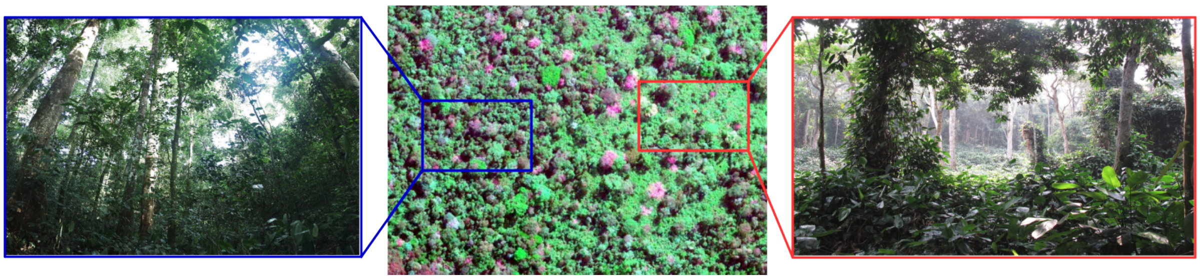
DEGRADED STABLE STATES IN TROPICAL FORESTS



Dense (left) and Marantaceae (right) forests coexist in central Africa as can be seen in a satellite image. The question is: is this coexistence stable? and if yes how and why?

Table 1: Summary table of persons involved in the project. Work package (WP) coordinators and the scientific coordinator are highligthed in bold and bold and underlined, respectively. Additional human resources to be undertaken by the project are described in the Staff expenses section.

Lab	Name	First name	Position	Months	Implication
AMAP	**BARBIER**	**Nicolas**	Researcher	8	WP2 coPI (section 1.3.3.1)
AMAP	**COUTERON**	**Pierre**	Director of research	6	WP3 coPI (all sections)
AMAP	FORTUNEL	Claire	Researcher	4	WP1 (section 1.3.2.1)
AMAP	MARECHAUX	Isabelle	Researcher	4	WP3 (sections 1.3.4.1-2)
AMAP	MAO	Zhun	Researcher	4	WP1 (section 1.3.2.4)
AMAP	PELISSIER	Raphaël	Director of research	4	WP1 (all sections)
AMAP	**REJOU-MECHAIN**	**Maxime**	Researcher	20	Coordination, PI WP0, co-PI WP1
AMAP	POUTEAU	Robin	Postdoc	12	WP2 (section 1.3.3.1)
AMAP	VIENNOIS	Gaelle	Research engineer	11	WP2 (section 1.3.3.1)
ISEM	**BREMOND**	**Laurent**	Assistant professor	8	WP2 coPI (section 1.3.3.2)
ISEM	DAKOS	Vasilis	Researcher	2	WP3 (all sections)
ISEM	**FAVIER**	**Charly**	Researcher	8	WP3 coPI (all sections)
ISEM	KEFI	Sonia	Researcher	2	WP3 (all sections)
F&S	DOUMENGE	Charles	Researcher	4	WP1 (all sections)
F&S	**GOURLET-FLEURY**	**Sylvie**	Researcher	3	WP1 co-PI (all sections)
F&S	FORNI	Eric	Research engineer	2	WP1 (all sections)
F&S	ROSSI	Vivien	Researcher	3	WP1 (all sections)

Requested amount (546 k€) differs (7.6%) from the initial request (507 k€) due to a revaluation of salaries and missions.

1 Proposal's context, positioning and objectives

1.1 General context and objectives of the project

Forest degradation refers to cases where discrete disturbance events lead to substantial changes in the ecosystem, which nevertheless remains a forest, as opposed to what happens in case of deforestation. Forest degradation affects ten times the area that is affected by deforestation globally[1]. It is likely to release more carbon than deforestation in some areas[2] and to alter several other ecosystem services, thereby lowering the ability of forests to provide income for rural livelihoods[3]. Some may argue that forest degradation is not a significant issue because natural processes will systematically bring back the forest close to its initial state because the system remains a forest assumed to be resilient. However, this view is probably biased by the fact that forest degradation in the tropics has been mostly studied from an ecological succession perspective[4], where successional processes bring the system to a state considered as stable and mature, with similar functional properties to the pre-disturbance state. In many cases, successional processes will indeed operate in the absence of new disturbances and lead to the recovery of ecosystem services in a few decades. However, **disturbances may also produce deep and lasting modifications of forest dynamics, pushing the system to bifurcate to an alternative stable state or to an arrested succession, with a lower ability to provide ecosystem services**.

