffuse *Maerua crassifolia-Acacia ehrenbergiana*-savanna on the fissured sandstone-plateaus of Tigidit and also Agadem-Homodji in Southeast Niger (see **Figure 1**, 21). These savannas depend on the cistern effects of the fissures, which collect and hold water from runoff and dew [27]. On the plains, however, one observes a densification of the tree lines and the transition into a savanna of the same elements within a short distance (see **Figure 1**, 20).



1. Pseudodiffuse vegetation on the fans along the greater wadis *(Acacia raddiana, Balanites aegyptiaca, salvadora persica)*, 2. Wadi heads, smallest wadis *(A. ehrenbergiana, A.raddiana, Aerva javanica)* 3. Upper stretches of the wadis *(A.ehrenbergiana, A.raddiana,Aerva javanica Panicum turgidum)* 4. Small wadis in the mountain zone *(A. ehrenbergiana, A.laeta, Seddera latifolia)* 5. Thin vegetation lines in the weathered granite 6. Middle stretches of the wadis *(A.raddiana, A. nilotica, Maerua crassifolia, Balanites aegyptiaca)* 7. Middle stretches of the great wadis *(A. raddiana, A.nilotica, Calotropis procera Panicum turgidum)*, Garden culture 8. Inundation plains in the enlarged wadis (*A.raddiana,Maerua crassifolia, St,pagrostis vulnerans*) 9. Lava-basalt plains (*Aerva javanica, Salvadora persica)* 10. Transition to the diffuse vegetation of the slopes *(A.laeta, Cymbopogon schoenanthus)* 11. Diffuse vegetation of slopes and hight plains *(A.raddiana, A.laeta, Commiphora africana, Rhus tripartitus)* 12. Small basins in the granite (A.seyal., *Hypoestes verticillata)* Greater basins in the granite *(A.laeta, A.raddiana, Ziziphus spina-christi, Balanites aegyptiaca)* 14. Plains and pediments on basalt and lavas *(A.raddiana, Aerva javanica, Stipagrostis sp.)* 15. Inundatiion plains, achabs, 16. Sources, pools (*Ficus salicifolia, Coccinea grandis)* 17. Gorges *(A.raddiana, Salvadora persica, Balanites aegyptiana)*

Figure 8.
Wadi Anou Mekkerene and the Agalak-Aroyane Mts. of the central Air Mts. The area of the Guide pasture reserve is indicated. The difference of the diffuse mountainous savannas and the linear desert vegetation is clearly visible as well as the densification of the alluvial vegetation following down the wadis. From [43], modified.

Thus, there is the definite transition from the desert to savanna within the Saharan realm. Similar features are confirmed for northern Mauretania and Mali [50, 51]. In northern Chad, this transition is modified by substrata [52]. Large inundation plains are quasi devoid of plants, which appear only on sand ridges. On the sandy plains at about 16°N, the change into a tree-tussock grass savannah occurs similarly as it is the case for Niger. Akthar-Schuster [53] reports a comparable transition belt for the northern Sudan too. This boundary is the most disputed limit between landscape zones, as it caused the misunderstanding of degradation-desertification, etc.

Finally, the Sahara is a tripartite landscape system, where the desert takes the greatest part but has its borders to the semidesert in the North and the savanna in the South. Thus, the main change in the landscape system, that of desert to savannah, takes place within the Saharan realm.

.... quarum unam dominat semideserta, aliam deserta et tertiam savanna saharica.

4.5 The climatic implications

At this point of description, we should also deal with climatic conditions. In the aftermath of Dubief [54], the main boundaries are often paralleled to - or defined by mean annual precipitation. However, there are also dew, runoff and especially the access to groundwater which determines plants and vegetation. So, various components are summed up. Note, that two main systems interact: the summer rains of the monsoon and the Mediterranean winter rains and trade winds. We also have to consider the aleatoric rainfalls during the whole year derived from monsoon or cold airdrops from the North. They are responsible for achabs and the short time floras demonstrate their existence. The northern boundary of the Sahara is usually assigned to an annual precipitation of about 100 mm – mainly in winter. More to the centre of the Sahara mean values are fictional. Rainfall becomes aleatoric and accident is the main component in the ecosystem. The southern limit of the semidesert may be attributed to about 50 mm/y and the southern border of the desert within the Sahara is more or less parallel to 150 mm/y of summer rain. As mentioned above, both limits largely depend on the combination of rainfall, runoff, dew and storage of humidity in soil. Anyhow, these clear boundaries are among the few pure climatic ones. They are visible across the whole continent.

4.6 Life strategies

As mentioned above, there are two basic strategies to cope with the uncertain resources. These are the 'achab-strategy,' to answer with a mass of unprotected organisms to aleatoric resources – here rainfall. They fulfil their life cycle with these limited resources before returning back to the dormant state in the seeds. The '*Acacia*-strategy' includes the use of tap-and flat roots and vegetative/generative propagation. Useful rainfall is exploited by the germinating of seeds. The saplings grow in the first years below the surface and develop taproots until they reach a groundwater lens or horizon. Afterwards, they grow above the surface, develop lateral roots and are more or less independent from the actual climate.

4.7 Differences in concepts and analyses/interpretations

Different concepts may produce different interpretations. The vegetation map (**Figure 1**) differs in several points from the concepts of other colleagues especially in type and position of the southern boundary of the Sahara. We do not follow the interpretation given by Medail-Quezel [24] or White [55] for the North-extensions of the Sahel in the southwester forelands of the Adrar des Iforas (N-Mali) and of the Air Mts. (Niger) as well as for the southern half of the Air Mts. [56].

The forelands are not seen as part of the Sahel but as regions of enlarged wadis see [45, 46]. The Air Mts. are considered as Saharan desert-mountains with a Sahelian altitudinal change – as for example, the Ahaggar Mts. or the Tibesti, which do not belong to the Mediterranean out of their high altitude vegetation. White [54] takes the northernmost savannas as part of the Sahel. Another point is the statistical approach as shown by Linder et al. [57]. They define various borderlines of Sahel versus Sahara out of all zoological and floristic elements. Most of those boundaries reach several hundreds of km more to the North – into the region of plain desert. This represents the principal difference of field analysis and pure statistical analysis without any ground check. Another point is the difference and extension of the Sudan- and Guinea-zones. The concepts of the Kew and Toulouse schools [58, 59] differ at the Nigeria-Cameroon border. In that case, we follow the 'Toulouse' school.

5. The Sahel and its savannas

A few km to the South, the aspect of landscape changes again (see **Figure 1**, 23-33, **Figures 9, 10**). The savanna remains but the floristic composition differs. Beside *Acacia, Commiphora* becomes characteristic and the annual grasses like *Aristida mutabilis*or *Cenchrus biflorus* are dominant. It is the definite change from the Sahara to the Sahel. Phytosociologically, it is defined by the transition from the*Acacio-Panicion* to the *Acacio-Aristidion* [47].

As **Figures 9** and **10** demonstrate, the Sahelian savannas are intensively exploited. The northern ones are pasture areas, and millet growing dominates in the *Acacia-Piliostigma* savannas. These are cultural landscapes and they demonstrate

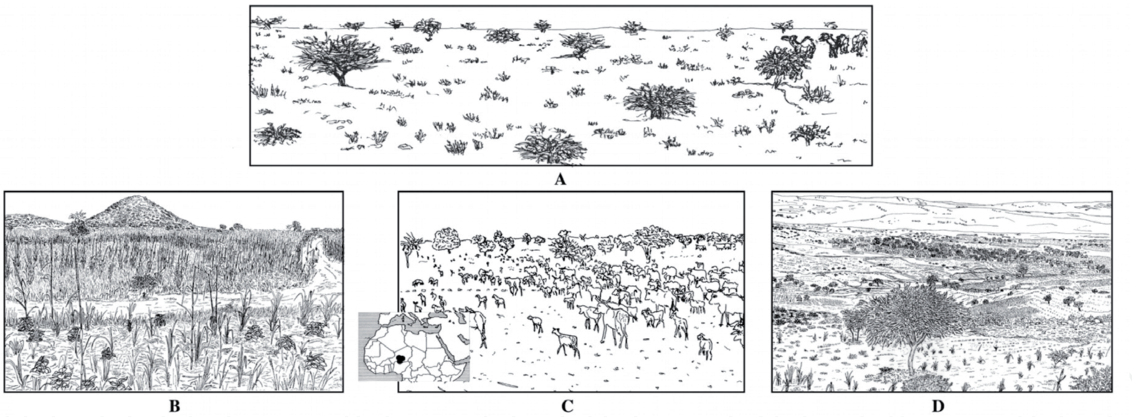


Figure 9.
Aspects of the Sahel. (A) The Sahelian savanna on the Tigidit plateau, Central Niger Acacia, Commiphora, Maerua *and annual grasses. (B) Millet fields near Birni-n-Konni, southern Niger. (C) Animal keeping near Abalak, northern Niger. (D) Desertification. The overexploited area of Ader, near Koutous, central Niger. Drawing Schulz.*

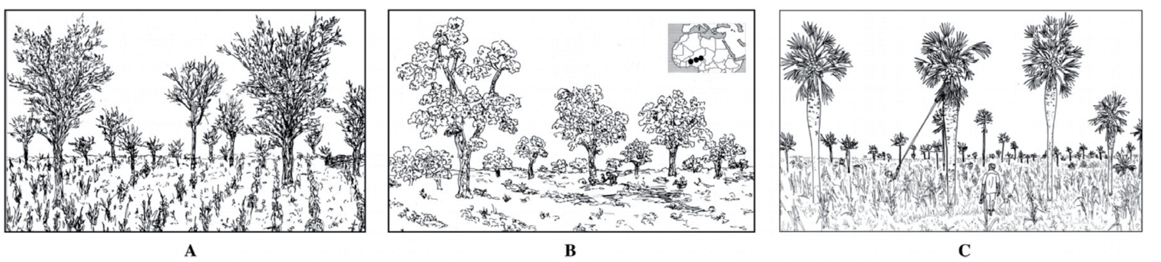


Figure 10.
The aspects of agro-forestry. (A) Faidherbia albida*-Park for animal keeping and agriculture in southern Niger. (B) Karité-Park (*Vetiveria paradoxa*) in northern Togo. Tree cultivation for fat and agriculture with the general employment of fire. (C) Ronier palm-Park (*Borassus aethiopum*), southern Niger, for various exploitations of the trees and agriculture. Former defence parks. Drawing Schulz.*

the variety of degradation. The southern Sahel is also a region of the old rooted agroforestry systems – the parks [60–62]. They are dual and integrated systems of animal (cattle) keeping and agriculture. The main feature is the two storey aspects of trees of a restricted species composition and only one or two generations. The Gao (*Faidherbia*)-parks, however, often show several generations of shrubs and trees. The intention of these parks is the production of vegetal or animal fat and agrarian products. They have been constituted by selection from a pre-existing vegetation (*Vitellaria* and *Parkia*-parks), by tolerance and assistance- as for the *Faidherbia*-parks – or by former defence plantation as it is the case of *Borassus*-parks [61]. Fire is still a part of the agricultural management.

Either it is a tool to clear land for new fields – few areas where fallow – either shifting cultivation is still practised or it is used for cleaning or sanitary purposes [63–66]. The Sahel is a savanna region and climatically it is influenced by tropical summer rains (monsoon) with a gradient from about 800 to 150/ 200 mm/y and with a rainy season of 3–5 months.

For long periods, the Sahel was only regarded as a transition zone to the real (Sudanian)-savannas [33, 50]. From the 1970s, this region was accepted as one of the consistent savannas [67] even widely transformed to cultural landscapes [68].

6. Lessons from the past. The last 200 years

Type and dynamic of landscape may often be read and understood from its history (see **Figures 11–16**). A series of more or less precise descriptions is on our

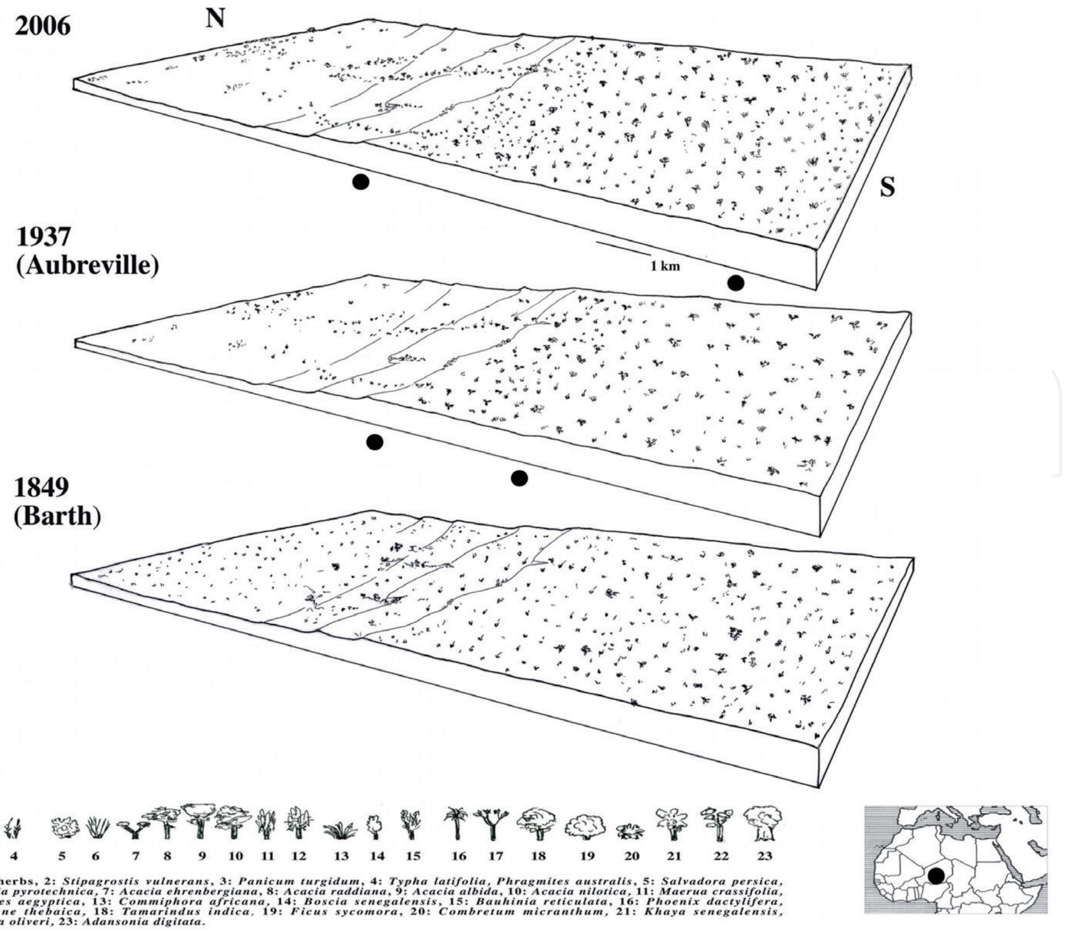


Figure 11.
The history of the southern limit of the desert and the Sahara at the Tigidit plateau, northern Niger (from [69], modified).

