The Luki and Yangambi Biosphere Reserves: laboratories for climate change research and sustainable development

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Abstract. The UNESCO Biosphere reserves of Yangambi (235 000 ha) and Luki (33 000 ha) are both situated within the semi-deciduous moist forests of the Democratic Republic of the Congo. These forests are part of the second largest tropical rainforest belt in the world and signify still a persistent carbon sink, rich in biodiversity and an essential provider of ecosystem services, including natural resources for economic development. Luki and Yangambi offer, thanks to the concept of Biosphere Reserve, an appealing opportunity to develop activities of research, training and education and serve, as such, as potential models for the reconciliation of nature conservation, economy and welfare. Both Yangambi and Luki have a particularly rich history of research. They can be considered as the cradle for investigations in Central-African botany, forest ecology, tree physiology, climatology, tropical agronomy and silviculture. The archives, databases and scientific reference collections (curated both locally and in natural history collections in Belgium) related to these reserves are a treasure trove for actual research needs in the domains of global change (evaluations of carbon fluxes) and forest resilience. Some experimental plots are still present after their establishment, 70 years ago, and offer unique research material, in a region where there is a dire need for long term observations of vegetation dynamics and environmental fluctuations. We give an overview of ongoing research projects relevant to the topics of carbon fluxes and forest resilience, all including wood analysis in a context of vegetation history, tree physiology and forest ecology. We show how this is relevant for designing biodiversity management and we demonstrate how the MAB reserves of Luki and Yangambi are key research sites to document the debates on global changes and resilience of rainforests.

1. Introduction

1.1 Wood matters as biodiversity component

“Biodiversity” or “biological diversity” is often understood as synonymous for “species richness”. The concept is much richer than listings of abstract clades of animals and plants. There is indeed growing interest to incorporate as well functional diversity which includes ecological structures and processes. This is believed to offer better opportunities for a valuation of ecosystem services that is maximally useful in a context of conservation and nature management. Also the Convention on Biological Diversity (CBD) uses a much larger definition than richness of taxa, as has been formulated in its article 2 [1]:

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"Biological diversity" means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems."

This definition refers not only to the abstract concept of species, but also to the concrete notion of organisms. This nuance has far reaching consequences for ecological research and for management of ecosystems. Listing richness of fauna and flora indeed doesn’t give information on size of individuals, other functional components and the physical environment of the ecosystem. When individual organisms and other tangible ecological complexes are being integrated into biodiversity, size of individuals gains significance. An emergent tree being more than 40 m tall has a much stronger control over fluxes of materials and energy within a forest ecosystem than a seedling of the same species but a hundred times smaller. The difference between small and large individuals in forest ecosystems is in essence a difference in quantity of wood. This evidence provides interesting opportunities for forest ecology to make use of a methodology borrowed from wood science, a discipline that is rather associated to technology than to ecology.

**Figure 1.** Biodiversity is more than species counts. Emergent trees don’t contribute much to species richness, but they have a strong control over the fluxes of material and energy within an ecosystem. Example of an *Entandrophragma utile* tree (sipo) growing in the core area of the Luki Biosphere Reserve (Nkula park), Mayombe, DRC. (Hans Beeckman © RMCA)

Research on wood indeed supports traditionally technological investigations, but also botanical disciplines like taxonomy and physiology often rely on wood anatomy. There is an additional and strongly growing interest that is driven by the commonly accepted understanding that forests are crucial to assure ecological functions and services at different geographic scales. Here we cite [2]:

"Locally, forests provide resources for the economy in a potentially sustainable way and assure environmental protection. Globally, they play a key role in the climate regulation of the planet. The scientific essence to which these discussions can be reduced is the thermodynamics of the global ecosystem of the earth. Forests comprise indeed a large share of the free energy of terrestrial systems, energy that is available to perform work, or, in ecological terms, energy that is useful to produce goods and deliver services. Deforestation and forest degradation signify higher levels of entropy, lower potential to perform work and, therefore, less goods and services and reduced survival means for mankind. Despite high levels of deforestation and forest degradation, especially in the tropics, the remaining forests still continue to sequester carbon dioxide: there is an estimated net sink of 1.1 +/- 0.8 Pg C year^-1(3). This phenomenon can be understood as a global indicator for relatively stable stocks of organic carbon and concomitant amounts of free energy stored in forests.