Successional pathways may indeed involve early-successional species or plant functional types that, rather than facilitating succession, block tree regeneration for an extended period, or even permanently[5]. For example, we have shown that a large patch of liana-infested forest in Amazonia may be an example of a shift towards a longstanding, possibly stable, degraded forest state with a lower ability to store carbon and a much lower diversity than the initial forest[6]. By accelerating forest dynamics (i.e., increasing turnover rates), lianas induce changes in abiotic and biotic conditions that in turn have a positive effect on liana recruitment and growth. Another example from the tropics is the Acanthus-dominated systems in Uganda, where a native shrub colonizes forest clearings and blocks the succession by inhibiting tree recruitment and growth and by promoting elephant disturbances with positive effects on Acanthus-dominated systems[7]. These examples illustrate that different ecological mechanisms may be involved in the stability of degraded forests. **The spatio-temporal dynamics of these degraded forests, their long-term stability and the conditions that determine ecosystem shifts are poorly understood and therefore not nowadays predictable.**

Our project will focus on a system that likely corresponds to a stable degraded forest state in central Africa, the Marantaceae forests. These forests are widespread in central Africa (e.g., thousands of km^2 in the North of the Republic of Congo, hereafter called North Congo, Fig. 1A) and have been understudied, though representing a critical issue for forest managers due to the very low regeneration of timber trees after logging operations[8]. Compared to adjacent dense forests, Marantaceae forests exhibit a lower tree density (usually a few trees of medium to large size), almost no tree regeneration, a lower floristic diversity and an impenetrable dense understory composed of perennial giant herbs (up to 5 m) from the order Zingiberales, principally belonging to the families Marantaceae (arrowroot) and Zingiberaceae (ginger)[9]. The few available studies suggest that Marantaceae forests are extremely stable in time[9–12], some likely resulting from anthropogenic disturbances dated to more than a thousand years BP[9,10]. Besides human disturbances, some Marantaceae forests may have established following extreme dry events such as El Niño events[9]. Thus, **Marantaceae forests are predicted to expand in the future at the expense of dense mature forests under the on-going conjunction of climate change and increasing anthropogenic disturbances**[9,11]. This would have a very strong negative impacts on forest biodiversity, carbon sequestration and other ecosystem services on which the local economy relies, including logging activities, the most important source of income in the region, and for which international certifications require logging companies to design sustainable harvesting schemes.

The main objective of our project is to study the spatio-temporal dynamics of the central

African Marantaceae forests in order to understand the mechanisms that underpin their origin and maintenance. The ultimate goal of the project is to anticipate the potential consequences of global changes on the dynamics of central African forests and thus to provide recommendations for forest preservation and management to achieve a sustainable use of forest resources.

Combining local in-situ and ex-situ field experiments, remote sensing analyses at regional scale and mathematical modelling, we will specifically investigate two main questions and hypotheses:

1) **What are the main drivers of Marantaceae forest dynamics?**
Hypothesis: Human and/or climate-induced disturbances are major drivers of the expansion of Marantaceae forests, which then maintain through negative feedback mechanisms against trees.

2) **What is their observed contemporary (<100 yrs) and long term (> 500 yrs) dynamics?**
Hypothesis: Marantaceae forests significantly expanded during the last decades, while no shifts from Marantaceae forests to closed-canopy forests occurred in the last millennia.

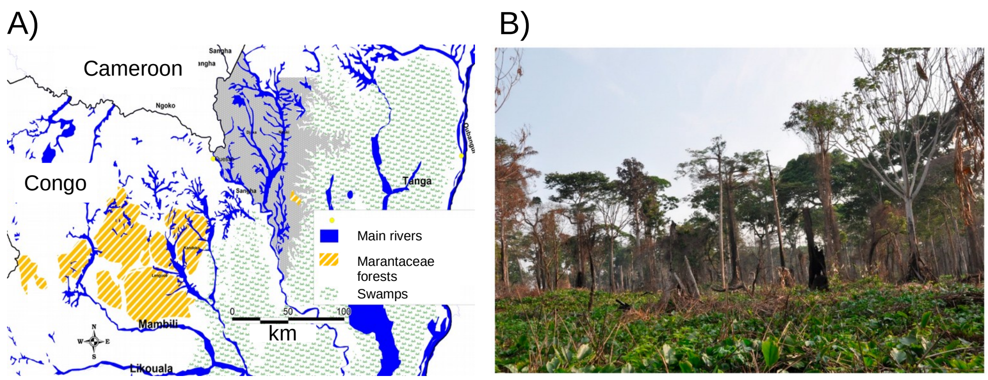


Figure 1: A) A large patch of Marantaceae forest from North Congo (ca. 500,000 ha in hatched orange), whose extent was estimated from a satellite image (adapted from Gillet[9]). B) Regrowth of giant herbs in an area affected by a fire that occurred five months before (taken from Verhegghen et al.[13])

1.2 State of the art on Marantaceae forests of central Africa

Given the importance of Marantaceae forests, in terms of spatial extent, ecological peculiarities and economic consequences, it is rather surprising that Marantaceae forests have so far received scant attention. Most studies have been published in French (e.g.[8,9,14,15]), often in technical reports (e.g.[8,15]) and/or PhD dissertations[9,10]. In the following paragraphs, we briefly summarize our current knowledge on Marantaceae forests.