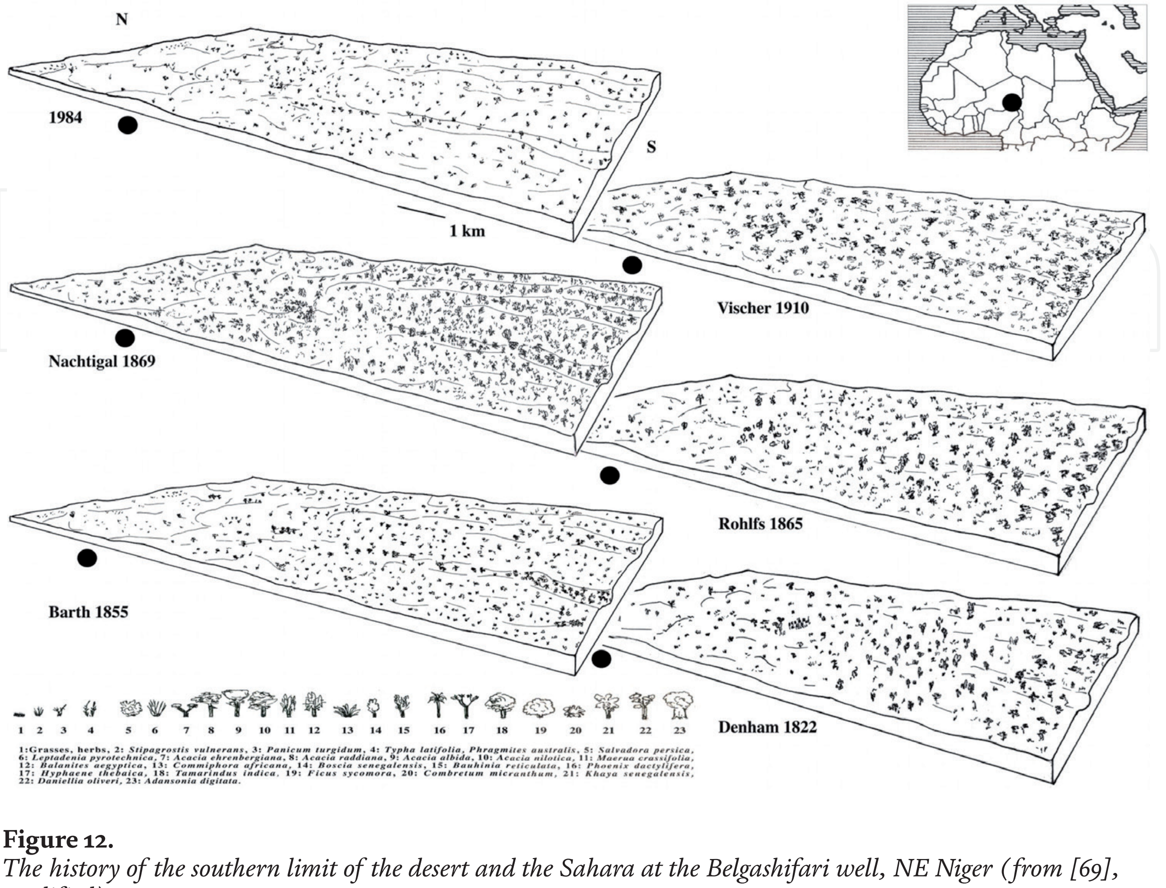


Figure 12.
The history of the southern limit of the desert and the Sahara at the Belgashifari well, NE Niger (from [69], modified).

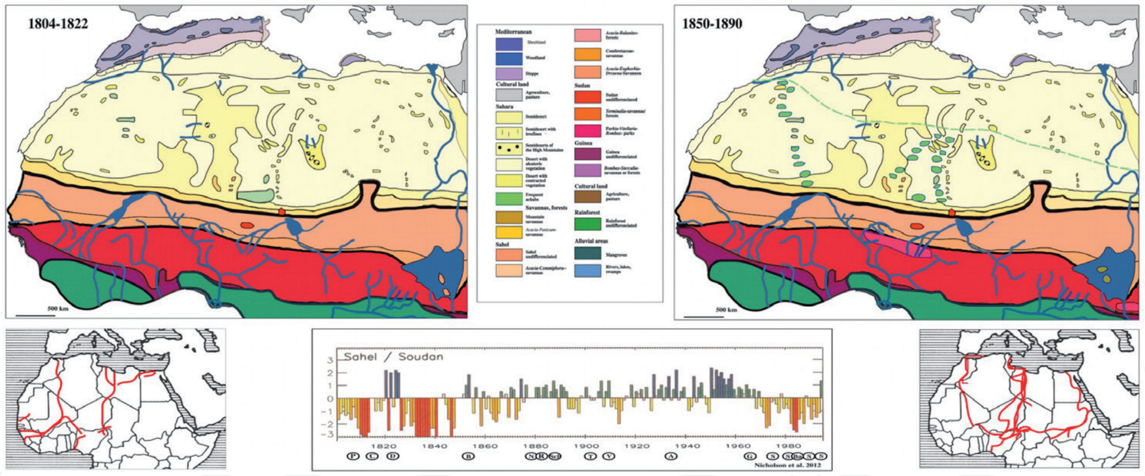


Figure 13.
Northern and western Africain the nineteenth century. Vegetation maps and a reconstruction of precipitation based on the reports of the early explorers [70]. The importance of the achabs is visible in the second half of the nineteenth century. Cartography Schulz.

disposition centred on the traditional transsaharan trade routes from the 1820s on. For the present case, the historic 'Borno-Road' – Tripolis-Kukawa and its deviation via Ghadames-Rhat-Agadez – served as a perfect source of information. It was the most frequented caravan-route in the nineteenth and early twentieth century, whereas the Tombouctou-Fez (Morocco) road was already less used. From 1822 on, we have for every 30 years a report of the voyagers [20, 71–76] on the nature of the landscapes. As wells were crucial points for the caravans, they also served as reference points in all the reports. Vegetation has always been an important topic in their reports which relied on the vernacular names of plant species – in Arabic or in other languages. Thus, we have a suitable base to reconstruct the plant cover for the nineteenth and for the first half of the twentieth centuries as we can use the indicator values of the modern vegetation.

6.1 At first, we will present the landscape changes at the desert-savanna-transition: at the reference points Tigidit cuesta and at the Belgashifari well (see above)

6.1.1 The Tigidit cuesta (16°25′N, 7°55′E)

As mentioned above, the contrast between the contracted mode of the *Acacia-Panicum*-vegetation (desert) in the foreland of the cuesta and its diffuse mode (savanna) on its top is clearly visible (cf. **Figure 17**). The dots depict the extension of the Saharan savanna and the change to those of the Sahel. At 1937, the situation was similar but the belt of the *Acacia-Panicum*-savanna was smaller and the extension of the Sahelian *Commiphora*-savanna was greater [20]. In the middle of the nineteenth century, the situation was different. A large grass cover masked the main transition and the Saharan savanna was much more extended [13].

6.1.2 The transition at the Belgashifari well (16°2 N, 13°14′E)

In 1984, the change from contracted to diffuse (permanent) vegetation was as clear as at Tigidit (see above). However, the Saharan savanna was much more extended (see **Figure 12**). In 2014, the situation was comparable, but trees were much more scarce. It was in 1822, when Denham [71] gave the first of the historical descriptions: he reported the change from desert to savanna near its present position. After a belt of a lush savanna, he described a clear change to a dense savanna.

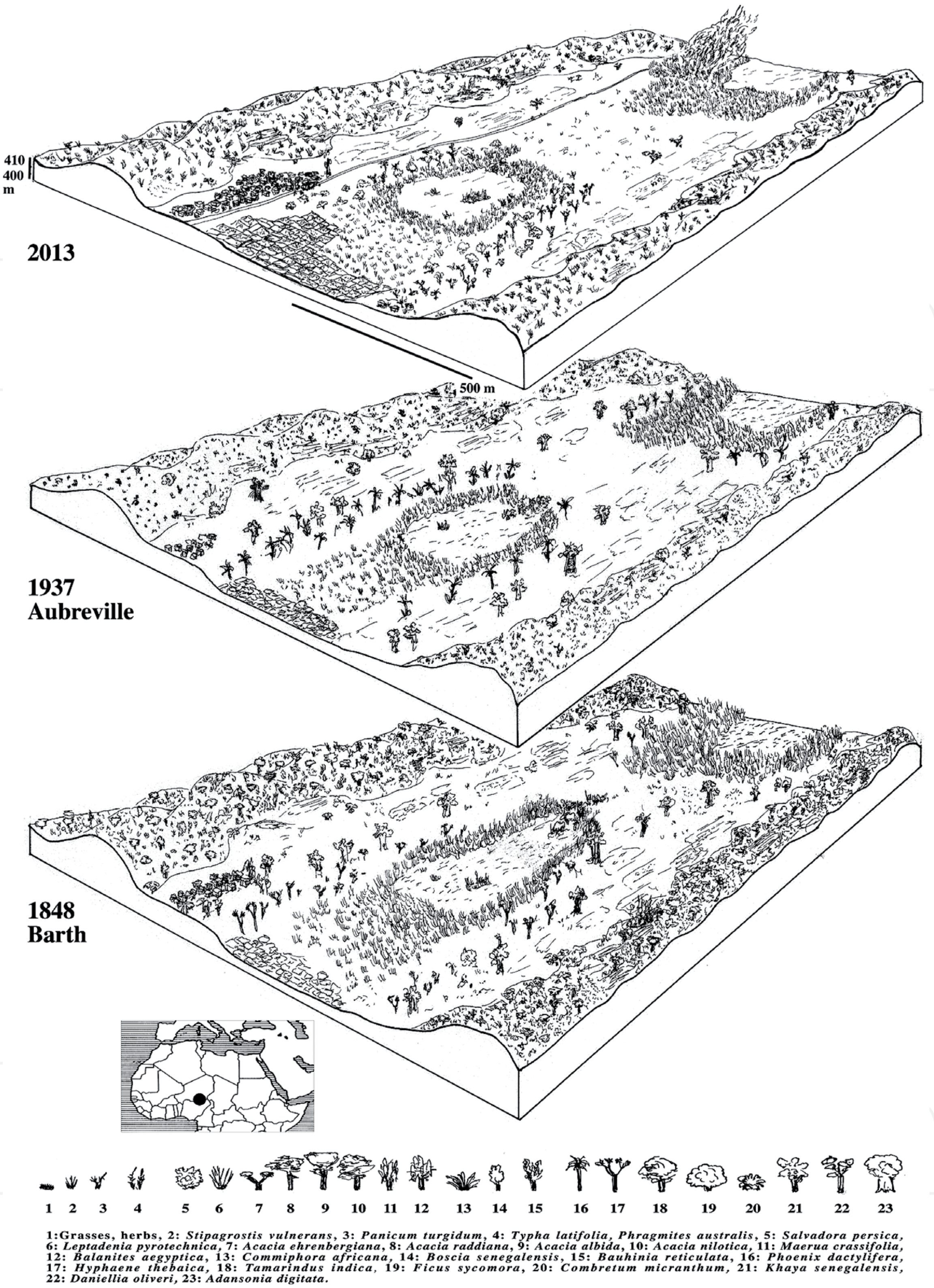


Figure 14.
The present situation and the historical development of the Guidimouni depression/SE-Niger (from [69], modified).

Thirty years later, Barth [72] saw again the desert-savanna-boundary in a similar position as at present; however, he noted a dense herb and grass cover and an important tree-vegetation in the dune depressions. Rohlfs [74] described a dense grass and herb cover that masked the main transition, and for the South of Belgashifari well, he noted a dense savanna with Sudanian trees in the dune valley. Nachtigal [73] confirmed this mosaic too. Thirty years later, Vischer [75] described a loose grass and herb cover with the desert boundary near the present position.

However, the tree cover south of it was less dense than described by his predecessors. In conclusion, we state that the main boundaries did not change their position very much, but during the 1860s, the plant cover was much more dense and diversified with a remarkable Sudanian tree vegetation reaching far to the North in the dune valleys.

