The potential of agroforestry to increase primary production in the Sahelian and Sudanian zones of West Africa

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Abstract

The article presents a critical evaluation of agroforestry systems as regards their potential to increase primary production in the Sahelian and Sudanian zones of West Africa. The suggestion that trees would always and everywhere be profitable for the region will be counterproductive, the basis for disappointments and a waste of money. One has to consider carefully which properties of woody species could serve which objective, where and under what circumstances.

Primary production is limited by water availability in the north Sahelian zone only, elsewhere in the region nutrient availability is critical. Woody species influence the water balance via rainfall interception, the influence on evapotranspiration and the influence on water infiltration. The ultimate result for grasslands and crops depends upon local conditions; positive effects of windbreaks should be particularly attributed to protection against mechanical stress. Processes that influence nutrient availability under trees are those acting via redistribution, those reducing nutrient losses and those increasing soil fertility. Of the latter processes, serious limitations exist in the region concerned: nitrogen fixation is limited by phosphorus shortage mainly and deep rooting is very limited and so is possible uptake of minerals from deep soil layers.

The positive influence from woody species on soil fertility and primary production varies with average annual rainfall and soil type; its importance increases more than proportionally with rainfall going south. This positive influence is basically linked to the redistribution of nutrients and water, an internal nutrient cycling and the related enlarged plant-litter-soil nutrient cycle. Taking advantage of its effects is difficult and risks further depletion of soil fertility. Moreover, since woody species generally compete with the herb layer, it will be difficult to develop agroforestry in such a way that the positive influences are not overridden by negative ones. Windbreaks are more beneficial under conditions which are rare in the region.

More research is needed to determine under which conditions introduction of woody species may be beneficial.

Résumé

Le potentiel de l'agroforesterie pour augmenter la production primaire dans les zones sahélienne et soudanienne de l'Afrique de l'Ouest

Une évaluation critique de l'agroforesterie est présentée, qui concerne la possibilité d'augmenter la production primaire dans les zones sahélienne et soudanienne de l'Afrique de l'Ouest. La supposition que dans cette région des arbres seraient toujours et partout avantageux, ne sera pas productive, la cause de déceptions et un gaspillage de ressources. Il faut se demander quelles propriétés des espèces ligneuses pourraient servir quels objectifs, où et sous quelles conditions.

Seulement dans la zone nord-sahélienne la production primaire est limitée par la disponibilité en eau; ailleurs c'est la disponibilité des éléments nutritifs qui est la plus déterminante. Des espèces ligneuses influencent le bilan d'eau par l'interception de la pluie, par des modifications de l'évapotranspiration, et par une amélioration de l'infiltration d'eau. La conséquence pour les pâturages et les cultures dépend des conditions locales; les avantages de brise-vents dépendront notamment de la protection contre le stress mécanique. Des processus influençant la disponibilité des éléments nutritifs sous les arbres sont ceux agissant par la redistribution, par la diminution des pertes et par l'augmentation de la fertilité. Les derniers processus ont des limitations sérieuses dans la zone: la fixation d'azote est surtout limitée par le manque de phosphore et l'enracinement profond paraît limité et ainsi la possibilité de profiter d'une disponibilité de minéraux en profondeur.

L'influences positive des espèces ligneuses sur la fertilité du sol et la production primaire varie avec la pluviosité annuelle et le type de sol; son importance accroît plus que proportionnelle avec la pluviosité vers le sud. Cet influence positive est liée à la redistribution des éléments nutritifs et de l'eau, au recyclage interne des éléments nutritifs et le cycle agrandi y en être la conséquence, de ces éléments en plante-litière-sol. Pour profiter de ses effets est difficile et on risque l'épuisement supplémentaire des éléments nutritifs. En plus, suite à la concurrence entre les espèces ligneuses et la strate herbacée, c'est difficile à développer l'agroforesterie d'une telle façon que les avantages ne seront pas surpassés par les inconvéniences. Des brise-vents sont avantageux sous des conditions qui sont rares dans la zone.

Plus de recherche est nécessaire pour déterminer les conditions sous lesquelles l'introduction des espèces ligneuses peut être profitable.

Introduction

Most of the land use systems in the Sahelian and Sudanian (savanna) zones of West Africa are characterized by low-input technologies where production almost solely depends on renewable resources. Sustainable arable cropping requires fallow periods on the majority of the land, while livestock production must be limited according to the carrying capacity of rangeland. If these practices and restrictions are not adhered to, the renewable resources will be depleted and land degradation will occur [9, 41].

Agro-ecological analysis of the land use systems show a deterioration of formerly effective and adapted agriculture due to the combined effects of overpopulation, drought and changed land use conditions in relation to production technologies and access to land [9]. Agricultural production levels are very low and variable due to very poor soils and variable rainfall. Theoretically, substantial increase in yield will result from correcting soil nutrient deficiencies as has been confirmed experimentally [40, 41]. It is unlikely, however, that use of fertilizers or legumes to improve rangelands will be profitable. For arable farming of cash crops it may be feasible in the Sudanian zone, but much less so for domestic food production [9, 32, 40]. Meanwhile the population of West Africa is growing at nearly 3% per year, producers and production systems are becoming increasingly competitive, and the renewable resources are degrading progressively. Still the tendency to increase production by extending the area of cultivated land remains stronger than to intensify production [e.g. 5].