Giant herbs form large patches in central African forests. For instance, in the well-known Odzala National Park in North Eastern Congo (2800 km^2), half of the area is covered by Marantaceae forests, with a tree canopy cover below 20%[16]. Other large patches were also described in Cameroon[17], South Congo[14] and central Gabon[18]. However, **the total extent of Marantaceae forests and their determinants remain unknown**. The abiotic environment is unlikely to be a major determinant of the relative success of giant herbs over trees[9]. Indeed, Brugière et al.[8] found no evidence for a role of soil or topography on the occurrence and density of giant herbs. In addition, Brcnic[10] found that some giant herb species displayed significant variation in abundance along a soil fertility gradient, but not the giant herb species that form monodominant forest patches.

The origin of Marantaceae forests is controversial in the litterature. In the 1960s, Rollet[19] used aerial photographs taken over the North Congo and was the first to hypothesize that closed-canopy forests were shifting into Marantaceae forests, themselves shifting into savannas. Rollet formulated two explanations: either Marantaceae forests would result from old and widespread human disturbances or from a natural process of invasion due to the «agressive» nature of giant herb species. Rollet's point of view was also supported by Lejoly[15] who suggested that Marantaceae forests correspond to a regressive forest dynamics. A second hypothesis suggests that Marantaceae forests would result from a natural process of expansion of enclosed savannas, under a more humid climate, where the giant herbs would establish concomitantly or just after the first pioneer trees[14,18,20]. In this scenario, strictly opposed to that of Rollet, Marantaceae forests would constitute an intermediate successional stage between very early and late successional forest stages, even if the time needed to shift from a Marantaceae forest to a closed-canopy forest was assumed to be very long[14,18]. For example, working in the same area as White[18], Cuni-Sanchez et al.[12] showed that Marantaceae forests did not change substantially in structure or diversity over a 20-year period. A third hypothesis proposes that Marantaceae forests are a signature of old human disturbances/activities[9–11]. The positive correlation between the occurrence of Marantaceae forests and both charcoals and archaeological artefacts, some of which dating back from 1000 to 2500 years, suggests that these forests originate from disturbance events and then persist over long periods thanks to self-maintenance mechanisms. This hypothesis suggests that current disturbances of medium intensity (e.g., logging) coupled with dry years may favour the long-lasting maintenance of Marantaceae forests. **Testing these three different hypotheses requires assessing the contemporary and long-term spatio-temporal dynamics of Marantaceae forests, tracking the direction of shifts in forest types and testing for the conditions of stability of Marantaceae forests**.

Disturbances may play a major role in the genesis of Marantaceae forests. Two main types of disturbances have been discussed. First, many observations support the hypothesis that giant herbs significantly expand after logging activities or in natural forest gaps[8,9]. Canopy opening is indeed expected to stimulate the growth and colonization of light-demanding and fast-growing giant herbs. However, **the effect of logging activities on the dynamics of Marantaceae forests has rarely been assessed quantitatively, which limits the development of sustainable management practices**. The second type of disturbance that may impact the dynamics of Marantaceae forests is fire. Some authors have suggested that fire events may be a major cause of giant herb establishment or maintaining[9,11], because they create large gaps in which the giant herbs may thrive (Fig. 1B). This assertion is mostly based on indirect evidences, i.e., a higher occurrence and mass of charcoals in Marantaceae forests compared to closed-canopy forests. Giant herbs may also be conducive for fire spread while their rhizomes are well protected, allowing a much faster regrowth of giant herbs than trees. Major fire events (e.g., resulting from El Nino events) may thus be an important driver of the shift from close-canopy forests to Marantaceae forests[13]. However, the effect of fires on Marantaceae forests remains controversial as fires may also reinitiate the successional dynamics to closed-canopy forests through the post-fire recruitement of pioneer trees[15]. Hence **the effect of fire on the dynamics of Marantaceae forests is still uncertain due to a lack of monitoring over a sufficiently long period**.