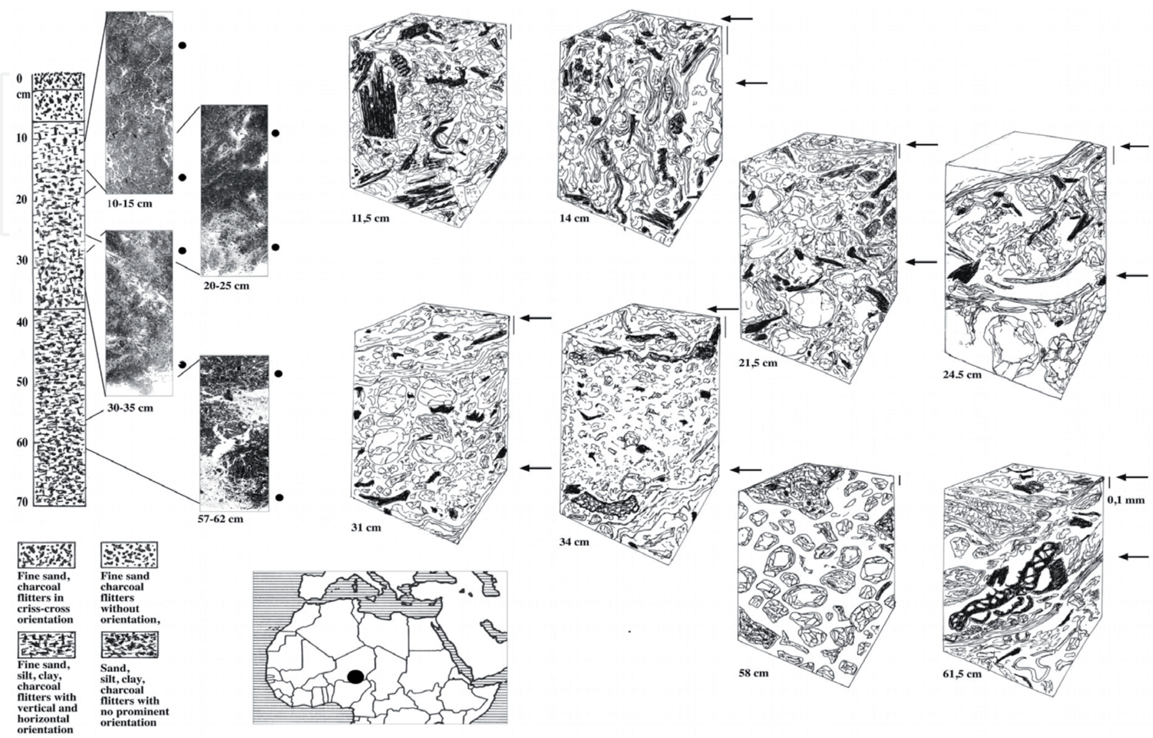


Figure 15.
The sediment structure of the Guidimouni record/Southeast Niger. It demonstrates the stability of the sediments by the formation of algea-layer sand also the steady presence offire asproved by the charred material (from [69], modified).

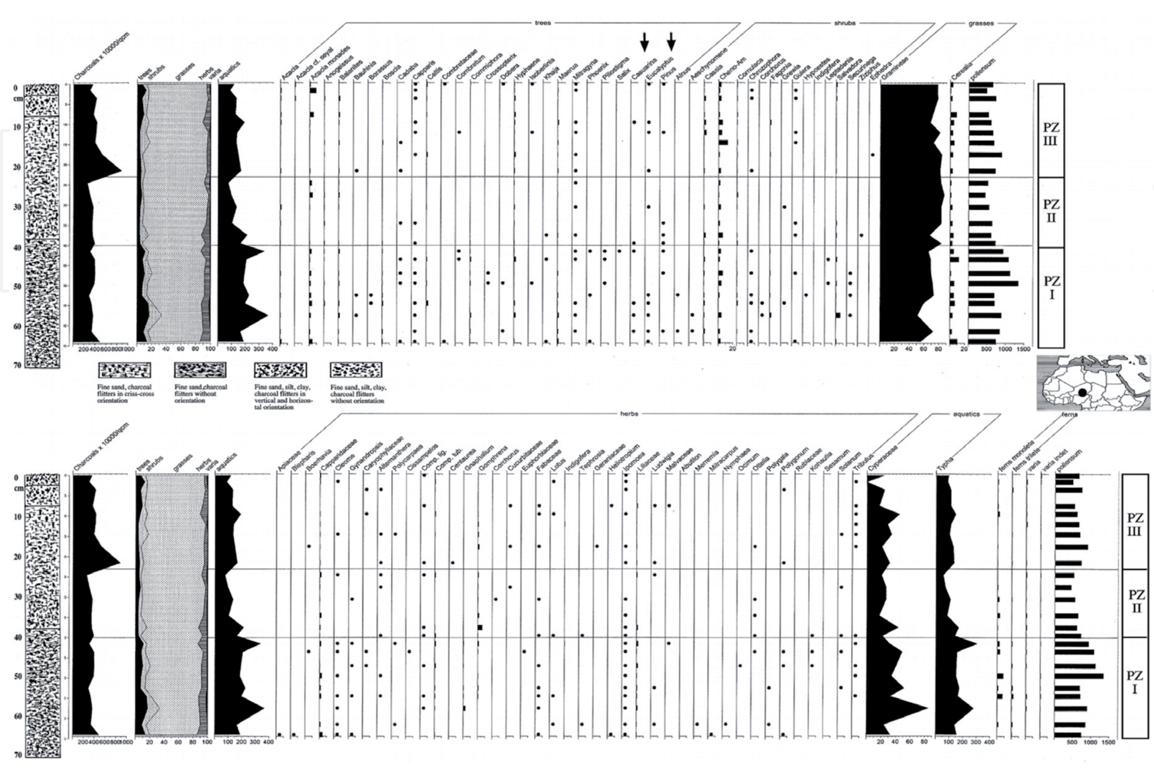


Figure 16.
The Guidimouni pollen record/ SE-Niger (from [69], modified).

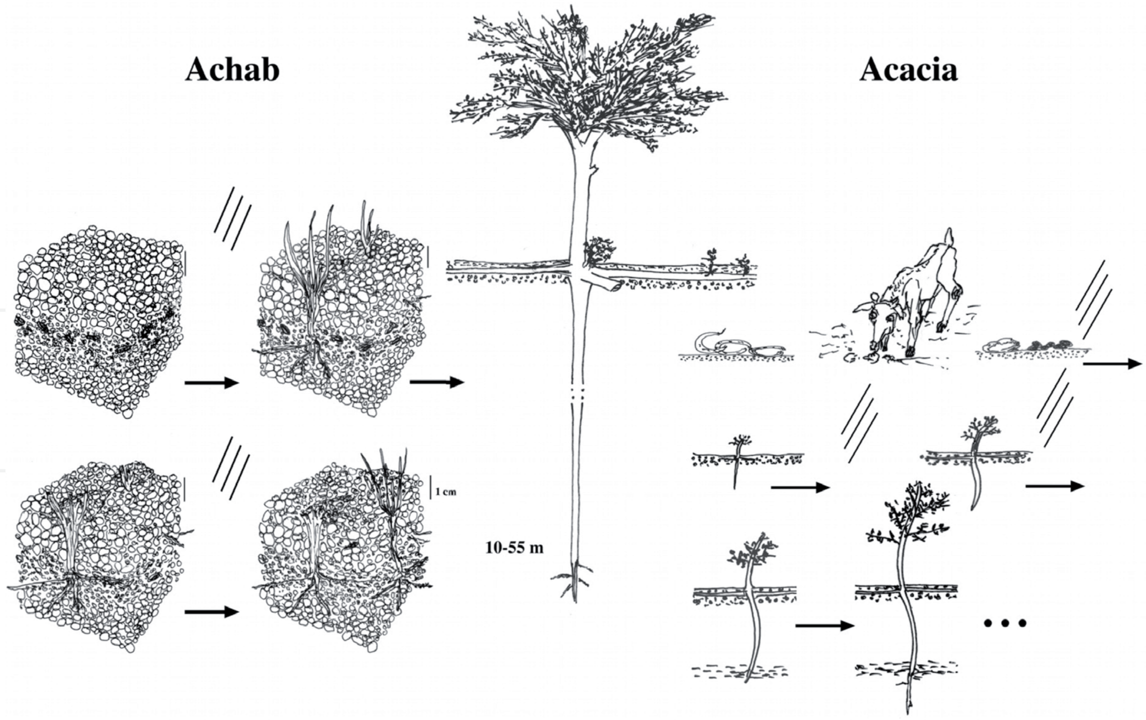


Figure 17.
The strategies of life in the desert. (A) Achab. Development of therophytes after aleatoric rainfall and the formation of a root carpet. (B) Vegetative and generative strategy of Acacia*. Deep and lateral roots with root suckers, seed germination and development of deep roots for groundwater. Drawing Schulz.*

6.2 Mapping the past

These reports made it possible to establish vegetation maps for the first and for the second half of the nineteenth century. The small maps give the expedition routes. It is clear that the information does not cover the whole area, and the interpretation is certainly limited. The maps rely on the written reports, and the descriptions for the central part of the region were the most precise ones. For the southern parts of the visited regions, the descriptions are mostly based on trees, which were mentioned by their vernacular names. Due to several robberies or damages during the transport, most collected plants were lost. Finally, the bombing and burning of the Berlin Herbarium in the Second World War destroyed the last preserved plant specimens [77].

6.2.1 Climate history

Nicholson et al. [70] reconstructed the mean precipitation for the last two centuries based on the landscape descriptions of early voyagers, early measurements and interpretations out of lake level- or sediment records. The diagram (**Figure 13**) is also marked for the expeditions of the early voyagers. The record depicts a long drought period from the beginning of the nineteenth century to about 1850 with a short humid spell around 1820. During the 1850s, some humid years occured followed by a series of dry years up to the 1870s. Afterwards, a humid period lasted with some interruptions until 1910. After another dry period up till 1920, the twentieth century, a long humid period occurred until the end of the 1960s. Suddenly, the climate changed to a long series of droughts, which only at the end of the 1980s seemed to diminish.

6.2.2 The vegetation

Mapping is based on the present vegetation map (**Figure 1**) and documents the differences, which could be read from the historical reports. The two maps show similarities and differences. They correspond in their regular presence of trees in the northern semidesert and in the position of the southern boundary of the Sahara. The Sahel region was described for extended *Acacia*-thickets and forests in the northern part and Combretaceae-savannas in the South. The Sudanian region was similar to the present one; it was, however, denser. A further differentiation was not possible. But the presence of parks was regularly mentioned. The rain forests were much more extended and consequently the Guinean zone much more restricted – compared to the present situation. The most important information lies in the regular presence of achabs in the Sahara during the second half of the nineteenth century. We conceive quasi-permanent pastures by repeated rainfall in the Sahara up to 25°N. Certainly, this was the base of a strong nomad economy providing the base for their dominance over sedentary people.

All voyagers agreed on the rich and diverse game in Sahel and Sudan. They mentioned in particularthe large elephant populations. Together with the large extension of *Acacia*-forests-thickets, we have to think on elephant-landscapes [78–82]. Elephants are known as landscape engineers. They produce a twofold landscape. For the one they transform forests to medium high thickets by positive and negative selection of tree species and the elimination of high trees and for the other they also create new structures. They open the forests for their tracks giving chance to grasses, herbs or shrubs with a ruderal behaviour. In this way, they form thickets and provide dry and combustible material. So, elephants also create fire-prone landscapes too. Elephants are bound to water and they make or enlarge pools for drinking, bathing and also the uptake of minerals. As they are social animals with a long life period, they school their young generations to maintain and preserve these types of landscapes. The *Acacia*-thickets around lake Chad or in northern Cameroon give an – even poor – model of these former landscapes.

6.3 The landscape history of the Sahelian savannas during the last 100 years. Guidimouni – a key locality for the Sahelian savannas

In addition to the historical descriptions (see above), we also dispose on physical archives,which describe the landscape evolution during the last 100 years. They come from southeast Niger. The dune depression of Guidimouni in southeastern Niger has been described several times in the last 200 years [20, 72]. Moreover, it was possible to core the upper part of the lake sediments [76].

6.3.1 The physical situation of the Guidimound depression

A long interdune depression in SE-Niger (13°42′N/9°32′E) represents the situation of the Middle Sahalian savannas (see **Figure 1**). The region is part of that area, which was supposed to be endangered by an enchroaching desert [19]. The depression has two lakes which are fed by fresh water sources assuring a more or less permanent water body.

Figure 14 depicts the present situation of the depression and its recent history. The upper diagram shows the whole depression in its present situation. A degraded Middle-Sahelian savanna surrounds the lake, mainly consisting of *Acacia*- and *Balanites*-trees, *Leptadenia*-bushes and grasses. At present, it is still a regular habit to burn the reed in spring in order to have space for gardens and fields. In parallel, the *Leptadenia*-bushes on the dunes are cut and the branches afterwards burned (slash and burn) to prepare new fields after a fallow period of several years. Soils in this region belong to the arenosol-, regosol- or chambic-arenosol groups [83].

In 1848, Barth [72] described the Guidimouni depression as densely vegetated by grasses and herbs the dunes bearing an *Acacia-Commiphora-Leptadenia*-savanna. The depression itself had an *Hyphaene-Phoenix*-belt around the *Typha*-reeds. Also some *Adansionia* trees were planted. A comparable picture was given in 1936 by Aubreville et al. [20]. However, the savannas on the dunes were not as dense as Barth described it but some Sudanian trees were still present, such as *Daniellia sp.* This situation was one of the strongest arguments against the idea of an enchroaching desert.