It is within this context that interest in agroforestry has grown. It is inspired by both the recent scientific interest in the potential of agroforestry to contribute to low external input agriculture such as that prevailing in West Africa [37, 58], and the findings of relatively high fertility of the soil under tree canopies in the tropics, such as *Faidherbia albida* trees [62], and the success of alley-cropping systems in some humid tropical regions [e.g. 28].

The long term environmental advantages of woody species are well documented [e.g. 39,62] and would be particularly applicable to the fragile ecosystems of the Sahelian and Sudanian zones. The role of woody species in relation to crop and livestock production is complex, yielding direct products and sustaining the production capacity of the agro-ecosystem [20, 58, 60]. Following the Sahel drought which brought world-wide attention to the land degradation, a seminar was held in Niamey (Niger) on the potential for agroforestry in Sahel countries [58]. There is a belief that agroforestry can increase overall food production, but this aspect is too often based on uncritical evaluation of the evidence [46].

Studies evaluating overall productivity of agroforestry systems usually refer to cash crop plantations in humid tropical regions under fertile soil conditions. Increased productivity is often largely the result of improved management, including inputs such as fertilizer [56]. Productive agroforestry systems for semi-arid regions have been designed on theoretical grounds, but as yet there is very little experimental evidence to support the claims [25,31].

This critical evaluation aims to prevent disappointments in the future and to improve the rationality of rural development efforts in the area. The arguments are based upon an analysis of the influence of woody species on the factors determining primary production in the Sahelian and Sudanian zones. These zones are defined according to climate and vegetation characteristics (Table 1). The analysis is related to the natural presence of woody species in these zones. The synergistic effect of woody species with the herb layer of the rangelands or annual crops is emphasized.

Table 1: Climate and vegetation characteristics of the Sahelian and Sudanian zones of West Africa [32, 59]

Zone	Annual rainfall ($mm.a^{-1}$)	Vegetation
North Sahelian	150-300	grass/shrub savanna
South Sahelian	300-600	shrub savanna

North Sudanian	600-900	shrub/tree savanna
South Sudanian	900-1200	tree savanna

Primary production in West Africa

A generalized water balance equation for the rangelands of the south Sahelian zone shows that yearly about 15% of the precipitation is used by the vegetation. About 60% evaporates from the soil surface and some 25% is lost as surface run-off. At the end of the agricultural growing season 20% of the precipitation may still remain in the soil within reach of plant roots [40]. Thus, in the south Sahelian zone it is not water shortage that stops vegetation growth. If chemical fertilizers are applied, both water use and primary production are stimulated. If sufficient nitrogen (N) and phosphorus (P) are applied, under natural rainfall conditions, production could increase up to five-fold, in which case 50% of the precipitation could be effectively used by the vegetation [40].

Nearer the Sahara, fertilizer application becomes increasingly less effective. Rainfall eventually becomes so low that, in the short growing period, the vegetation cannot even utilize the limited, naturally occurring nutrient resources. Towards the south, moving into the Sudanian zone, plant production increases with rainfall. Since the availability of N and P in the soil remains almost constant, a concurrent decrease of their concentrations in the plants was found [40].

The year to year availability of N and P for the plants depends strongly on the depth and duration of soil wetting and the distribution of organic matter in the soil profile. Wetting of the first 50 cm leads to mineralization of organic matter from which plants absorb an average of about 10 kg $N \cdot ha^{-1}$ and 1 kg $P \cdot ha^{-1}$. Wetting of the next 150 cm provides only 5 and 0.5 $kg \cdot ha^{-1}$ more N and P respectively. Water percolation below 200 cm risks losses of nutrients. In other words, the average maximum availability of N and P is 15 $kg \cdot ha^{-1}$ and 1.5 $kg \cdot ha^{-1}$ respectively, which is reached with water infiltration of between 300 to 1200 mm, for coarse sands to heavy clays respectively [8, 33].

At least for N these results are typical for West African rangelands [48]. Analysis of the availability of N and P for crop production in Burkina Faso and Ghana confirm the rangeland data and show that they are also applicable to annual crops in the south Sudanian zone [52].