Giant herbs are well-adapted to disturbance through a high rate of clonality, mostly via rhizomes[9]. This mechanism can provide positive feedbacks at local scale, which has been assumed by some authors to be a major advantage of giant herbs over trees for the rapid colonization of gaps[8,9]. A recent study genotyping ramets from *Haumania danckelmaniana* (Marantaceae) in an undisturbed forest of eastern Cameroon, suggested a predominant outcrossing in this species[21]. The authors, however, acknowledged that a much higher rate of clonality may be observed after disturbance, similarly to climbers that rely on clonality to colonize forest gaps faster than tree seedlings after a canopy opening[22]. Thus, **testing for a differential allocation to sexual and vegetative reproduction of giant herbs under disturbed or undisturbed conditions may shed light on the colonization strategies of giant herbs**.

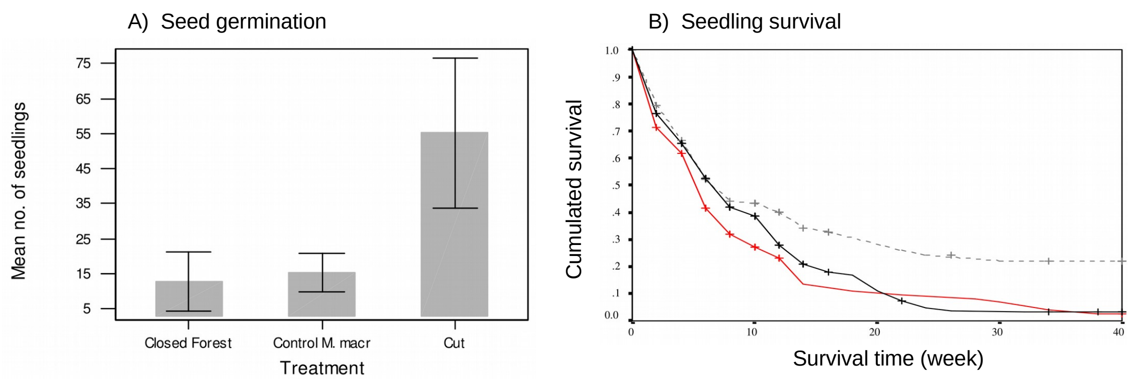


Figure 2: Results from a seed germination and tree seedling monitoring conducted by Brcnic[10]. A) Comparison of tree seeds germination in a closed-canopy forest understorey and in a Marantaceae forest where the aboveground parts were left intact (control) or cut. Bars are 95% confidence intervals. B) Graph of the cumulated survival as a function of time for naturally germinated seedlings in the three treatments: closed-canopy forest understory (grey dashed line); control Marantaceae forest (solid red line); and cut Marantaceae forest (solid black line). Crosses represent censored observations. Figures adapted from Brcnic[10].

Only a few studies have studied the interactions between giant herbs and trees[8–10]. During her doctoral research, Brncic[10] developped a comprehensive experimental design with multiple treatments (i.e., plant mixture design) to disentangle the effects of above- from below-ground competition between giant herbs and trees (Fig. 2). Her results showed that germination rates were similar in closed-canopy and Marantaceae forests but germination rate was significantly higher when the above-ground part of giant herbs was removed (Fig. 2A). Moreover, seed survival rates were higher under closed-canopy forests than in presence of giant herbs, or of only their root system (trenched treatment; Fig. 2B). These results suggest that the root system of giant herbs inhibits tree seed germination and increases tree seedlings mortality. However, whether this results from belowground competition alone or from an additional allelopathic effect is unknown[8–10]. Hence, **a better understanding of below-ground interactions between giant herbs and trees is needed**.

As shown here, much uncertainty remains on (i) the spatial distribution and extent of Marantaceae forests in central Africa; (ii) the origin of Marantaceae forests; (iii) the effect of global change, in particular anthropogenic activities and climatic anomalies, on the dynamics of these degraded forests; (iv) the ecological mechanisms promoting the potential stability of Marantaceae forests. The present project aims at contributing to filling these major knowledge gaps.

1.3 Methodology and risk management

The project will be organized in four complementary work packages (WP; Fig. 3). WP0 will aim at synthesizing our current knowledge on Marantaceae forests; WP1 will investigate the ecological mechanisms underlying their dynamics; WP2 will assess their contemporary (<100 yrs) and long term (> 500 yrs) spatio-temporal dynamics and; WP3 will aim at understanding the theoretical conditions of their post-disturbance stability. WP3 will thus bridge the local ecological mechanisms (WP1) and the long-term dynamics (WP2). Our questions will mostly be investigated from Marantaceae forests located in North Congo where the largest patches in central Africa are found and where experimental works are already on-going in collaboration with a forest logging company.