The major part of the energy in forests is stockpiled in organic molecules and woody biomass in particular. The carbon stock of the world’s forests is estimated as 861 +/- 66 Pg C (tropical forests represent 55 % of this carbon, while the boreal belt holds 32 % and the temperate forests 14 %). On
average 44 % of the carbon is present as organic soil compounds, 42 % as live biomass (below and above ground), 8 % as dead wood and 5 % as litter [3], but there are large differences between biomes, with a higher proportion of carbon in living biomass in the tropics and more carbon in the soil of the boreal forest. Interestingly the largest part of the forest biomass consists of wood and bark: above ground this rises up to 98 % in tropical and temperate forests and 87 % in boreal forests [4], but also below ground much of the carbon is kept in woody materials, including coarse roots, a part of the detritus and even a substantial part of the fine roots contain secondary tissues. Heterotrophs (less than 1 % according to[5], tree foliage and herbaceous plants, although functionally vital, constitute only small fractions of the carbon stocks. Is has been estimated that 400 Pg carbon is stored in wood globally[6]. These are reasons enough to include wood research into investigations of planetary carbon budgets and hence global change”.

Wood is clearly omnipresent in the living nature, but there are many examples where it became a scarce economic commodity decisive for the rise and fall of many civilisations[7]. The scarcity of wood has been the very fundament of the notion of sustainability, now extended by the Convention on Biodiversity to the use of components of biodiversity (CBD Article 1. Objectives: “…conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits…”(1)). The creator of the concept is Hans Carl von Carlowitz[8], born in 1645, who published in 1713, one year before he died in Freiburg, Germany, a 420 pages book titled Sylvicultura oeconomica. In this book he summarized his theoretical thoughts and lifetime practical experiences with the material wood. He was observer of sharply rising wood prices and scarcity of timber for upcoming mining industries, but also for construction purposes and the navy (he witnessed the fire of London in 1666 and was probably still in the city when the British Navy was almost completely destroyed by the Dutch in June 1667 near Chatham). In his book he stated that wood is as precious as bread and he developed proposals for long lasting solutions to cope with the scarcity of this natural resource. These were based on the principle of not cutting more trees than the increment of the standing stock. He advocated that an economy should be designed such that there is never a lack of wood. He coined the term “Nachhaltigkeit” which became, translated into “sustainability”, the central concept of many ongoing debates on the future of the planet. Sustainability has nowadays a more general meaning than the original connotation of continuous production of wood. However, given the importance of forests for environments and economies, it seems to be imperative not to lose out of view the importance of soundly using and conserving wood stocks.

Management of biodiversity, aiming at a sustainable production of goods and services, is not feasible without a scientific approach that includes measurements, processing of data, and development of theories on carrying capacity and resilience of forests. Appealing opportunities for this type of research, focussing on as well climate change impacts and on models for economic development are present within the Biosphere Reserves. Monitoring of ecological processes and fluxes in the central areas provides information on responses of intact forests, whereas in the buffer areas there are good opportunities for experiments with forest management and sustainable production systems can be implied in the transition areas. Especially research in the Biosphere Reserves that are located in the tropical dense moist forests should get priority attention, given that actual knowledge is not at all in proportion to the global importance of this biome. We give examples of how wood research in two Biosphere Reserves in the Central-African rainforests relates to questions of sustainable use of biodiversity..