6.3.2 The Guidimouni sediment record

The sediment core was taken in 2013 in order to reconstruct the recent landscape and vegetation history [69]. The lakes of the Guidimouni depression are shallow lakes or ponds, and they are not more than 2 m in depth. However, their surface varies much during the year. In drought periods, the lakes may dry out (see [83]). Thus, one has also to think on the risk of disturbance by wind and breaking waves and also of deposition gaps caused by desiccation. A 70 cm-long tube could be enforced into the sediments of the western lake. The sediment record consists of silty or sandy gyttias with a variable content of organic matter. Four thin sections were made in the Mineralogy Department of Szeged University, Hungary. They should help to understand the sedimentation processes and also detect possible zones of reworked sediments.

At a first look, the sediments seem to be uniform or amorphous. However, at 400× magnification, it was possible to discriminate into two mayor features, which are explained by **Figure 16**. Under a disturbed section of about 12 cm, the deposits are organised in fine – millimetric – layers, which are separated by algae/bacteria films, respectively, by their jellies. These are always densely coloured by Fe-oxides. The uppermost sediment is mixed and does not show a distinct structure, but it depicts the presence of diatoms. Thus, the sedimentation starts with an inwash/inflow of sandy-silty material and alterated organic matter. On this layer, a film of algae/bacteria-jelly is formed indicating a eutrophic and energy-rich shallow water body. It fixes the sediment beneath. Small arrows indicate the positions of these films. However, the water-rich and unstable layers of the upper cm are exposed to wave action, slumping phenomena or other disturbances. So, they may be contorted, displaced or mixed again. The upper two columns of **Figure 16** show these phenomena. The central part of the record (about 20–53 cm), however, is mainly made of sands or silt, but still separated by the algae layers. There is information that this part belongs to the drought period of the 1970/80s. During this time, the lakes became almost dry as reported by locals (Adamou, frdl. comm.). Anyway, a certain amount of water still must have persisted to allow the formation of the algae/bacteria films. The lowest thin section depicts an in-wash of weathered middle and coarse sand and a dense organic rich gyttia, which again is divided by algae/bacteria layers. The general formation of bacteria/algae films will counteract the disturbance effects of waves in the shallow water. Considering these facts, a sampling with a distance less than 5 cm seemed not to be useful – out of the disturbance risk.

An important feature is the regular presence of charred material. It is made of grass coal-flitters consisting of cuticulae, leaves or parenchyma remains. Charcoal from wood seems to be very rare. These flitters are kept in the thin layers and are oriented along the algea-films. Thus, during the time of the deposition of the record, fire always was an important part of landscape dynamics. At present, the inhabitants regularly use fire to clear the dune area and the reeds in order to prepare their fields. So, it is likely to adopt this model also for the past. It is indicated by the regular presence of grass-coal flitters. Coarse ones will not have been transported over long distances.

6.3.3 Vegetation history of the last 100 years

The detection of the stabilising bacteria/algae films visible in the thin sections allowed exploiting the record for pollen analysis. The diagram (**Figure 16**) was constructed on the base of all pollen but aquatics were excluded. The most of the arboreal and non-arboreal elements show only values of less than 1%. Thus, they are only represented for their presence in the diagram. The pollen diagram is characterised by the elements of an open Sahelian savanna of the *Acacia-Balanites*-type. Dominant are grasses and aquatics (*Typha,* Cyperaceae). Cerealia are persistent.

The arrows point to the *Casuarina*- and *Eucalyptus* curves.

Three pollen zones could be discriminated on the base of the variation *Typha*-Gramineae for the one and for the other on the base of the diversity of floristic elements:

PZ I. 65–40 cm: The aquatics have high values against the low values of grasses. Arboreal pollen shows a relatively high diversity including some Sudanian/Sahelian elements (*Guiera, Khaya*, Combretaceae).

PZ II. 40–23 cm: The part of the aquatics is reduced by rising values of grasses. The diversity of arboreal and non-arboreal elements is reduced too.

PZ III. 23–0 cm: There is a rise of the aquatics against reduced values of grasses. Trees and shrubs recover but do not reach to the diversity of PZ I.

6.3.4 Charcoal

The charcoal record, which mainly consists of grass coal, depicts the general presence of fire in the region as it is. It still today comprises flaming of the reeds in order to get place for new fields and also slash and burn on the dune slopes. The sharp rise in PZ III represents an accelerated burning for new fields after the end of the drought period.

6.4 Time frame

The nature of the sediments will not allow a radiocarbon dating. However, the presence of *Eucalyptus* and *Casuarina* (see the arrows in the diagram) shows that the sequence is not older than the beginning of the twentieth century. The colonial authorities of Nigeria planted both tree species as ornamental or afforestation elements as well as roadside-trees [84, 85]. Their pollen takes part in the long distance transport. Thus, in combination with sediment modes and the fact that PZ II is apparently contemporaneous to the desiccation of the lake during the drought of the 1970s up to the beginning of the 1980s, the base of the core might be deposited during the l920 years.

The only comparable record reaching to the present time is that of Oursi in Burkina Faso [86], which shows a similar open vegetation due to extensive agriculture and animal breeding. However, the record of grass coal stands unique also compared to the upper parts of the Manga lake records [87–89]. But tiese lakes did not provide suitable sediments to follow them up to the present. This record is the first to discriminate between the two main elements in the charred material (grasses and trees) – at least for the Sahel.

7. Regeneration. A confusion of concepts, different observations and realitiy

The discussion about regeneration is controversial. There is the position of a definite or long-time degradation, which Miehe et al. [90] explain by a short time of resilience and then a declining to a lower ecological equilibrium. This corroborates the conclusion from the Guidimouni-record as presented above. Hahn and Kusserow [91] and Kusserow [92] report a severe degradation of the Sahel from remote sensing over a long period and also report the algae crusts on silty/clayey sediments as indicators/results of a definite decline of savannas. However, she states that sandy environments will much faster regenerate. Thus, it is necessary to differentiate between the types of environments and also to take the periods of observation into consideration.

7.1 The first steps of regeneration

An example is given by the investigations in the Guidimouni depression (see above). Field work and observations on the lake-cores structure revealed the general regeneration potential of soil surfaces on sandy and clayey sediments. The upper centimetres of the dune tops and their middle slopes expose fine layers of blown sand which are covered and fixed by bacteria/algae films together with their gelly formations (biofilms). These biocrusts are the first stages of reorganisation and they represent a general phenomenon in its bimodal feature: deposition of a mineral layer which is afterwards settled and covered by bacteria and algae. This represents a general phenomenon of soil surface organisation: that of film like OPS/PSO (pellicular surface organisation) in the sense of Pomel [92], see also [93–95]. Thus, it is obvious that even under intensive exploitation, the tendency of regeneration of vegetation and soil still exists.

The general mode of sandy crust formation is explained by **Figure 18** (above). The upper series represent the regular repetition of coarse and fine sand layers mainly fixed by cohesion as it is the case for sand layers in the desert described above for the achabs. Anyhow, the normal development is that of biocrusts as represented in the middle series. The ever present spores of cyanobacteria and algae germ rapidly and create a biofilm of jellies and thus stabilise surfaces. The algae belong to the *Nostoc*- and *Lyngbya*-realm with a nodular and chain-formed appearence [91]. When covered by another sand layer the bacteria/algae will rapidly form another cover. Even though these crusts are fragile and may crack easily, they enable a further succession of grasses and herbs as a next step. Seeds may be blown in cracks and they may germ and exploit the nutrition reserves of the biocrusts. Finally, these crusts may be seen as functional types representing the early stages of soil development [96, 97].

On silty/clayey stones or sediments, the situation is different as **Figure 15** (below) may show. The surface of these fine grained rocks or shallow soils are often covered by thick cyanobacteria/algae layers which may reach to several mm thickness (cf. [91]). They are coherent and impede an implantation of seeds. When covered by dust or fine sand, they easily reform. Finally, their smooth surface is water repellent and for longer periods, they may be an obstacle to a colonisation of grasses or herbs – not to speak about trees.

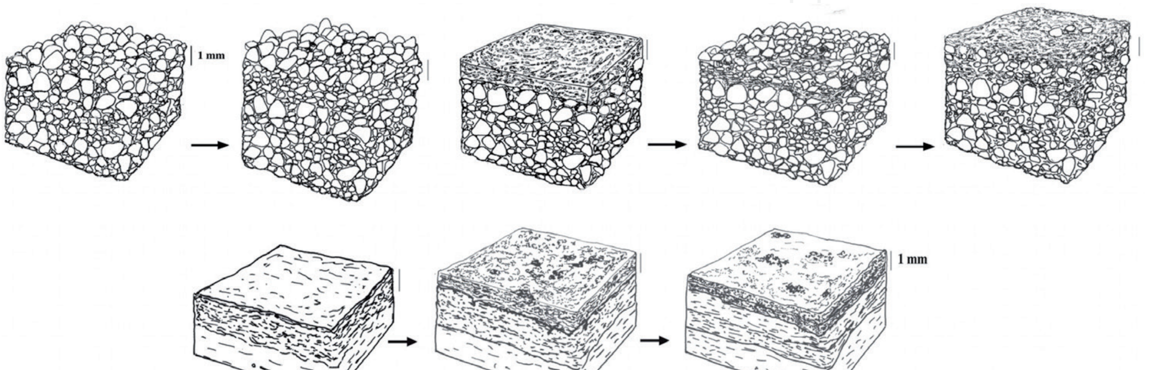


Figure 18.
The first steps of regeneration and biocrusts in sandy (above) and clayey (below) sediments (from [69], modified).

In contrast to them, the rapid regeneration mode of the cyanobacteria/algae crusts on sandy soils is successfully exploited in the dune rehabilitation of Northern China [98, 99]. The crusts are collected, crushed and afterwards sprayed over loose sand surfaces or dunes, which gives a good example of working with natural succession.

7.2 Regeneration in the landscape scale

If one regards the philosophy, performance and success of the various projects which are active or planned in the Sahel, we have to differentiate between the large scale technical ones and those, which are adapted to the conditions of the population.

7.2.1 Gourma – guide – great green wall. The limits of regeneration

Among the large-scale projects, we have the extended dune fixation by fencing and tree plantation [102] or the transcontinental 'Great Green Wall' [17, 18] still based on the idea of an extending desert (see **Figures 8, 19, 20**). The second type is the creation of large natural reserves or national parks in the Sahara and the Sahel. They are initiated or proposed for auto-regeneration of vegetation and wildlife – following mostly the WWF-philosophy see [14, 16]. Very often their aim is to protect emblematic animals, which are supposed to act as key stone organisms (see for both **Figure 1**).

The opposite is the creation of pasture-rotation systems to exploit the limited resources but also guarantee their regeneration. Finally, they are the counterparts of the old shifting/fallow cultivation, which by now in the Sahel is only rarely carried out. Several examples will illustrate these projects.

7.2.2 The rotation pasture system 'Gourma'

The northern part of the Gourma region (Mali) from the Niger-bow to the mountains of Hombori (17°-15°N) is a perfect example of Middle and Northern

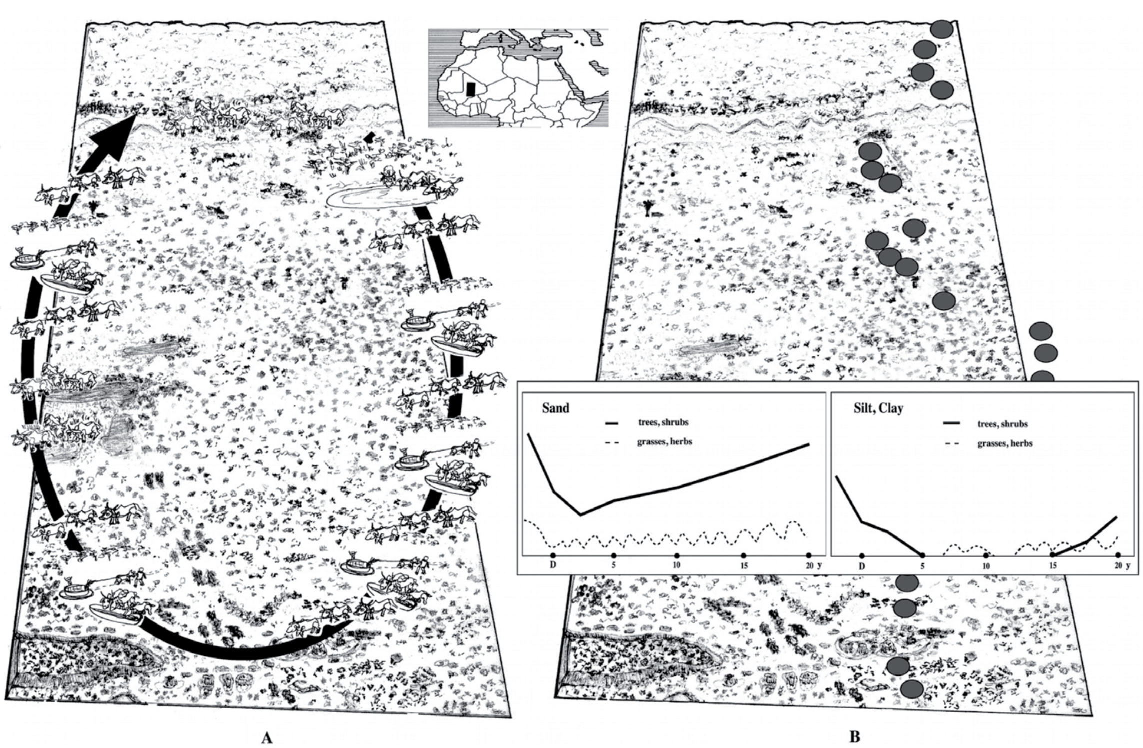


Figure 19.
The pasture-rotation system of Gourma/Mali during the 1970s and 1980s and the long time observation project of regeneration up to 2017. Graphs on regeneration without scale [8, 100]. Drawing Schulz.