These data do not consider the nutrients absorbed by shrubs and trees. A model was used to estimate the annual primary production in relation to water availability, annual nitrogen losses from the above ground phytomass and the total cover of woody species. It appeared that the model did not need to take into account the competition between woody species and the herb layer as cover of woody species remained below 15% [8]. In other words, with 15% cover N demand by woody species can be accounted for by niche differentiation. But a cover of woody species twice as high in the south Sahelian zone appeared to lead to a decrease of the N-yield of the herb layer by at least 4 $kg \cdot ha^{-1}$ [40]. To the south, at the 1100 mm isohyet, the annual production of the herb layer is suppressed from 5000 to 1000 $kg \cdot ha^{-1}$ of dry matter by an increase in the cover of woody species from 10 to 40% [49]. Such a negative relationship between the cover of woody species and herb production is commonly found, for temperate as well as tropical zones [7, 56, 61].

Which processes, specific to woody species, are likely to influence primary production under different mixes of shrubs and trees? Is it really an improvement of the environment as a whole due to water availability, improved mobilization of nutrients, for example, symbiosis with mycorrhiza, biological weathering and solubilization? Or is the answer the efficient internal recycling of nutrients?

The influence of woody species on plant production factors

Water availability

Moisture availability for herbaceous plants under trees may be higher than in the open field [11,44], but opposite observations also exist [6,30]. An example is provided for *Racospermum aneurum* desert woodland in Central

Australia, a vegetation type and climate resembling the Sahelian zone, showing a deep drying of the soil (200 cm) in the grove, the intergrove without shrubs and trees drying only to 75 cm. The grove was also shown to receive run-off from the intergrove, where the infiltration rate is much less [51].

The following processes influence moisture availability for plant growth under woody species, as compared to the open field, or in agroforestry systems as compared to treeless fields.

1. Rainfall interception

Fine rains are largely intercepted by the tree foliage and never reach the soil surface. In West Africa rains are however generally heavy and driving, and a proportionally large amount of rainfall is intercepted by the canopy, reaching the soil surface as throughfall and stemflow. The result of these processes depends upon the interception storage capacity of the canopy and the nature of the rainfall. Data from Senegal with *Faidherbia albida* trees show a 5% decrease and a 20% increase in water availability for the herb layer under the tree as compared to the open field, with fine rains and heavy rains respectively. The overall result on an annual basis is an increase of 10% [16]. Similar estimates are reported from Australia [43]. However for *Eucalyptus* trees the result seems to be always negative [42].

Basically, this process is only a redistribution of rainwater within a defined ecosystem. Dew interception, in coastal and highland regions, would form an exception as it can increase water availability.

The next processes could as well influence total water availability for plant growth, due to decreased losses of water from the ecosystem.

2. Evapotranspiration

The evaporative demand per unit leaf area of a woody species may tend to exceed that for the herb layer due to its position and structure. The relatively high leaf area index also causes a more favorable transpiration-evaporation ratio which could lead to a higher production of woody species than the herb layer, if water is the limiting factor. The higher evaporative demands may however also lead to a more rapid depletion of water resources. To offset this disadvantage, a tree canopy may exercise greater control of water loss by anatomical and stomatal adaptations [14]. Most woody species in semi-arid regions have adapted such structures, or strategies such as leaf-drop in the dry season. Nevertheless they may effectively exploit all available water resources before regulating water use [42].

Due to shelter (reduced wind speed and sunshine intensity), the potential evapotranspiration under a tree canopy is considerably reduced as compared to the unprotected open field [e.g.24]. In general, the herb layer growing in association with trees is submitted to a lower evaporative demand. The consequence, slower depletion of water resources, is of no advantage in the presence of woody species. Yet it has been suggested that under semi-arid conditions the total transpiration of the herb layer in association with trees may be higher, as the herbs continue to grow and transpire for a longer period than in the open field [19]. This seems possible only, when the other processes mentioned have caused a higher water availability for the association.

3. Water infiltration

Under tree canopies water infiltration generally is faster and as a consequence deeper than in the open field. Losses by run-off and evaporation will be less. Mechanisms involved are high organic matter concentration, high root densities and more biological activity in the soil under trees.

Infiltration is also stimulated by "stem flow" along the trunk and main roots; for most trees and shrubs stemflow amounts to 5-10% of annual rainfall, but for trees with a favorable branch morphology and bark structure (e.g. *Acacia seyal* in West Africa) this figure may amount to 40% [34]. Although with increased water infiltration the risk of losses by leaching increases, it is commonly stated that for a water catchment area as a whole, the introduction of woody species will generally decrease the amount of water leaving the system by run-off or leaching [e.g.47].

Long taproots help certain species to exploit water from deep soil layers. There are suggestions that part of the uptake may again diffuse upward into the topsoil at night in dry season (*Faidherbia albida*; Alexandre,D.Y. pers.comm.).

4. Rainfall induction

The last process is the unproven, but commonly claimed higher rainfall in afforested areas, compared to treeless regions in the same zone [e.g. 10]. Micro- and macro-scale are too often mixed up as far as this aspect is concerned.