2. **Luki and Yangambi: Biosphere Reserves in the rainforests of the Congo**

There are two Biosphere Reserves in the Democratic Republic of the Congo that are situated within the rainforest belt of the Congo Basin: Luki in the west and Yangambi in the north-east. Both have a long history of research and conservation and actually suffer from increasing demands of the populations in the surrounding villages.

Luki, 120 km away from the Atlantic coast, is part of the Mayombe forest. The climate is quite uncommon, with relatively low quantities of precipitation and a distinct dry season characterized by
high humidity. Since the end of the 19th century and certainly from 1930 onwards there was intensive logging (80% of the exported timber from the Congo at that time came from the Mayombe) resulting in gradually diminishing stocks of precious timber species. Luki is now the only forest in the southern Mayombe of some importance and is therefore a target for illegal logging for both charcoal production and timber, especially for local or regional markets. This is in the first place a serious threat for the existence and conservation of intact forest, but at the same time it puts spotlight on the dire needs for developing science-based forest management outside the core area of the reserve aiming at a sustainable production of wood to satisfy the economic needs. There are attractive opportunities for relevant research. In the buffer area some well-preserved forest plots, originally from sylvicultural experiments, still exist and offer a quite rare opportunity to evaluate long-term effects of thinning, clear cutting and planting. The 33000 ha of the biosphere reserve actually include 6000 ha of old growth forest, 3000 ha of regrown forest, often characterized by Terminalia superba, 20714 ha of sylviculturally treated forest and 3000 ha of savannas.

The Yangambi reserve is 100 km east of the major city of Kisangani. It is with an area of 235 000 ha much bigger than Luki. It consists of typical Congolean forest types, including young regrown forest occupying 13% of the total area, old regrown forest characterized by light demanding species (42%), semi-deciduous forests (16%) and evergreen forests (11%). The remaining part of the reserve is a mosaic of experimental plots, cash crops and agricultural land. Among the sylvicultural plots there is a remarkable experiment of raising the proportion in the natural forest of *Pericopsis elata* (commercial name Afrormosia), a species that is nowadays being considered as the flagship species of the Congo Basin rainforests and is listed on Appendix II of the CITES. Trade of Appendix II species is only possible if a non-detrimental finding is made based on a sound scientific analysis of the carrying capacity of the wild populations for logging pressure. The Yangambi *Pericopsis* experiment has been set up between 1948 and 1954 in a forest covering almost 250 ha, including control plots. The experiment consisted of systematic forest thinning around mother trees of precious timber species. The actual situation offers interesting opportunities for long-term evaluations of forest management measures. This contributes to the value of the Biosphere Reserve of Yangambi as reference site for the surrounding forest concessions where industrial logging is taking place.

3. Vegetation history and archaeological: long-term forest dynamics

Fire is a major origin of forest disturbance. It can have a natural cause or it can be anthropogenic. Also some degree of interference between these two causes is possible, for instance when people occupy new land on naturally burnt forest. Forest fires leave behind big quantities of charcoal. Sometimes this charcoal forms layers in the soil profile with each layer corresponding to a particular fire event. Interesting is that the wood anatomical structure is largely being conserved in charcoal: the original tissues and cells can still be observed microscopically notwithstanding that all the organic molecules are turned into inorganic carbon. Wood and charcoal can be identified through the observation of anatomical features and the subsequent comparison with scientific reference collections. This offers an unique opportunity to reconstruct the floristic composition of the burnt forest, certainly in combination with radiocarbon dating of the material: dates and species assemblages of soil charcoal layers archive the forest fire history of a certain site.

We sampled soil charcoal in Luki and Yangambi [9]. There were charcoal layers in almost all of the pedological pits, suggesting that forest fires occurred all over during the last ten thousand years and that the Central-African rainforest is not an invariable landscape. Radiocarbon dating of the charcoal fragments put forward three distinct eras of fire events: 1) 7800-6800 BP, 2) 2300-1500 BP, and 3) 800 BP-present time. These fire occurrences coincide or lag behind the well documented Holocene droughts (the 8.2 ka events, the 3rd millennium rainforest crisis and the Medieval Climate Anomaly). Probably these Holocene droughts were followed by degraded and fragmented vegetation that is particularly fire prone. The floristic composition, deduced from identification of charcoal fragments, of the burnt vegetation showed a higher proportion of pioneer and savanna species the last
eight centuries, probably caused by more frequent drought events and perhaps anthropogenic disturbances.