A B

Figure 20.
The pasture rotation project 'Guide' in the Central Air Mts. [43, 101]. (A) The Wadi vegetation in the innerpart of the ring structure. (B) The regeneration of trees and shrubs after the second year of closure. See also the dense herb cover under the Acacia*-umbrellas. Drawing Schulz.*

Sahel-savannas. They range from a Combretaceae-savanna of tiger bush in the South to the *Acacia-Commiphora-Balanites*-savannas of the North. East of Tombouctou there even existed a real *Acacia*-forest, which was formerlyx exploited for the steam boat lines to Bamako [103–105]. The savannas represented for long time a rich pasture, which could not be exploited [100] as only a few wells or water points existed. Thus, human impact was restricted to the river-banks and the northern savannas, where the cattle keepers had constructed a series of hafirs (rain fed pools). The other regions were the oxbows of river Niger in the West and the agriculture areas near the mountains in the South. Instead there was an intensive elephant pasture creatred by the greatest herds of West Africa [106]. Probably, these savannas may be regarded as the gullivers of elephant impact [107], giving a good example for the reports of the voyagers of the nineteenth century (see above). Only a few wells were constructed in the first half of the twentieth century. But the aureoles of overgrazing developed rapidly around them. With the drought of the 1960s, the Sahel started to degrade. However, in the Gourma, it went differently. Together with the local cattle keepers and authorities, the geologist R. Reichelt from CILSS developed a rotation system of new wells and pasture. It was based on the opening and closing of wells depending on the state of the pastures around, which were regularly controlled. When degradation started, the wells were closed and the cattle keepers were obliged to proceed to other wells and pastures. This system worked from the end of the 1960s on and revented the desertification phenomena, which had hit the regions around. But in 1984 – at the peak of the drought, a great number of cattle keepers from then North of Niger River invaded the region. They were not familiar with the rotation system and did not respect it. After severe quarrels of the herders, the rotation system collapsed.

Anyway, for long years, it represented a sustainable pasture system, which saved the Gourma region from the desertification as it occured in the regions around. It is one of the curiosities in science that these experiences were completely forgotten and were not taken into account in the whole discussion on desertification and regeneration management.

From about 1984, a long time observation project (see **Figure 19B**) was installed in the same region. Its goal was to follow the degradation-regeneration processes under various conditions and exploitations [8]. It was a multidisciplinary project mainly based on field observation and remote sensing. It could evaluate the regeneration chances of the different savanna systems and it well demonstrated that regeneration started early on sandy substrates both for herbs and trees, but on clayey sediments degradation continued even after protection. Here, the regeneration started only after a long period, which corroborated the experiences from other regions (see above). But the general insecurity of the regions forced the colleagues to abandon the project in 2014 [4].

7.2.3 The pasture rotation project 'Guide' in the central Air Mts

The extreme degradation of herb and tree pastures in the Air Mts. on the one hand and the octroyance of the Reserve Naturelle de l'Air et Ténéré (see **Figure 6**, [101, 108]) with the exclusion of the herders from traditional pasture areas on the other initiated the planning of a new regeneration concept together with the local authorities of the Timia village in the central Air Mts. [108]. **Figure 8** explains the general situation. It shows the two granite ring structures of Agalak and Aroyan and the upper part of the Wadi Anou Mekkerene, one of the greatest of the Air Mts. And it also depicts the altitudinal change in the Air Mts. from the mountain savannas to the middle stretches of the wadi Anou Mekkerene heading to the West.

Within 4 or 5 years, a rotation system, which functioned on the closure of pastures for several years, aimed to assure the regeneration of grasses, herbs and trees. At the same time, a sustainable exploitation system of the pastures should impede a new degeneration by overgrazing or other forms of over-exploitation. The first of these closures was the mountain pasture 'Guide' southeast of Timia (see **Figures 6, 8**). It is situated in the Aroyan-granite ring structure, which could easily be closed in 1986 for 4 years. This area showed the typical transitions from the contracted desert vegetation to the mountain savannas of the Sahelian type. The soil cover of vegetation did not exceed 10% but could rise to 70% under the umbrella of Acacias. The first years showed an enormous growth rate of trees as well for the seedlings-saplings as for branches and twigs —30 cm – for *Acacia* and *Maerua*. Apparently, trees could profit from the good rainy season and from the reduced concurrence of herbs, which suffered from the preceding drought. In 1990, a first two-days-opening was organised for fruit collection and grass cutting. The enclosure was mapped for vegetation, a floristic inventory was organised and also some demilunes/half moon sand accumulations and stone lines were constructed in order to collect rain water [101, 109]. Within 4 years, the development of tree and grass pastures was as astonishing high, and also people from other villages had planned to initiate comparable systems. After the controlled opening in 1991, a second pasture was closed for regeneration. For the long run, the village council discussed the models of an interdiction of pastures but with controlled collection of grass and fruits or controlled pasture. In the mountain savannas, the protection and controlled collection of medicinal herbs was an attractive point too. Anyway, a permanent following up of vegetation development was planned for the future. The Guide-project evidenced the chances of local and accepted regeneration initiatives and it could have been a model for other regions. Unfortunately, as for the Gourma project, the rebellion and the successive insecurity put a premature end to this success.

7.2.4 Think big! Bridging Sahara and West Africa

7.2.4.1 National parks or natural reserves

The creation of extended reserve areas or national parks have been generated by the ideas of an auto-regeneration through excluding further human exploitation or through the protection of emblematic animals as key stone organisms.

For the Sahara, the three National parks or natural reserves of Air-Ténéré (see **Figures 1, 6**), Termit-Tin- Toumma and Wadi Rime-Wadi Achmed in Niger and Chad should protect huge ecosystems and also support regeneration of vegetation and wildlife (see **Figure 1**). These are the greatest protection areas in the Sahara and in Africa as a whole and were supposed bridge the areas of endangered key stone animals [15, 16, 110]. Moreover, there was already a survey on the chances to establish a system of monetary exploitation of ecosystem services [111]. However, these initiatives often disturbed the traditional pasture systems, and due to the insufficient involvement of the local populations, it led to various problems and frictions. Anyhow, the sense of these protections and reserve areas was not really communicated to and accepted by the concerned populations. Thus in the 1990s, with the beginning of the rebellions in Mali, Niger and Chad, these projects were no longer accepted by and the state could no longer maintain them. Today, most of them gained a status of 'being endangered' or 'in suspense' [112]. At present, the natural reserve Air-Ténéré continues in a certain cooperation with the local population in order to manage resources [113].

7.2.4.2 The 'Great Green Wall'

This is the continental flagship of the protection-regeneration projects and follows still the philosophy of expanding ecosystems and the combat against them (see **Figure 1**). The project was created by the African Union in 2007 [17, 114] as a 7800 km belt from Senegal to Djibouti. Fifteen kilometres wide, it should work as protection against wind and erosion. Afforestation should provide nutrients to the soil and also ameliorate pasture by foliage and shadow too. Finally, the tradition of agroforestry (parks see above) was taken as a model (see also [115]). Research on amelioration of soil and plant fertility is an important part such as investigation on the symbiosis of bacteria/fungi and acacias. Anyway, as for the other smaller or greater projects, this initiative came to an intermediate (?) end caused by the general insecurity in the concerned areas. But the research in the various institutes of the partner states continues in the hope to reactivate and readjust this flagship. However, it already serves for the governmental propaganda. The presidency of Niger claimed to have plated millions of trees in order to reduce soil erosion and to fix dunes [116].

7.3 'Small scale' as a chance!?

Several projects and activities concentrate on the regeneration and amelioration of degraded soils in order to restore the soil cover and to assure food production [117, 118]. They are mostly organised on personal or village level and so they are participative. These activities have to be seen on the background of a general extensification of agriculture, parallel to the intensification, e.g., irrigation cultures at favoured places [119]. Most Sahelian farmers are still subsistence-oriented. This means that they mainly crop to nurture their families rather than to produce market products. The steadily increasing population with growth rates of about 3%

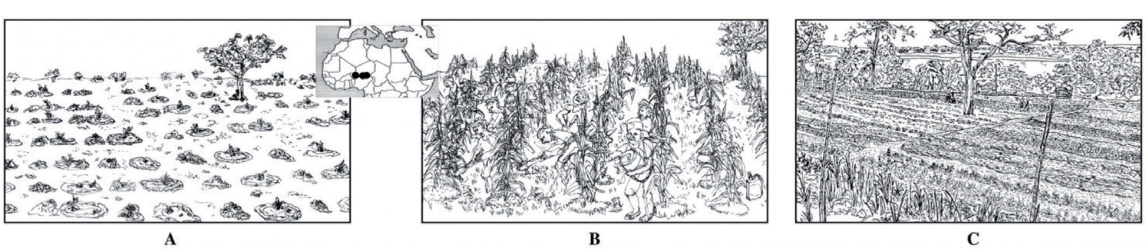


Figure 21.
Regeneration and food security measurements in Niger. (A) Tassa /Zai-cultivation on the Ader-plateau, Central Niger. (B) Reduced weeding in S-Niger. (C) Intensive irrigation for vegetable production at Niamey, Niger. Drawing Schulz.

per annum leads either to an expansion of cropped surfaces to marginal land or – where the population density is already high – to decreasing cropland per family. Several examples illustrate these activities (see **Figure 21**).

7.3.1 The restoration on heavily degraded soils

The 'tassa' or 'zai' culture (**Figure 21A**) is an old cultivation system of degraded soils [120]. It is based on dug in holes, 10–40 cm in diameter and 10–25 cm in deep in a distance of about 1 m. These holes can store rain and run off and thus support the regeneration of spontaneous vegetation. They may be filled with leaves or compost in order to attract the termites.

Experiments showed the possibilities of 640 kg–800 kg/ha yields of millet. The dug in holes must be renovated each year. As the financial component is quite low and as it is based on personal or village activity, 'Tassa' is the most appropriate and widely accepted cultivation system.

7.3.2 The amelioration of crop planting by preservation or planting of trees

In the Haoussa region around Maradi in Niger, average farm size has reached meanwhile about 2 ha. For the simple reason of survival, intensification of cropping is mandatory.

However, a number of obstacles exist that hinder the application of innovations. Among these are traditions, low educational level, low investment capacity and the need for risk management. The latter aspect means that farmers are risk averse and are not – in contrast to the normal economical theory– yield or income maximisers. First of all, the family members need to survive.

So the question is: how does innovation needs to be alike to be acceptable for farmers. The answer is manyfold: the innovation needs to be simple, affordable, relying on local resources, risk reducing, functioning under multiple weather scenarios and it cannot contradict local customs. There are not many innovations that fulfil these criteria, in particular if we want to address the 'regreening' of the Sahel. We can approach the 'regreening' from two angles. One is the re-establishment of ligneous vegetation, and the other is increasing the crop biomass production. At the first glance, these are contradictory objectives. Is this really so? In order to answer this question, we will discuss different options in the following.

7.3.2.1 Windbreaks (or agro-forestry in a more general sense)

Heavy convective storms are a regular phenomenon in the Sahel. They lead to erosion on open surfaces at the beginning of the rainy season and homogenisation of soil surface properties through redistribution of particulate matter [121, 122]. The saltating sand grains damage the young seedlings and can lead to crop loss at an early vegetative state. Therefore, it is reasonable to think of windbreaks as a solution to the problem. A lot of research has been done in this respect [118, 123]. However, we hardly see any adoption of this technology by farmers. What are the problems? It begins with legal problems. Planting a tree means to express a claim on property. This is delicate in societies were the land is distributed according to local traditions. Second, planting trees in a hedgerow means an investment that is hardly affordable for a single farmer. A third argument for rejection is the workload for making the trees survive after planting and for pruning in order to reduce competition with the neighbouring crop later. And the competition for land, water, light and nutrients is the fourth argument to set this technology aside. In conclusion, hedgerows are a typical innovation typical for scientists and based on on-station results, thus neglecting the constraints of the rural populations.

Are there more simple and adoptable solutions? One is, i.e., called farmer-managed natural regeneration [124]. It uses the regeneration of ligneous species by re-sprouting from rootstocks. Already Wezel et al. [125] could show in the 1990s that the minimum yield of pearl millet increased with the number of small bushes in the field. This is achieved through the reduction of the negative wind erosion effects and the increase of the organic matter stock that is the major provider of the major limiting nutrient phosphorus. As side effect, fire wood is provided. In contrast to hedgerow planting, with this technology, the only input to be provided is low: i.e., only pruning. The disadvantage is that it is only possible in non-mechanised agriculture. And, the woody species composition is hardly foreseeable. Studies in the Maradi area in Niger have shown that in densely populated areas, all still existing woody species are under use and that their distribution is depending on the distance to settlements (**Figure 22**).