The above mentioned processes allow shrubs and trees themselves to take more advantage of an increased water availability than nearby herbs or crops. However, windbreaks in crop land areas are claimed to be able to increase crop yields by increasing moisture availability due to lower evapotranspiration and improved infiltration [14,35]. Recent studies throw doubts on this simplistic explanation [54]. Under dry conditions in the USA protected crops may produce less, due to damage resulting from higher temperatures [19]. Expectations for semi-arid West Africa mostly refer to the case of the Majjia- valley in Niger, where deep, sandy soils, a high water table and strong year-round winds from one direction, offer optimal conditions for the use of windbreaks. However, no significant increase of crop-yields was measured [31]. On shallow soils windbreaks are difficult to establish and will cause a decrease of overall crop-yields [26]. If windbreaks result in more water becoming available for crops, it does not necessarily result in more production. In such a case increased nutrient inputs may increase the effect of the windbreak.

In arid zones the beneficial effects on crops by effect of reducing wind speed can also be explained by the decrease of the abrasive effect on plant seedlings by the wind- blown soil [35,36]. Protection against mechanical stress should also be considered [54]. Both primary and secondary wind injury effects (influence of air movements on physiology) may occur and depress plant productivity.

The effect of windbreaks on irrigated crop production in semi-arid areas can be positive, as for example in China, where most damage to irrigated crops occurs during establishment by strong dry winds from the desert [35]. But in the Sahelian zone, sowing takes place when the monsoon has already replaced the harmattan [8].

Nutrient availability

In semi-arid climates it is common to find higher fertility in the topsoil under tree canopies than in adjacent open land, as indicated by the availability of nutrients and organic matter [4, 12, 29, 63]. Increased soil fertility generally decreased significantly with radial distance from the center of the canopy or tree bole [4, 18, 29, 63]. One has to question whether a real increase of the nutrient availability for the ecosystem as a whole has occurred, or only a redistribution within the agro- ecosystem. The following nine processes were identified as influencing soil fertility under trees.

1. Redistribution: lateral roots

Lateral roots commonly exceeding 10 m in length, even with some shrubs not higher than 2 m, are reported from Somalia [22]. Data from West Africa indicate that lateral roots commonly reach up to 10 m in length, often 5 to 10 times as far as the crown radius [6,29]. The maximum recorded were those of *Bombax costatum* reaching 34 m [55]. If soil moisture throughout the year is concentrated in the topsoil most fine roots will be concentrated in the topsoil. Their lateral uptake of nutrients leads to a nutrient concentration under the woody plant at the expense of a nutrient depletion at some distance. An evenly scattered woody plant population would be able to exploit all topsoil if total crown cover is 10% and the horizontal root extension of the individual woody plants is three times the crown diameter.

2. Redistribution: run-off

In semi-arid areas woody species commonly establish and produce best at locations where run-off water, containing nutrients, collects and organic matter accumulates. Because of run-on, valleys get enriched at the expense of upland rangelands, and the more so when the latter are overgrazed. Especially on heavily grazed loamy soils micro-depressions receive high amounts of run-off water, resulting in abundant cover of woody species and at least a doubling of the available N for herbage production [40].

3. Redistribution: animals

Especially in the case of scattered trees, nutrients may be supplied by manure or dung of animals resting under or birds resting in the trees [e.g.4]. Bird droppings are especially rich in P. Large trees offering shade, and tree legumes of which the pods are highly palatable, are especially favored by herbivores as a place to congregate. The deposition of N by livestock through manure on the croplands, where the livestock is kept at night, is 4 to 10 times as high as on the grazing lands in the Sahelian zone [9]. High soil fertility under *Faidherbia albida* trees, offering shade in the dry season, may be partly the result of such dung accumulation, possibly during years prior to the study [46].

4. Redistribution: rainfall and dust

In the presence of shrubs and trees nutrients originating from rainfall and dust are caught heterogeneously by through fall and stem flow of rainwater, and by deposition of dust due to reduction of the wind speed. The latter has never been specifically demonstrated [62] but is clearly observed with grass-bunds [26] and hedgerows planted against erosion along the contours. Dust deposition in Kano (Nigeria) amounted to 1.2 kg P.ha-1 annually, originating from the Sahara at 1000-1200 km distance [38].

The scale of redistribution differs from those of the preceding processes.

5. Reduction of losses: soil erosion

In semi-arid regions soil erosion on agricultural lands is 5-50 times higher than for natural vegetation [47]. The stability of the latter is only achieved by the combined effect of the trees and the herbaceous ground cover, and their effects on soil characteristics such as organic matter contents. The direct cover of the herbage layer offers more effective protection against soil erosion than the tree layer. Trees such as Eucalyptus and Teak, with high water demands and poorly decomposing litter, prevent the establishment of an herb layer and may thus enhance soil erosion, especially when the litter is removed by wind or for use as fuel [42]. In general, an agroforestry system with inadequate protection of the soil cover (due to burning, removal of crop residues, hay making or intensive grazing) will therefore not lead to a good protection against erosion [60].