Figure 2. Looking for charcoal in the soil of the Yangambi forest. The rainforest soil often contains charcoal layers that allow a dating of the fire event. Since the microscopic structure of the charcoal conserves the original arrangement of wood anatomical features, an identification of the taxon is possible. Identifying the charcoal fragments of a soil layer gives an idea of the floristic composition of the burnt vegetation. (Nils Bourland ©RMCA)

4. Phenology: sensitivity of a forest community to climatic influences
These last years a clear tendency can be observed from a classical species-based endeavour to a trait-based ecology. Plant traits are understood as morphological, physiological and phenological features measurable at the individual level and constituting the phenotype. Information on traits is considered as the key to understand and predict the adaptation of ecosystems in the face of biodiversity losses and global changes. The idea is that traits allow an evaluation of the fitness of individuals which can be upscaled to higher levels of system integration and eventually incorporated in earth system models aiming at climate projections[2]. Phenological traits, referring to periodic phenomena like flowering, leaf shedding and cambial activity, are considered as significant since they are related to reproduction and responses to the environment, key factors of forest resilience.

Figure 3. Phenological assessment of flowering, fruiting, leaf fall and sprouting of Pericopsis trees in the Yangambi Biosphere Reserve (Nils Bourland ©RMCA)
Both in Luki and Yangambi there are unique historical data sets on phenological traits available. The phenological studies are actually being continued (Fig. 3) including with the help of time-lapse camera’s that register phenological events at high resolution. The classical phenological observations of flowering, fruit production and leaf shedding are being completed with registrations of cambial activity, a phenological aspect hidden behind the bark (Fig. 4), but extremely important because of its direct relation to growth and carbon sequestration. Therefore its assessment needs indirect methods like periodic sampling and inflicting artificial wounds, but high resolution dendrometer measurements that register also swelling and shrinking of tissues are very informative.

![Image](image.png)

**Figure. 4.** Transverse section through the cambial zone of *Milicia excelsa* from the Luki Reserve. The left part shows the lignified xylem comprising fibres and parenchymatic rays. The right part shows the living phloem. In between there is the cambial zone with two vessels embedded in a parenchyma band (Camille Couralet ©RMCA). The cambium is active (see the still expanding big vessel and several rows of undifferentiated and un lignified cells).

In tropical forests, a particularly wide variety of phenological patterns exist. Trees often, but not always, follow an annual and quite regular rhythm of growth and reproduction. We used archived phenological data from the Luki reserve for a detailed analysis of periodical phenomena. The same data were used for the determination of the diameter at reproduction, which is still largely unknown for most of the tree species, although this is essential information for forest management.

Systematic phenological monitoring was conducted in Luki on 3.642 trees belonging to 158 species and 39 families with observations every 10 days from 1948 to 1957 [10,11]. Synchronicity of phenological events among trees was tested, both at the community level (for the forest as a whole) and individually for 87 species well represented (observations on more than 20 trees per species). The Luki reserve shows a seasonality of precipitation that is bimodal with a distinct dry season from June to September) and a short dry season (December - January) of lower amplitude and intensity. The majority of trees and species follow an annual and regular phenological rhythm. They bloom between December and February, during the short dry season, although flowers and fruits can be observed throughout the year. There is some variability in the diameter of reproduction between species but most species start reproduction at a rather small diameter. Phenology seems to be driven by rainfall periodicity, but there is, however, some variation between and within species that remains to be explored.