Close to settlements, old *Faidherbia albida* trees dominated are protected, since they deliver high quality animal fodder and do not compete during the rainy season with the crop due to the leaf cover developing in the off-season. Farther away from the settlements, *Piliostigma reticulata* and *Combretum glutinosum* dominate are mainly used as fire wood resources. Also crops differ with distance to the settlements, cash crops like cowpea grown more closely to the settlements on the more fertile sites. Reasons are protection against theft and higher expected

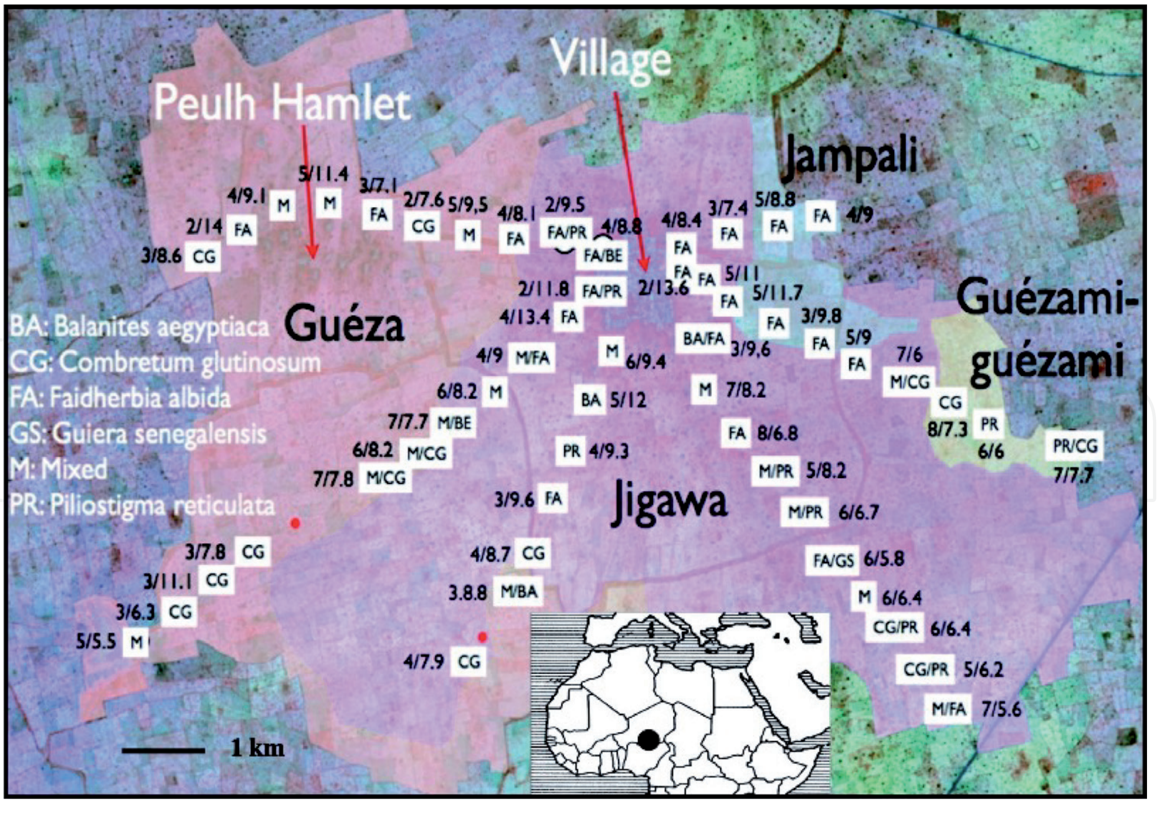


Figure 22.

A survey on tree vegetation in the Faidherbia-*park zones around a village in southern Niger. Dominance (>40% counts) of woody species >1 m crown diameter (white boxes) and number of woody species detected and their average height (number/heigth m) on transects with increasing distance to the village Warzou, central southern Niger (Jigawa, Jampali, Guezami-guezami and Gueza being local soil names indicating increasing clay content in this order). Survey and assembly by Herrmann 2017.*

yields due to nutrient concentration closer to the settlements. Another variable explaining crop diversity is soil conditions, *Sorghum* preferentially being cropped on the more loamy sites.

7.3.2.2 Partial weeding as wind erosion barrier and intermediate nutrient stock

If one wants to reduce wind and water erosion effects on cropping, the simple technique of partial weeding is an option (**Figure 21B**). Under Sahelian conditions, sowing and weeding are the most time-consuming agricultural actions. Labour shortage during these periods limits agricultural performance, since crop surfaces fall out of the scheme. Partial weeding, i.e., stripwise weeding in the sowing lines or circular weeding around the sowing pockets, reduces the workload for the first weeding by about 50%. The herbs and grasses left standing then act as a semi-natural erosion barrier. In addition, this vegetation component stores nutrients that were otherwise leached. In this way, the weeds can be used as an intermittent nutrient reservoir that can be managed, and nutrients are provided to the crop when needed by a timely second weeding.

7.3.3 Varieties

The Sahel is the genetic center for the major staple crop pearl millet that is mainly planted on the sandy sites. Many different land races exist that have been developed by local communities by mass selection over generations. These local communities have a quite determined idea about what a variety must provide with regard to pest and drought resistance, taste, and yield, just to name a few aspects. Independent development of so-called 'improved varieties' has repeatedly failed, simply due to the fact that breeders were not aware of the mandatory properties for different communities, and they did breeding on-station under conditions that are not comparable to the farm environment. Therefore, the future agricultural research needs to be more participatory and include the farmers perspective already at the state of objective definition. Then, higher biomass yielding varieties can be developed.

7.3.4 Seedballs

Under the Sahelian conditions, dry sowing before the rainy season is an option if fields are too far from the settlements, if the rainy season starts very later or for women, when they are not able to sow at the time due to the obligation to help her husbands on their fields first. However, dry sowing imposes the risk of seed loss through predation or early droughts. In order to assure a timely establishment of the pearl millet crop, the seedball technology was developed [126]. It uses local resources like sand, loam, seeds and a little bit of fertiliser (NPK or wood ash) to form small balls of about 2 cm diameter. Seedballs have shown to increase biomass and yield by about 30% under all kinds of conditions in sandy low fertility soils. The only constraint is the labour required for seedball production. However, this can be accomplished during the dry season when opportunity costs are low.

7.3.5 Microdosing

The sandy soils of the northern Sahel are characterised by a low chemical fertility, phosphoruns and nitrogen being the main limiting nutrients for cereal crops. The soils are so poor that even the smallest amounts of nutrient addition can boost the yield. Based on this knowledge, micro-dosing as fertiliser strategy has been developed [127, 128]. Micro-dosing means a placed fertilisation (in contrast to broadcast application) into the sowing pocket at sowing or early in the season, where the nutrients are needed most. Only 2 kg of phosporus are able to double the yield on the poorest sites. Micro-dosing at sowing supports the early establishment of the plant. Once the crop is established and crop loss ha not to be expected, further fertilisation can be done without the risk of investment loss.

However, for the poorest farmers in remote areas, even market access to fertiliser is limited. They can rely on wood ash as local fertiliser, since cooking is done with firewood. Wood ash provides soluble phosphours, potassium, calcium and other micro-nutrients. It can be considered as a complex fertiliser, since it stems from plants. Consequently, it provides most nutrients needed by plants. two grams of wood ash placed into the sowing pocket but at little distance to pearl millet seeds has proven to be effective in increasing yield on poor sites. For legumes, this local fertiliser is applied shortly before flowering.

7.3.6 OGA

OGA is fermented human urine that is used as liquid fertiliser. It is an autochthonous innovation developed by the farmer organisation Fuma Gaskiya in the Maradi area of Niger taking Asian practices as example. It mainly contains nitrogen and potassium as fertilising compounds and has shown to consistently increase pearl millet biomass and grain yield. It is a resource that is locally available for free. It is placed application makes it efficient in annihilating the nitrogen constraint of crop production. Combined with wood ash application (as source for soluble phosphorus), two local resources can be used to fight the notorious soil deficiency with respect to these nutrients. In addition, it is reported by farmers that the smell of OGA is effective to chase off harmful insects.

7.3.7 Biological insect control

The head miner became a major during the Sahelian droughts of the 1970s. Pesticide control is out of reach for subsistence farmers. In consequence, a biological control mechanism using the parasitoid wasp *Habrobracon hebetor* was developed. The parasitoid can potentially be produced locally. However, there is still no agro-enterprise that has taken up this innovation. Perhaps, production is too sophisticated and potential price levels or too high for application by subsistence farmers.

7.3.8 The diversification or the counter-season production

Food security shall be enlarged by intensified and irrigated vegetable production. It constitutes by now a widely accepted activity, wherever the bases are given (**Figure 21C**). It ranges from the vegetable and fruit production in the vicinity of towns or to intensive onion production for export [83, 129]. It can be run on as personal activity or as a collective one.

Thus, these small-scale projects proved chances on the personal of village level to earn its own living and to build sustainable base for villages. They fulfil the demand for participativity and local decision on the projects. Moreover, they are less endangered by the overall insecurity and they may develop their systems by own experiences, and guaranteeing thus a long performance, independently from external pressures.

7.4 Finally, the 'Greening'

After all there is an augmentation in the plant cover. It is evident too in the southern Sahara and the northern Sahel as well as in the Park region of the southern Sahel, from where it was taken by [130, 131] as a sign of a principal 'regreening'. But there is still degradation of ecosystems parallel to that recovery in some regions [7, 12].

7.5 In the long run – future prospects

Finally, the green future of the Sahelian areas needs a landscape approach where the different stakeholders jointly act in a way it takes into account that the multiple angles of natural and socio-economic environment. Short-term action by decision makers who want to see short-term results and who are driven by the dogma of novelty – in particular in science – will not lead to a sound outcome. In contrast, the basics need to be understood, more participatory action is needed, and long-term development concepts need to be supported. Agriculture has to and is able to support the landscape productivity and thus 'greening'. No sophisticated approaches are needed, but the insight that subsistence oriented agriculture needs innovations that are simple, affordable and based on local resources. In a long-term, a re-integration of crop and livestock production is inevitable to partly close the nutrient cycle.

The decade long experience of our colleagues from university of Abdou Moumouni university of Niamey [132, 133] came to the general conclusion on regeneration possibilities of degraded landscapes (see **Figure 21**). Damage and degradation of *Acacia-albida*-parks and Combretaceae-savannas in the Southeast of Niger (stages 1 and 2) diminished the resources for the local population in such a dimension that an intervention was necessary. The classical stonewalls on the slopes alone provoked runnels climbing up the slope and aggravated the situation (stage 3). Thus, it was necessary to intervene at all points and for a long period in order to stop further linear erosion and to allow the auto-regeneration of vegetation and soil (stage 4). Especially on silty-clayey grounds, it will take time to collect sufficient organic material on the surface to allow an implantation of grasses and herbs as further stages of succession. Mulching, however, turned out to be successful to attract ants of termites to transport

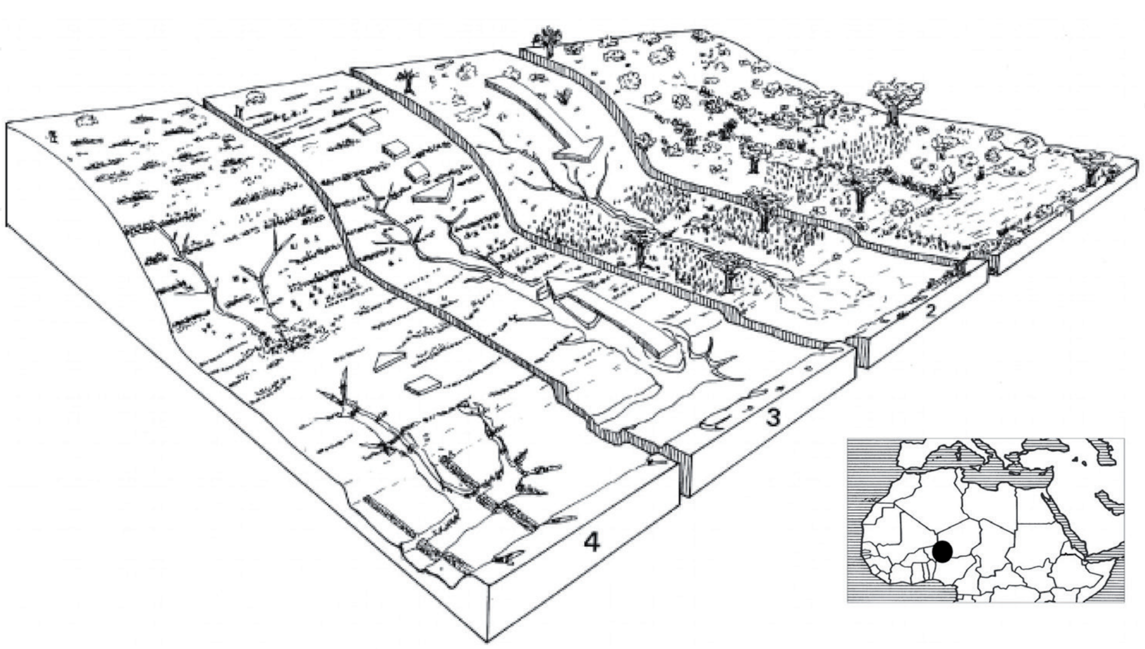


Figure 23.
Experiences with the regeneration of an overexploited Faidherbia-*park Southwest of Niamey [69, 132], modified.*

fines from the deeper parts of the sediments up to the surface (see also [134]). And finally, also follows the ideas of the different 'Tassa' initiatives (see above).

Supported by strong farmer organisations, farmers can make significant progress indepently from the national political situation. Agricultual research should not only focus on single management measures but also adopt a farming systems approach, where combined innovations are researched always under the paradigm of adoptability taking the farmers' view into account [135, 136].

In the long-term, a part of the population needs to gain its living from activities outside agriculture. The pre-requisites to reach this goal are infrastructure and education. The latter should begin in rural areas with agriculture becoming a regular subject in grammar schools (**Figure 23**).