6. Reduction of losses: leaching

Relatively deep rooting shrubs and trees may recapture leached nutrients. Leaching is a common process under sub-humid or humid conditions. Under (semi-)arid conditions leaching is restricted to run-on locations such as valleys and water courses. Deep rooting is however not as common as generally assumed (see further). A perennial root system may also decrease losses by leaching in the non-growing season, as compared to annual species.

7. Reduction of losses: recycling

At the end of the growing season a considerable proportion of the minerals of the leaves are translocated to perennial plant parts before the leaves are shed (e.g 50% of the P reserves [40]). This internal circulation is not subject to losses due to volatilization and fire. Grazing shortly after flushing will however greatly reduce translocation of nutrients unless manure is returned to the soil. Nutrients from litter deposition are not as easily lost as in the case of a herb layer, due to the presence of a permanent root system.

8. Enrichment: N-fixation

By their symbiotic relations with N-fixing Rhizobium bacteria, leguminous plants may fix atmospheric di-nitrogen, thus increasing their own supplies. However, active N-fixation occurs only when the water availability and P supplies are sufficiently high [53]. However, most soils in the region are deficient in phosphorus [40], a situation that aggravated by soil acidification under continuous cropping [41]. On the other hand, when N-supplies are sufficient, the potential of N-fixation may be only partly realized [23]. Bacterial N-fixation with *Faidherbia albida* was shown to occur only with young plants on sterile soils, which only recently lead to the conclusion that the contribution of N-fixation to the increased soil fertility under this tree is likely to be very limited [15]. Few data exist on root nodules of other native tree legumes occurring in West Africa; their potential for N-fixation is expected to be very low [17].

N availability in the topsoil under tree legumes is generally not higher than under non-legume trees, nor is herbage or crop production [1,21]. For *Racosperma aneurum* in Queensland (Australia) N-fixation has been shown, but there was apparently no build up of total N within the soil profile [2].

9. Enrichment: mycorrhiza and fungi

Mycorrhizal associations are almost universal in the roots of plants and are known to increase the yield of the host plants under conditions of low fertility. The available evidence suggests that fungal hyphae absorb P from the same nutrient pool as uninfected roots, but have an additional exploration potential [14]. More extensive root systems of woody species implicate a better access to minerals with low mobility due to low solubility, like P-compounds. In addition, long lived tree roots are claimed to promote the solubilization of nutrients in the rhizosphere due to increased acidity [59]. Clearly, increased P- availability could lead to increased N-availability by bacterial N-fixation.

Rooting patterns

The described processes make it clear that the rooting pattern of woody species is a key factor in determining the potential of the woody species to increase nutrient availability. Data on rooting patterns are however scarce and very site- specific. Rooting patterns studied in semi-arid Somalia show that most trees have predominantly shallow roots, with none or only few vertical roots [22]. This pattern is explained as an adaptation to limited soil depth and soil wetting. Numerous data refer to the absence or scarcity of deep roots in the humid tropical savanna [e.g.29,63]. The available evidence from semi- arid West Africa shows that root systems of woody species are in general concentrated in the upper 20 to 50 cm [6, 40]. Most woody species have some roots at 60-120 cm soil depth enabling them to survive and produce in the dry season when upper soil layers are dry. But even deep rooting trees in the Sahelian zone appear to have 80-90% of their root biomass in the upper one meter of the soil (Penning de Vries,pers. comm.). In Tanzania the vertical distribution of fine roots (smaller than 2 mm in diameter) was studied of five non-native tree species. All of these species had a decline in root biomass from 0-100 cm soil depth similar to that of maize [27].

Well known for having deep roots are, for example, *Prosopis juliflora* and *Faidherbia albida*. However, these and other deep rooting trees will only survive, where soils are penetrable by roots and deep water supplies are available. In semi-arid areas such rooting develops where redistribution of water takes place on soils with a high run-off leading to local deep water infiltration. Vast areas in the Sudanian zone have developed highly compacted subsoil layers or simply shallow soils on parent bedrock, which effectively inhibit root penetration to deeper soil layers of the soil profile [22,32].

When considering the possible uptake of nutrients from deep soil, it should be realized that most available nutrients are concentrated in the topsoil and that the uptake of nutrients is largely determined by root density of the finest hair roots and associated mycorrhiza and symbiotic fungi [14,59]. In the upper soil layers organic matter and soil moisture are highest and decomposition processes are concentrated. For *Acacia seyal* trees on sandy soil in the Sahelian zone, it was estimated that the contribution of P from the soil layer deeper than 50 cm to the annual total P availability, can be only little more than 0.1%.

Nutrient availability in the presence of woody species

In central Mali, on a transect of the rangelands between 200 and 1000 mm annual rainfall, the average P yield of the above ground herbaceous biomass on 35 sites increased significantly in relation to water availability. On the same transect the cover of woody species varied between 0 and 50%, but no correlation was found between P yield of the herbaceous biomass and the woody plant cover at a certain level of water availability. The possible improvement by woody species of the P availability for the ecosystem as a whole appeared little as compared to the variability by other factors. In addition, the annual contribution to this possible improvement, to be eventually exploited, will be even smaller. If P availability remains low, so consequently does bacterial N-fixation.