Comparison of archived phenological observations from both Luki and Yangambi suggests that the trees in Luki show more synchronicity and longer periods of leaf shedding than in Yangambi. However, the probability to observe a leafless tree of a deciduous species during the dry season is
similar in Luki and Yangambi. Evergreen species, to the exception of Tetrorchidium didymostemon, show weak differences between sites and the probability to observe them leafless is low in both sites. Although species known as evergreen can show long leafless periods (Pycnanthus angolensis – 115 days, Ongokea gore – 50 days), the number of years with leafless events is extremely low compared to species that are reported as deciduous.

There are many intriguing phenomena that need to be explored with additional observations and associated physiological experiments. There are for instance vital trees that do not show any diameter increment at breast height in a certain season, even when the growing season is normal and trees of the same species produced normal rings [12].

5. Tree growth: the direct link to carbon stocks and sinks

Tree growth is directly related to carbon fluxes and is a key factor for evaluations of stocks and sinks in forest ecosystems, together with mortality and recruitment. Tree growth results in subsequent xylem layers that are cumulatively formed one above the other each growing season. Since these increments are influenced by the environment (a prosperous season generally gives a larger increment) such that environmental information is being stored into growth patterns on a pith to bark gradient. Decoding of this stored information is the theme of dendrochronology. Dendrochronology has been very successful at high latitudes in different contexts like there are climate reconstruction, dating of art historical objects and forest ecology. Dendrochronological applications in the equatorial rainforests are still a big challenge because of many reasons, including absent or less distinct ring boundaries, uncertainty about the annual nature of the rings, complacent growth and absence of synchronous growth rhythm of trees from the same population.

There are a few examples of successful dendrochronological investigations from as well Luki [13] and Yangambi [14].

Terminalia superba is an emblematic species of the Luki reserve. It has a large distribution area and ring borders that are customarily anatomically distinct. Tree-ring analysis was performed on 60 plantation trees and 41 trees from the wild in Ivory Coast and from Luki. Natural forests and old plantations (50–55 years) showed similar growth patterns. Regional mean chronologies were developed for the two sites and showed a long-distance relationship for the period 1959–2008. Growth in the Mayombe was associated with early rainy season precipitation, but no relation was found between tree growth and precipitation in Ivory Coast. Congolese trees possibly show a higher climate-sensitivity than Ivorian trees, perhaps because precipitation in the Mayombe is more limiting. Tree growth in the Mayombe was also influenced by the sea surface temperatures of the Gulf of Guinea and the South Atlantic Ocean during the early rainy season. Tree growth was sensitive to the El Niño event in both regions. In the Mayombe, La Nina years were associated with stronger tree growth whereas in Ivory Coast, El Niño years corresponded with stronger tree growth. This suggests an influence of global climate variability on tree growth.

The forests of the Yangambi region are home for the long-lived pioneer species Pericopsis elata. It is one of the rare tropical timbers on the list of the Convention on International Trade of Endangered Species. This listing strengthens the need for accurate and reliable growth data. In one planted and one natural forest, respectively four and 37 Pericopsis stem disks were collected. The tree-ring series of planted trees were used to verify annual tree-ring formation. For the natural forest, a mean tree-ring chronology could be constructed comprising measurements of 24 stem disks ranged from 1852 up to 2008. This chronology was compared with time series of local precipitation, showing significant correlations with the second half of the rainy season (September–November). This seasonal precipitation was related with sea surface temperatures of the West Indian Ocean.

The existence of annual tree rings encourages further tree-ring analyses of P. elata and other flagship timber species in order to further document climate-growth responses and to provide the long-term framework that is needed for sustainable management planning.

Tree-ring analysis is particularly attractive when it can be combined with repeated measurements of tree diameter at breast height in permanent sample plots. The Biosphere Reserves of Luki and
Yangambi contain both permanent sample plots of 1 ha where we are organizing periodic forest inventories.