8. Conclusion

Field observation revealed the clear partition of the Sahara in three main landscape types: The Semidesert, the Desert and the (Saharan) Savanna. Thus, the divide between desert and savanna occurs within the Saharan realm. Historical reports and sediment records reveal a stable southern boundary of the desert in the secular scale. Apparently, the boundaries of the desert are the rare climatic ones on the continent. Most savannas South of it are cultural landscapes – including 'elephantscapes' – as preserved in the Gourma/Mali. The degradation-desertification of the last 80 years resulted in a decline to a lower ecological equilibrium. However, the first steps of regeneration are always visible. Their further development, however, depends largely on the type of environments and on human interference. Several projects and initiatives evidenced a principal chance of regeneration or at least preservation. They also showed that small scale projects have a better chance to be accepted and to be continued by the local population. Il became clear that any initiative must be based on the participation of the respective population and must be conceived for a long time. We still do not know how many years or decades the different ecosystems need to fully recover – or if they will remain on a lower level of ecological equilibrium. We should consider the whole discussion and the various activities that take place on the background of a rapidly increasing demography. And finally, the situation changed completely. The general insecurity for the civil population in the regions concerned stopped most initiatives or set them in a state of 'suspense' or 'endangeredness'. As this situation exists already since more than a decade and as it will probably continue, one should accept the latter and adjust all kinds of plans and initiatives to it.

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References

[1] Brandt M, Grau T, Mbow C, Samimi C. Modelling soil and woody vegetation in the Senegal Sahel in the context of environmental change. Landscape. 2014;**3**:770-790

[2] Brandt M, Grau T, Mbow C, Samimi C. Woody vegetation die off and regeneration in response to rainfall variability in the West African Sahel. Remote Sensing. 2017;**9**:39. DOI: 10.3390/rs9010039. 21 p

[3] Brito JC, Godinho R, Martines Feira F, Pleguezuelos JM, Rebelo H, Vale GG, et al. Unravelling biodiversity, evolution and threats to conservation in the Sahara-Sahel. Biological Research. 2014;**89**:215-231

[4] Dandel C, Kergoot L, Hiernaux P, Mogin F, Grippa M, Tucker CJ. Regreening Sahel: 30 years of remote sensing data and field observations (Mali, Niger). Remote Sensing of Environment. 2014;**140**:350-364

[5] Gonzales P. Desertitication and a shift of formations in the West African Sahel. Climate Research. 2001;**17**:217-228

[6] Hellden U. Desertification-time for an reassessment. Ambio. 1991;**20**:372-383

[7] Herrmann SM, Tappan GG. Vegetation impoverishment despite greening: A case study from Central Senegal. Journal of Arid Environments. 2013;**90**:55-66

[8] Hiernaux P, Diarra L, Soumagel N, Lavenu F, Tracol Y, Diawara M. Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali. Journal of Hydrology. 2009;**371**(1-2):114-127

[9] Hutchinson CF, Herrmann SM, Mankonen T, Weber J. Introduction: The greening of the Sahel. Journal of Arid Environments. 2005;**63**:535-537

[10] Karlson M, Oswald M. Remote sensing of vegetation in the Soudano-Sahelain zone: A literature review from 1975-2104. Journal of Arid Environments. 2016;**124**:257-269

[11] Olson DM, Eklung L. Aido: A recent trend greening oft he Sahara-trends patterns and potential causes. Journal of Arid Environments. 2005;**63**:556-566

[12] Ousseini I. A green Sahel: Perceptions, facts and perspectives. In: Symposium Documentation Green Sahel, GIZ, Division 45 Agriculture, Fisheries and Food; 2010. pp. 14-20

[13] Schulz E, Hagedorn H. Die Wüste, wächst sie denn wirklich? Die Geowissenschaften;**12**:204-210

[14] Boulanodji E, Harouna A. Réserves sahélo-sahariennes du Niger et du Tchad. Noé; 2018. 3 p

[15] Giazzi F. La Réserve Naturelle Nationale de l'Air et de Ténéré. Analyse descriptice. Gland, MH/E-WWF-UICN; 1996. 712 p

[16] Newby JE, Dulieu D, Lebrun JP. Avant –Projet de classement d'une aire protegée dans lÁir et le Ténéré (Republique du Niger). Niamey: UICN, WWF; 1982. 122 p

[17] Dia A, Duponnais R. Le projet majeur africain de la Grand Muraille Verte. In: Concepts et mises en oeuvre. Mayenne: IRD; 2010. 44p

[18] Escadafal R. Le projet africain de Grande Muraille Verte. Quels conseils les scientifiques peuvent-ils apporter? Montpellier: Dossier d'actualité; 2011. CSF-désertification.org/grande-muraille–verte. 45 p

[19] Stebbing EP. The enchroaching Sahara: The threat to the West African colonies. The Geographical Journal. 1935;**95**:500-551

[20] Aubreville A, Paterson JR, Collier ES, Brynmor J, Dundas J, Mathes J, et al. Rapport de la mission forestière anglo-francaise Nigeria-Niger (décembre 1936-février 1937). Revue Bois et Forets des Tropiques. 1973;**148**:3-26

[21] Tucker CJ, Dregne H, Newcomb WW. Expansion and contraction of the Sahara desert from 1980 to 1990. Science. 1991;**253**:299-301

[22] Thomas V, Nigaru S. 20th century climate change over. Africa: Seasonal hydroclimate trends and Sahara desert expansion. Journal of Climate. 2018;**31**:9

[23] Chevalier A. La végétation de la région de Tombouctou. Actes du IIIme Congres international de botanique; 1900. pp. 248-276

[24] Médail F, Quezel P. Biogéographie de la flore du Sahara. Une biodiversité en situation extrème. Marseille: IRD; 2018. 366 p

[25] Barry JP, Celles JC, Musso J. Le problème des divisions bioclimatiques et floristiques du Sahara. Note V: du Sahara au Sahel. Un essai de définition de cette marche africaine aux alentours. Ecologia Mediterranea. 1986;**XII**:187-235

[26] Reichelt R, Faure H, Maley J. Die Entwicklung des Klimas im randtropischen Sahara-Sahelbereich während des Jungquartärs- ein Beitrag zur angewandten Klimakunde. Petermanns geographische Mitteilungen. 1992;**136**(2-3):69-79

[27] Schulz E, Abichou A, Adamou A, Ballouche A, Ousseini I. The desert in the Sahara. Transitions and boundaries. In: Baumhauer R, Runge J, editors. Holocene Palaeoenvironmental History of the Central Sahara. Palaeoecology of Africa. Vol. 29. 2009. pp. 63-89

[28] Cole M. The Savannas. Biogeography and Geobotany. London: Academic Press; 1978. 418p

[29] Le Houerou HN. La végétation de la Tunisie steppique. Tunis: Annals of the National Institute of Agronomic Research; 1969. 142p

[30] Walter H. Die Vegetation der Erde. In: Ökophysiologischer Betrachtung. Vol. 2. Jena: VEB G.Fischer; 1964

[31] Hagedorn H. Formen und Bilder der Wüste am Beispiel der Sahara. Natur und Museum. 1985;**115**:210-230

[32] Rognon P. Biographie d'un Desert. Paris: Plon; 1989. 348p

[33] Bornkamm R, Kehl H. Pflanzengeographische Zonen in der Marmarika. Flora. 1985;**176**:141-151

[34] Kehl H, Bornkamm R. Landscape ecology and vegetation units of the western desert of Egypt. Catena Supplement. 1993;**26**:155-176

[35] Stahr K, Bornkamm R, Gauer J, Kehl H. Veränderungen von Böden und Vegetation am Übergang von Halbwüste zur Volwüste zwischen Mittelmeehr und Quattara Depression in Ägypten. Geoökodynamik. 1985;**6**:99-120

[36] Stokker O. Steppe-Wüste-Savanne. Veröff. Geobot. Inst ETH Zürich (Rübel). 1962;**37**:234-243

[37] Stokker O. The water-photosynthesis syndrome and the geographical plant sistribution in the Saharan desert. In: Lange O, Kappen L, Schultze ED, editors. Ecological Studies, Analysis and Synthesis, 11. 1976. pp. 506-521

[38] Blanco J, Genin D, Carriere SM. The influence of Saharan agro pastoralism on the structure and dynamic of acacia stands. Agriculture, Ecosystems and Environments. 2015;**213**:21-31

[39] Jaouadi W, Hamroudi L, Khouja ML. Phénologie de *Acacia tortilis* ssp. *raddiana* dans le Parcc N atgional de Bou Hedma en Tunisie, effet du site sur les phénophases de l'espèce. Boir et Forets des Tropiques. 2012;**312**(2):31-41

[40] Noumi Z, Chaieb M. Dynamics of *Acacia tortilis* (Forsk) Hayne subsp. radd*iana* (Savi) Brenan in arid zones of Tunisia, Acta Botanica Gallica. Botany Letters. 2012;**159**:121-125

[41] Sghari A. A propos de la presence d'une steppe tropicale au Jebel Bouhedma en Tunisie présaharienne. Approche géomorphologique. Quaternaire. 2009;**202**(20/2):255-264

[42] Van Collie F, Delaplac EK, Gabriels D, De Smet K, Ouessa M, Belgacem AO, et al. Monotemporal assessment of the population strucure of *Acacia tortilis* (Forssk.) Hayne ssp.*raddiana* (Savi) Brenan in Bou Hedam National Park, Tunisia: A terrestrial and reomote sensing approach. Journal of Arid Environments. 2016;**129**:80-92

[43] Schulz E, Adamou A. Die Vegetation des Aïr-Gebirges in Nord-Niger und ihre traditionelle Nutzung. Giessener Beiträge zur Entwicklungsforschung, I. 1998;**17**:75-86

[44] Monod T. Modes "contracté et diffus" de végetation saharienne. In: Cloudsley-Thompson JL, editor. Biology of Desert, 3. London; 1954. pp. 5-44

[45] Voss F, Krall P. Principaux biotopes du criquet pelerin dans le Nord du Tilemsi (Mali). Berlin: GTZ/Institute of Geography, Technical University of Berlin; 1994a

[46] Voss F, Krall P. Principaux biotopes du criquet pelerin dans l'Adrar des Iforas (Mali). Berlin: Gtz/Institute of Geography, Technical University of Berlin; 1994b

[47] Schulz E, Adamou A. Die Grenzen der "neolithischen Revolution". Gab es einen frühen Ackerbau in der Sahara? Würzburger Geographische Arbeiten. 1997;**92**:71-95

[48] Quezel P. La végétation du Sahara duTchad à la Mauretanie. Geobotanica selecta. Stuttgart: G. Fischer; 1965. 333p

[49] Morel A. Les hauts massifs de l'Air (Niger) et leurs piemonts. Etude géomorphologique. Paris; 1984. 404p

[50] Barry JP. La frontière méridionale du Sahara entre l'Adrar des Iforas et Tombouctou. Ecologia Mediterranea. 1982;**7**:3

[51] Barry JP, Jaquen X, Musso J, Riser J. Le problème des divisions bioclimatiques au Sahara. Note VI: entre Sahel et Sahara. L'Adrar mauretanien. Approches bio-géographiques et géomorphologiques. Ecologia Mediterranea. 1987;**XIII**(1/2):131-142

[52] Schulz E. The southern margin of the Sahara in the Republic of Chad. Vegetation, soil, and present pollen rain. Zentralblatt für Geologie und Paläontologie. 1999;**I**:483-496

[53] Aktar-Schuster M. Degradations prozesse und Desertifikation im semiariden randtropischen Gebiet der Butana/Rep. Sudan. In: Göttinger Beiträge Land- und Forstwirtschaft in den Tropen und Subtropen, 105. 1995. pp. 1-165

[54] Dubief J. Le climat du Sahara. Trav. de l'Inst. Rech. Sahar. Alger 312, 1956. 1963. 275 p

[55] White F. The Vegetation of Africa. Paris: Natural Resources Research, Paris: UNESCO; 1983. 356 p

[56] Anthelme F, Waziri Mato M, Maley J. Elevation an local refuge ensure persistance of mountain refuge vegetation in the Nigerien Sahara. Journal of Arid Environments. 2008;**72**:2232-2242

[57] Linder HP, DeKlerk MM, BornJ, Burgess ND, Fieldsa J, Rahbeck C. The partition of Africa. Statistically defined biogeographical regions in Sub Saharan Africa. Journal of Biogeography, 39-1189-1205; 2012

[58] Barbour KM, Oguntoyinbo JS, Onyemelukwe JOC, Nwafor JC. Nigeria in Maps. London: Hoder and Stroughton; 1982. 148p

[59] Letourzey R. Végetation. In: Laclavère G, editor. Atlas of the United Republic of the Cameroons. Paris: Editions J.A; 1980. pp. 20-24

[60] Krings T. Kulturbaumparke in den Agrarlandschaften Westafrikas – eine Form autochtoner Agroforstwirtschaft. Die Erde. 1991;**122**(2):117-129

[61] Seignobos C. Matières grasses et civilisations agraires (Tchad et Cameroun). Annales de l'universite de Tchad. Ser Lettres, Langues vivantes et schiences humains Vol spec. 39-119; 1979

[62] Seignobos C. Strategies de survie dans les économies des Razzias (Ronier, Ficus, et Tubercules sauvages). Annales de l'université de Tchad. Ser Lettres, Langues vivantes et sciences humaines Vol spec. 1-37; 1979

[63] Seignobos C. Des mondes oubliés. IRD Editions: Marseille; 2017. 310p

[64] Ballouche A, Dolidon H. Forets claire et savane ouest-africaines: Dynamique et évolution des systèmes complexes a l'interface nature/societe. In: Taabni M, editor. La fôret: enyeux comparés de formes a l'approproation de gestion et exploitation dans les politiques environnementales et de contexte d'urbanisation géneralisé. Poitiers Maisons des Sciences d l'homme et de la societé. Université de Poitiers; 2003. pp. 56-70

[65] Dolidon H. L'espace des feux en Afrique del'Ouest [thesis]. Caen: Université de Caen; 2005. 345p