Nevertheless the improvement of the soil under trees is undeniable, and the amount of nutrients used for annual production and stocked in the plant biomass increases much more from the Sahara to the forest zone in case of an intact cover of woody species as compared to only a herbage layer.

Before the drought and human influences of the last decades, the cover of woody species increased from about 5% in the north Sahelian zone to about 50% in the forest (Guinean) savanna zone, and the above ground biomass from less than 2 to 50 t.ha-1· Consequently, the annual nitrogen use for the above ground production increased from about 4 to 80 kg·ha-1 [32], compared to an average maximum of only 15 kg.ha-1 for annual herbs. In the rangelands dominated by perennial grasses the vegetation can already yield up to 65% more N and P than the maximum presented above for annual herbs [8, 40].

Most of this difference can be primarily explained by the cumulative effect of uptake of nutrients by the woody species and the high fraction recirculated internally. The gradual accumulation of nutrients is incorporated into an enlarged plant- litter-soil nutrient cycle, occurring similarly with perennial grasses. The extensive perennial root system also keeps the external circulation effective, whereas substantial amounts of nutrients originate from rapid decomposition of roots [63]. Due to this nutrient recycling and perennial status, woody species gradually build up biomass and nutrients, about 30% of which concerns the root biomass.

High decomposition and mineralization rates under woody species as compared to the open field are due to improved soil conditions under a tree canopy. In this respect the relatively high organic matter content under a tree canopy is a key factor [3,63]. A high litter production which is not exploited and an undisturbed soil environment enabling optimal microbial activity, are essential for a well functioning agroforestry system [3]. Note that shade alone may already stimulate N uptake by grasses, possibly related to an altered balance of mobilization /immobilization of soil N [62].

These considerations imply that positive influences of woody species on primary production will increase more than proportionally with rainfall going south. With increasing rainfall in East Africa, maximum soil fertility was found to occur at approximately 750 mm of annual rainfall. This phenomenon was related to a maximum base saturation of the soils in this region, due to an optimal relation between organic matter buildup by the vegetation and mineral losses due to leaching [49].

The N availability is related to the water availability and the average fraction of N in the above ground biomass lost annually by volatilization, herbivory and fire [40]. The increase of N availability with increasing rainfall is less than expected because of increased losses. But with woody species the losses are much lower due to internal recirculation of nutrients, the relatively low preference by herbivores for woody species, and lower fire-risk. This explains the higher N-yields mentioned for woodlands; mixed vegetations of herbs and woody species give intermediate values. Above a threshold of 15% canopy cover every additional 5% cover signifies an average of 1.3 kg N.ha-1 of less available N for the above ground production of the herbage layer. This value explains quantitatively the competition between the woody species and the herb layer.

Natural presence of woody species

Considering the foregoing an hypothesis can be formulated to explain the natural presence of woody species in the region, in relation to rainfall and soil type, based on the competition for the growth limiting factors of water, nutrients and light.

In the north Sahelian zone water is the most limiting factor and woody species can only establish on places where, by run-on, water accumulates in such quantities that enough water is stored beyond the reach of herbaceous roots. On sandy soils with homogeneous water infiltration the soil is not wetted deep enough to permit such niche differentiation. Even if individuals establish in years with good rainfall, they cannot become strong competitors. The absolute availability of nutrients is too limited to rapidly develop an enlarged plant-litter-soil nutrient cycle, which would enable the canopy of woody species to become dense enough to profit from light competition, nor to develop a root system taking advantage of water and nutrient interception. The growth period of annual species is generally determined by day length (photoperiodism), leaving some water for the survival of perennials during the dry season. But during drought years, the annual species will use all available water during growth and the perennials die when their reserves are exhausted [55].

Towards the south, with increasing rainfall, ecological conditions favor the establishment of woody species. Places with water beyond the reach of herbaceous roots become more numerous and extended, due to higher rainfall and the abundance of heavier soils with run-on run-off patterns. Drought years are less extreme and less frequent. Though nutrients are more limiting than water, their absolute availability permits the woody species to successfully compete with the herb layer, favored by light interception. A gradual improvement of soil fertility is related to the build up of organic matter [49]. Nevertheless, the landscape remains open since conditions favoring the herb layer continue to exist on large areas, especially on light or shallow soils.

Especially in the south Sahelian and north Sudanian zones the presence of woody species provokes a strong horizontal heterogeneity of fertility from which the herb layer may profit. In a so called park landscape, the competition for light is localized and limits crop production under trees, unless the canopy is high above the ground, enabling light to penetrate from sides. Some annual crops and herbs are especially adapted to shade conditions and reach highest covers under trees (e.g. the grass *Panicum maximum* in East Africa [30]). High crop production under *Faidherbia albida* is basically the result of its leafless status in the growing season [15].