**Figure 5.** Periodic measurement of girth of trees in the Yangambi Biosphere Reserve. The point of measurement needs to avoid the influence of development of buttresses to allow a reliable calculation of tree increments (Nils Bourland ©RMCA).

6. **Wood energy: the most sustainable energy source to fuel local development**

Organic carbon and more particularly wood contains high levels of free energy. In tropical regions this is often the most obvious and least capital intensive way of energy source, both for domestic cooking as for electricity production in power plants. Moreover, this way of energy production is potentially sustainable, provided that management plans assure that not more wood is logged than the annual increment.

The town of Yangambi, close to the Biosphere Reserve of the same name, lost its electricity production capacity during the civil wars in the DRC at the end of last century. Several options have been compared for a new electricity plant and finally it has been decided to make use of the woody biomass in the abandoned plantations of cash crops and to establish new wood-energy plantations.

Vegetation surveys have been made in the plantations of rubber (*Hevea brasiliensis*) and oilpalm (*Elaeis guineensis*) in order to assess the quantity of energy stored in the above-ground biomass (AGB) (15). One-hectare plots in plantations and abandoned agricultural fields have been set up. Dendrometrical data have been collected including diameters at breast height (1,3 m), trunk height, total height, bark thickness, Dawkins and Van Daalen indexes. Tree cores have been taken with Swedish increment corers. The dendrometrical data have been transformed in above ground biomass values, also making use of specific wood densities. Calorific values have been measured.

The stratified sampling showed that there are actually 830,21 ha of *Hevea brasiliensis* in the neighbouring town of Ngazi and 675,68 ha in Yangambi. There are 1123,09 ha of *Elaeis guineensis* in Yangambi. The total above ground biomass is 315 158,49 Mg for *H. brasiliensis* in Ngazi, 213 316,53 Mg in Yangambi and 230 775,84 Mg for *E. guineensis* in Yangambi. Compared to palm oil plantations, the rubber trees plantations hold more AGB per ha. The specific diversity is greater in palm oil trees plantations than in rubber trees plantations, but the opposite is true for the density of
trees per ha. The amount of energy estimated for all the plantations (Ngazi and Yangambi) is 3 758 765.5 kWh.

7. Conclusion: climate change research and sustainable development in Luki and Yangambi

The Biosphere reserves of Luki and Yangambi have the potential of becoming model reserves of the Unesco MAB program with both considerable regional and global importance. Ecosystem services of the reserves are key for the local economies and welfare. They indeed provide clean water, energy, food and natural materials for the surrounding towns. Their global importance lies in the extraordinary opportunities for the type of research that is direly necessary for underpinning of the policy concerning climate control and biodiversity management. Since they are situated within the rainforest belt they should gain extra research focus because these forests are more important than other terrestrial biomes as carbon sinks and stocks. At the same time there are still wide research gaps concerning growth and ages of trees and their responses to environmental fluctuations. As well Luki and Yangambi offer excellent opportunities for monitoring of forest structures and functions as well in intact vegetation in the core areas as in different grades of disturbances and degradations in buffer and transition areas. Both reserves are also sites with a particularly long history of research and experiments. A big share of the archived data is gaining importance because of their actual pertinence. New research projects could harvest the fruits of long term observations. This opportunity is rather exceptional. Success of these projects depends on a strong research capacity and the preservation of the research potential of the reserves. Key for the integrity of the forest is the implication of population in the transition zone. Investments in development and educational projects in schools seem therefore to be of equal importance as the establishment of conservation and research projects.

Figure. 6. New Laboratory for Wood Biology under construction in the buffer area of the Yangambi Biosphere Reserve. EU funding and the FORETS project, coordinated by CIFOR, allows the establishment of a laboratory aiming at state-of-the-art analysis of wood tissue in a context of carbon fluxes, wood-energy issues, forest ecology and enforcement of international conventions and regulations concerning forest protection and timber trade. (Mélissa Rousseau ©RMCA)

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