[66] Pomel S, Pomel-Rigeaud, Schulz E. Les indicateurs anthropogènes de la végétation et des sols de quelques savanes de l'Afrique de l'Quest. In: Maire R, Pomel S, Salomon HN, editors. Enregistrateurs et indicateurs de l'evolution de l'environnement en zone tropicale. Bordeaux: Presses Universitaires de Bordeaux; 1994. pp. 173-200

[67] Monod T. The Sahel zone north of the equator. In: Evenary M, Nov-Meier J, editors. Hot Deserts and Arid Shrublands. Oxford; 1986. pp. 203-242

[68] Le Houerou HN. The Grazing Land Ecosystem of the African Sahel, Ecol Studies 75. Berlin: Springer; 1989. 282p

[69] Ibrahim S, Schulz E. At the sources of fear. Zentralblatt für Geologie und Paläontologie. 2017;**1**(2):11-25

[70] Nicholson SE, Dezfuli AK, Klotter D. A two-century precipitation data set for. The continent of Africa. American Meteorological Society. 2012;**93**:1219-1231

[71] Denham D. Mission to the Niger. The Bornu Mission. Cambridge: Reprint. pp. 1822-1825. 325p

[72] Barth H. Reisen und Entdeckungen in Nord- und Central-Afrika in den Jahren 1848 bis 1855. Vol. 4. Gotha: Justus Perthes; 1857. 1858

[73] Nachtigal G. Sahara und Sudan. Ergebnisse sechsjähriger Reisen in Afrika. Vol. 2. Parey: Weidmann; 1879-1881

[74] Rohlfs G. Reise vom Mittelmeer nach dem Tschadsee und zum Golf von Guinea. Vol. 2. Leipzig: Brockhaus; 1974

[75] Vischer H. Across the Sahara from Tripoli to Bornu. London; 1910. 308p

[76] Gardi R. Ténéré. Bern: Benteli; 1978. 288p

[77] Rabe K, Kilian, N. Georg Schweinfurth. Sammlung botanischr Zeichnungen im BGBM. www.bgbm.org/Schweinfurth (15.4.2019)

[78] Bouché P, Doamba B, Sissoko B, Boujju S. The elephants in Gourma, Maili: Status and threats to their preservation. Pachyderm. 2008;**45**(1):47-56

[79] Canney S. Les élephants du Gourma. Une synthese des connaisances, des récherches et des récommendations. Wild Foundation. 2007. summary-fr_19dec07_with–map.pdf

[80] Dublin HJ, Sinclair ARE, McGald J. Elephants and fire as causes of multiple stable states in the Serengeti-Mara (Tanzania) woodlands. Journal of Animal Ecology. 1990;**59**:1147-1164

[81] Guldemond RAR. The influence of savannah elephants on vegetation: A case study in the Tecah Elephant Park, South Africa [thesis]. Pretoria: Pretoria University; 2006. 163 p

[82] IUCN, SOS. Combating a new elephant poacing threat in the Gourma region of Mali. 3 p; 2012

[83] Ibrahim S. Evolution des paysages dunaires fixés par la végétation au Niger. Schriftenreihe Junges Afrikazentrum, 2016;**4**:171

[84] Buffe J. La plantation des *Casuarina equisetifolia* (Filao) dans le sud du Dahomey. Revue Bois et Forets des Tropiques. 1962;**84**:13-20

[85] Louppe D, Depommier D. Expansion, research and development of the Eucalypts in Africa. Wood production, livelihood and environmental issues: an unlikely reconciliation? Bujumbura: FAO/MEEATOU workshop "Eucalyptus in East Africa"; 2010. 9p

[86] Ballouche A, Neumann K. A new contribution to the Holocene vegetation history of the West African Sahel: Pollen from Oursi, Burkina Faso and charcoal of three sites in northern Nigeria. Vegetation History and Archaeobotany. 1995;**4**:31-39

[87] Salzmann U, Waller M. The Holocene vegetational history of the Nigerian Sahel based on multiple pollen profiles. Review of Palaeobotany and Palynology. 1998;**100**:39-72

[88] Waller M, Salzmann U. Holocene vegetation changes in the Sahelian zone of NE Nigeria: The detection of anthropogenic activity. Palaeoecology of Africa. 1999:85-102

[89] Waller M, Street-Perrott A, Wang H. Holocene vegetation history of the Sahel: Pollen, sedimentological and geochemical data from Jikariya lake, northeastern Nigeria. Journal of Biogeography. 2007;**34**(9):1575-1590

[90] Miehe S, Kluge J, Von Wehrden H, Retzer V. Long term degradation of Sahelian rangeland detected by 27 years of field study in Senegal. Journal of Applied Ecology. 2010;**47**:692-700

[91] Hahn A, Kusserow H. Spatial and temporal distribution of algae in soil crusts in the Sahel of W-Africa: Preliminary results. Willdenowia. 1989;**28**:227-223

[92] Kusserow H. Desertification, resilience and regreening on the African Sahel. A matter of observation? Earth System Dynamics. 2017;**8**:1141-1170

[93] Pomel S. La mémoire des sols. Bordeaux: Presses Universitaires de Bordeaux; 2008. 343p

[94] Abichou A. Les changements de paysages du basin-versant de l'oued Tataouine-Fessi (sud-est tunisien): Etude multiscalaire et micromorphologie des remplissages des sebkhas et études des étâts de surface. PHD – Université Michel de Montaigne – Bordeaux 3, France; 2002

[95] Belnap J, Büdel B. Biological soil crust as soil stabilisators. In: Weber B, Büdel B, Belnap J, editors. Biological Soil Crusts. An Organising Principal in Drylands. Ecological Studies 226. Switzerland: Springer; 2016

[96] Buis E, Veldkamp A, Boeken B, van Bremen N. Controls of plant functional surface cover types along a precipitation gradient in the Negev Desert of Israel. Journal of Arid Environments. 2009;**73**(1):82-90

[97] Prasse R, Bornkamm R. Effect of microbiotic soil surface crusts on emergence of vascular plants. Plant Ecology. 2000;**150**:65-75

[98] Guan P, Zhang X, Yu J, Cheng Y, Li Q, Andriuzzi WS, et al. Soil microbial food web channels associated with biological soil crusting and desertification renaturation: The carbon flow from microbes to nematodes. Soil Biology and Biochemistry. 2018;**116**:82-90

[99] Liu Y, Li X, Jia R, Lei H, Gao Y. Effects of biological soil crusts on soil nematode communities following dune stabilisation in the Tengger desert, northern China. Applied Soil Ecology. 2011;**49**:118-124

[100] Reichelt R. L'Hydraulique Pastorale et la Desertification au Sahel des Nomades en Afrique de l'Ouest – Réalités et Perspectives. Geologisches Jahrbuch, C. 1989;**52**:3-32

[101] Spittler G. Dürren, Krieg und Hungerkrisen bei den Kel Ewey (1900-1985). Studien zur Kulturkunde 89. Wiesbaden: F. Steiner; 1989. 199p

[102] Hallard J. Le barrage vert algérien est un exemple de lute contre la désertification des territoires. ISIAS, Arbres Forets Agroécologie Climat, 2. www.isias.lautre,net/spip.php/article547 15.4.1028; 2016

[103] Gallais J. Pasteurs et paysans du Gourma. Mém. Bordeaux: Centre d'Etudes de Geographic Tropicale CEGET; 1975. 209p

[104] Catella AM. Modifications de la végétation de Tombouctou depuis dix siècles. Ecologia Mediterranea. 1988;**XIV**(1-2):185-197

[105] Becker LC. Seein g green in Mali's woods: Colonial legacy, forest use and local control. Annals of the Association of American Geographers. 2001;**91**(3):504-526

[106] Canney S. Les élephants du Gourma. Une synthèse des connaissances, des récherches et des recommendations. Wild Foundation. 2007. summary-fr_19dec07_withmap.pdf

[107] Morrison TA, Holdo RM, Anderson TH. Elephant damage and fire or rainfall explains mortality of overstorey trees in Serenget. Journal of Ecology. 2015;**104**:409-418

[108] Rèpublique du Niger: Réserve Naturelle Nationale de l'Air et du Ténéré. Sanctuaire des Addax. Journal Officiel 4. 1988;**15**(3):4

[109] Maas I. Weiderotation in Timia, Niger. Stuttgart: Bericht über fünf Jahre Erfahrung; 1991. 57p

[110] Magrin G, van Vliet G. La réserve du Termit Tin-Toumma et l'exploitation petrolière au Niger: etat de lieux et piste d'action. Niamey: CIRAD, NOE; 2014. 34p

[111] Zonon A, Hervé C, Behnke R. A preliminary asssessment of the economic values of the goods and services provided by dryland ecosystems of the Air and Ténéré. The World Conservation Union; 2007. 36 p

[112] UICN/PACO. Parcs et réserves du Niger: evaluation de l'efficacitdé de gestion des aires protégées. Ougadougou, BF: UiCN/PACO; 2010. 78p

[113] Koudemoukpo B, Nignon P. Final Report of the Terminal Evaluation of the Niger COGERAT Project PIMS 2294. Geneva: UNDP; 2014. 82p

[114] République du Niger: Grand Muralle Verte. Niamey Minist de l' Hydrauliques et de l'environnement. 109 p

[115] Bayala J, Kalingare A, Tchoundjev Z, Sonclair F, Garrily D. Conservation Agriculture with Trees in the West African Sahel – A Review. Nairobi: World Agriforestry Centre Occas; 2006. Papers 14, 1. 57p

[116] Presidence de la République du Niger: Niger. Renaissance au sommet. Jeune Afrique. 2019;**3039**:7

[117] DFG. Atlas of Natural and Agronomic Resources of Niger and Benin. Bonn: CDRom; 2000

[118] Roose E, Dugue D, Rodrigues L. Une nouvelle strategie de lutte antei-érosive appliquée a l'amenagement du terroirs en zone sudano-sahelienne en Burkina-Faso. Bois et Forets des Tropiques. 1992;**233**:49-63

[119] Garraud S, Mahamane L. Evolution des pratiques d'adaptation des communautés agropastorales de la zone de Tillabery Nord et de Tahoua au Niger dans un context de changement climatiques. Secheresse. 2012;**23**:24-730

[120] Bouzou JM, Nomao DL. Le "Tassa" une technique de conservation des eaux et des sols bien adaptée aux conditions physiques et socio-économiques des glacis des régions seimiarides (Niger). Revue de Géographie Alpine. 2004;**1**:61-70

[121] Herrmann L. Staubdeposition auf Böden West-Afrikas - Eigenschaften und Herkunftsgebiete der Stäube und ihr Einfluß auf Boden- und Standortseigenschaften. Hohenheimer Bodenkundliche Hefte 36; 1996

[122] Bielders CL, Alvey S, Cronyn N. Wind erosion - the perspective of grass-root communities in the Sahel. Land Degradation and Development. 2001;**12**:57-70

[123] Michels K, Lamers J, Bürkert A. Effects of windbreak species and mulching on wind erosion and millet yield in the Sahel. Experimental Agriculture. 1998;**34**(4):449-464

[124] Reij C, Garrity D. Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. Biotropica. 2016;**48**(6):834-843

[125] Wezel A. Scattered shrubs in pearl millet fields in semiarid Niger: Effect on millet production. Agroforestry Systems. 2000;**48**:219-228

[126] Nwankwo CI, Mühlena J, Biegert K, Butzer D, Neumann G, Herrmann L. Physical and chemical optimisation of the seedball technology addressing pearl millet under Sahelian conditions. Journal of Agriculture and Rural Development in the Tropics and Subtropics. 2018;**119**(2):67-79

[127] Buerkert A, Bationo A, Piepho H-P. Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. Field Crops Research. 2001;**72**:1-15

[128] Hayashi K, Abdoulaye T, Gerard B, Bationo A. Evaluation of application timing in fertilizer microdosing technology on millet production in Niger, West Africa. Nutrient Cycling in Agroecosystems. 2018;**80**:257-265

[129] Tardiati M, Robbiota G, Rafiou SM. The onion sector of West Africa. Comparative study of Niger and Benin. Cahiers Agriculture. 2013;**22**(2):112-123

[130] Lawarnou M, Abdoulaye M, Reij C. Etude de la régéneration naturelle assisté dans la région de Zinder (Niger): une première exploration d'un phénomèn spectaculaire. Washington DC: Internat. Resources group for the US Agency for International Development; 2006

[131] Reij C. Agroenvironmental transformation in the Sahel. Another kind of "Green Revolution" Washington, D.C. IFPI Discussion paper; 2009;**00914**:54

[132] Bender H, Ousseini I. La protection des bas fonds au Sahel: Transfert de connaissances. ETH Zürich et Université de Niamey; 2000. 133 p

[133] Ousseini I, Karimou A. Amenagement de dix (10) sousbassins versants au moyen de seuils de crue dans le département de Tahoua. Analyse des impacts sur l'environnement. Cooperation Nigero-allemande LUCOP; 2007. 48p

[134] Larwanou M, Saadou M. Biodiversity of ligneous species in semiarid zones of southwestern Niger according to anthropogene and natural factors. Agriculture, Ecosystems and Environment. 2005;**105**:267-271

[135] Schulz E. Indicateurs de l'influence antropique sur la vegétation actuelle et passée. In: Maire R, Pomel S, Salomon JN, editors. Enregistreurs et indicateurs de l'evolution de l'environnement en zone tropicale. Espaces tropicaux 13. Bordeaux: PUB; 1994. pp. 129-142

[136] Casenave A, Valentin C. Les etâts de surface de la zone sahelienne. Paris: ORSTOM; 1989. 229p