In the south Sudanian zone nutrients are much more limiting than water. It is in this zone that the ability of tree roots to recapture leached nutrients becomes an advantage. Without the perennial vegetation component the absolute availability of nutrients would decrease. Without human influences woody species would dominate on most soils, hard pans excepted. The interference of crop production, bush fires, wood cutting or drought will favor the herb layer, while periods of good rainfall will favor the woody species. Heavy grazing by herbivores naturally promotes the woody species (bush encroachment) by reducing bush fires [7,61] and by eliminating preferred herbs. Soil compaction causes more marked run-on run-off patterns and more water infiltration to depths beyond the reach of annual species [40, 57]. Heavy grazing also reduces bush-fires, thus promoting establishment of woody species [7,60]. Heavy grazing of pastures on sandy soils leads to more water remaining unused in the subsoil to be exploited by woody species in the dry season.

Consequences

Silvo-pastoralism

The principal aim of silvo-pastoralism is improving animal production through relatively high quality browse available during part of the dry season, less risk in drought years since production of tree and shrub forage is less influenced by drought, and by erosion control.

Due to differences in accessibility, palatability and digestibility, the herb layer in the Sahelian zone is much more important as a feed resource than trees and shrubs. Only a fraction of the annual production of the latter can be consumed by livestock [8, 9]. Proteins in tree forage are in general only partly digestible due to tannins. Tree forage is generally considered an emergency feed at the end of the dry season for maintenance requirements only. The quality of the herbs however remains high, even during the dry season [40]. As a consequence the aims mentioned should be realized with only limited negative influence of woody species on herb production. This could be realized by taking advantage of the niche differentiation related to water availability, as takes place on loamy soils with important redistribution of rain water. Sandy soils, with homogeneous water infiltration, are much more common in the north Sahelian zone, where pastoralism is most important. Therefore no real combination is possible with the objective "wind erosion control", as may be desired in sandy Sahelian areas. Tree densities will have to remain very low to avoid too much competition with the herb layer. The benefits of woody species in the Sahelian zone would exceed the negative effects from competition up to a cover of 15%, from a pastoral point of view.

The combination of silvopastoralism with "water erosion control" seems more profitable. Water erosion is most prominent on loamy soils susceptible to surface crusting and therefore needing a much higher herbaceous biomass cover for soil protection than sandy soils [40]. Thus the consequences of an eventual competition with the herb layer are severe. Moreover, the niche differentiation on loamy soils has a limited potential; for dense stands of woody species or for large trees the evaporative demand becomes such that the scope for prolonging of the "green" season is limited.

Using woody species to improve the dry season pastures seems more likely beneficial in the Sudanian zone where herbs have very low quality in the dry season. But going south there will also be an increased competition for nutrients between woody and herbaceous species.

Thus, in neither zone will it be easy to develop silvo-pastoralism in such a way that the positive elements will not be overridden by the negative ones. It is worth mentioning that in the pastoral zone of Australia the presence of woody species reduces the range value for livestock in normal rainfall years but increases the rating in dry years [13]. Pulling or killing of shrubs and trees is a general practice in intensive livestock keeping systems in pastoral Australia.

Agrosilviculture

Agrosilviculture has as its principal objective the improvement of arable farming through the integration of trees into cropped fields, essentially pursued by an increased nutrient availability, by accelerating the regeneration of fertility of fallow land and by windbreaks.

The first two approaches will be most beneficial in the south, where nutrients most limit crop production. Agrosivilcultural practices should however not aim at stimulating those processes which concentrate soil fertility under the tree canopy by redistribution of nutrients; in that case woody species are favored at the expense of the crop. Those processes that can increase nutrient availability were shown to have low potential in the Sahelian and Sudanian zones, because:
(1) N fixation is limited by poor soil fertility, especially P shortage and soil aridity;
(2) deep rooting is restricted by shallow soils, by hydromorphy and by concentration of soil nutrients at the soil surface.

It could be more profitable to aim at those processes that diminish nutrient losses by leaching or run-off. However, the more effective these processes are, the stronger will be the competition of the woody species with crops. In that case it is advisable to take direct advantage of the properties concerned by using tree crops (e.g. fruit tree orchards).

Agrosilviculture will be beneficial if annual crops are to be produced in zones with high risks of leaching or run-off. In that case, it is not probable that the annual benefit to the nutrient availability of the crop will reach a level equal to the maximal nutrient enrichment by a tree fallow phase divided by the number of years of the fallow period. The reason is the enlargement of the plant-litter-soil nutrient cycle increasing exponentially with time, until an equilibrium is reached between the energy fixed by the annual photosynthesis and the amount needed for maintenance of the living plant biomass and for compensation of losses. It is difficult to take benefit from the upper part of the more than proportional increase, because by that time the cover of the woody species will exceed 15%, and competition with the herb layer will appear. Speaking of fallow- lands planted with woody species and crop production as "continuous fallows" [46] is therefore misleading, and only useful if the farmer is mostly interested in tree products.

In the Sudanian zone, the shelter belt function of woody species is not so interesting because water is not limiting plant growth, sandy soils (prone to wind erosion) are uncommon and hot dry winds, with their risk of abrasion, are rare during the growing season.

The usefulness of windbreaks increases northwards, but outside irrigation areas or valleys with favorable conditions such as the Majjia valley (see above), it will be difficult to take advantage of them, as has been explained.

The timber and non-timber products of woody species are considered in agroforestry as supplementary advantage. In existing agroforestry systems in West Africa, trees are left on the agricultural fields for their various products, as a famine strategy to minimize risk [58]. The trees tend to be removed however, following the successful introduction of cash-crops on fertilized soils. Only fast growing wood producing trees are interesting if wood is scarce and highly valued. But these species (mostly exotics) have particularly shallow and extensive root systems, enabling an effective exploitation of available water and nutrient resources, and thus their rapid growth. In every situation again one has to question if an integrated production is really higher and has a better cost/benefit ratio than optimalization for individual objectives: wood, fodder, fruits or improvement of arable farming or rangeland; particularly if regional differentiation of production is possible.

Conclusions

The way in which agroforestry in its broad sense is promoted nowadays is praise worthy in view of the attention needed for maintenance of the fragile environments of the Sahelian countries and the stabilizing role woody species play in the sustenance of the ecosystem. But the suggestion that trees would always and everywhere be profitable for the region will be counter productive, the basis for disappointments and a waste of money.

The potential of agroforestry systems to increase agricultural production in the Sahelian and Sudanian zones was evaluated in view of the ability of woody species to effectively increase water and nutrient availability for primary production.

In the north Sahelian zone only, primary production is in the first place limited by water availability, elsewhere in the region nutrient availability is critical [40].

Woody species influence the water balance in a different way than the herb layer does. Under certain conditions the positive influences can be more important than the negative ones, but it is difficult to identify conditions under which this is beneficial to the herb layer.

The limited soil fertility of croplands is the main problem for agriculture in the region [41, 58]. Woody species can influence nutrient availability by redistribution processes, by decreasing nutrient losses and by enrichment processes. Considering the processes that can decrease nutrient losses, woody species will not be particularly more effective than herbs. Woody species have advantages in comparison to herbs in the (sub-)humid zone only, where the risk of nutrient losses through water erosion and leaching is highest. The processes causing a redistribution of the available nutrients seem particularly effective in the region. On a small scale the topsoil under woody species may be fertile at the expense of the open field, or, on a large scale, an agrosilviculture system may be kept productive at the expense of heavily grazed rangelands, via the use of manure.

Natural processes, theoretically able to increase the nutrient availability of an agro-ecosystem as a whole, have serious potential limitations.The most interesting could be pumping of minerals through deep roots. But in the savanna most soils are relatively shallow, while in the Sahel low nutrient availability and dryness of deep soil layers limit the advantage of deep rooting. The other interesting process, bacterial N-fixation, is limited by P shortage.

Attention for the absolutean relative availability of water and nutrients enables to better understand the natural occurence of woody species in the region and to explain and quantify the generally observed competition between trees and crops, as well as observations of increased herb production (especially in terms of quality) under a tree canopy.

Woody species were shown to considerably increase nutrient use by the vegetation, as compared to annual species only. The surplus value thus provided varies with annual rainfall and soil type. To take advantage of this surplus value is difficult, especially in (semi-)arid regions for silvo-pastoralism as well as for agrosilviculture, for several reasons.

- The surplus value of woody species is linked most probably to the redistribution of nutrients and water, the internal nutrient cycling and the related enlarged plant-litter-soil nutrient cycle. Taking advantage of it leads to short term benefits only: "slash and burn" agriculture is a system of arable farming illustrating this in an extreme way. There is no reason to believe that exhaustive cereal production under, for example, *Faidherbia albida* should not lead to the same effects, nor all the ways to increase the exploitable fraction of fodder [56], nor the multiple use of multipurpose trees.

- Woody species compete with the annual crops and herbs for limited water and nutrients, so the final balance for consumptive production of crops and forage becomes negative.
- Woody species have the highest advantage in comparison to annual herbs, where the risk of nutrient losses through water erosion and leaching is the highest.

So, more than what has been done so far, one has to consider carefully which properties of woody species could serve which objective, where and under what circumstances. Managers have to realize that every advantage has its price. Words like "multipurpose tree" and "agro-silvo-pastoralism" easily become oaths, serving none of the objectives in an optimum way. When considering the introduction of woody species in rural development programs careful input/output calculations are needed. Not only capital and human efforts have to be regarded as inputs, but also the space occupied and overlap of niches between crops and woody species. Especially if increased environmental stability is the principal reason to include woody species in agriculture, their exploitation has to be a strongly controlled one.

Further studies are badly needed, and should place more emphasis on large-scale and long-term processes, considering especially the efficiency of the use of water and nutrients by agroforestry systems in comparison to annual plant species alone.

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