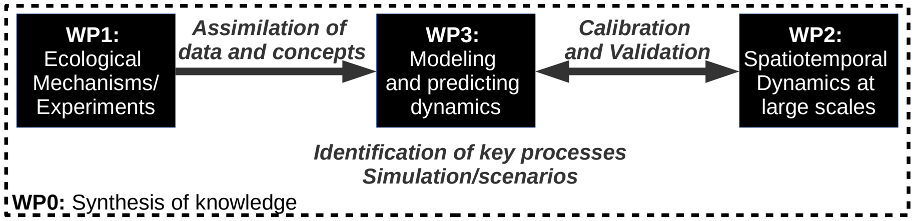


Figure 3: Schematic representation of the project organisation

1.3.1 WP0 Synthesis of knowledge

(Leaders: M. Réjou-Méchain, UMR AMAP)

Studies by White and collaborators in La Lopé (Gabon)[12,18,20] are among the few publications focusing on Marantaceae forests that are easily accessible to the international community. The literature review conducted while preparing this project revealed the dire need for a comprehensive synthesis of data and knowledge on Marantaceae forests to propose hypotheses about the mechanisms through which they originate and maintain. The initial step of the project will thus coordinate the few experts who worked on this forest system to contribute to a joint review paper that will define Marantaceae forests, reveal important unpublished results and list the main hypotheses regarding their origin and maintenance. Most of these experts have already been contacted and are keen to contribute to such a review, which has already been invited by the chief editor of *American Journal of Botany*.

1.3.2 WP1 Ecological mechanisms underlying the dynamics of Marantaceae forests

(Co-leaders: M. Réjou-Méchain, UMR AMAP & S. Gourlet-Fleury, UR CIRAD Forêts & Sociétés)

Previous works showed that giant herbs significantly compete with tree seedlings for above- and below-ground resources, considerably limiting tree regeneration in Marantaceae forests[9,10]. However, many uncertainties remain about the conditions under which giant herbs colonize areas and then outcompete trees, leading to a supposedly long-term giant herbs monodominance. In WP1, in collaboration with the team of Prof. Joël Loumeto (University of Marien Ngouabi, Brazzaville, Congo) and the CIB-OLAM logging company, we will conduct further experiments in order to better understand the conditions and mechanisms allowing the stability of Marantaceae forests.

1.3.2.1 Quantifying the encroachment of giant herbs after logging disturbance

The triggering effect of logging activities on giant herbs proliferation has been documented[8,9] and often observed by forest operators as soon as one to two years after logging. However, this effect has seldom been directly demonstrated and quantified[9]. To this aim, we started an experiment in North Congo in April 2017, in an undisturbed forest harboring several patches of Marantaceae forests embedded in a matrix of closed-canopy forests, hereafter referred to Loundoungou site. Over 5 months we inventoried the stems and vegetation cover of giant herbs at a 10-m resolution in four 9-ha permanent forest plots prior logging operations (total workload of 420 man-days). The four forest plots were established in 2015 in the frame of the DynAfFor project led by S. Gourlet-Fleury, in collaboration with the CIB-OLAM company. All trees $\geq$ 10 cm in diameter are monitored yearly allowing to estimate tree stand dynamics. Two of these plots were logged by the CIB at the end of 2018 whereas two control plots remained unlogged. This "giant herbs" experiment was set under the supervision of M. Réjou-Méchain in collaboration with E. Forni, S. Gourlet-Fleury and V. Istace (CIB company, Pokola).

Unmanned aerial vehicles (i.e., drones) are also used to survey a larger area (~ 800 ha) using high-resolution and multispectral optical sensors (< 10 cm in resolution; Fig. 4) and LiDAR systems. The first flight was completed in June 2018 before logging operations with a RGB camera. A second flight with a RGB camera was conducted in April 2019 over the logged area, three months after logging operations, to quantify canopy openness due to logging. A third flight was conducted in February 2020 with both LiDAR and multispectral sensors. A new ground-based sampling of giant herbs will be conducted at the begining of 2021 in the frame of the present project to assess the effect of logging on giant herbs dynamics. Field census, including giant herbs and trees censuses, will be undertaken as part of the present project and one additional drone survey will be conducted in 2023 to assess forest recovery and giant herbs encroachment five years after the logging operations. **We expect a significant increase in the extent of giant herbs patches three years after the logging disturbance and no change in the unlogged (control) areas**.

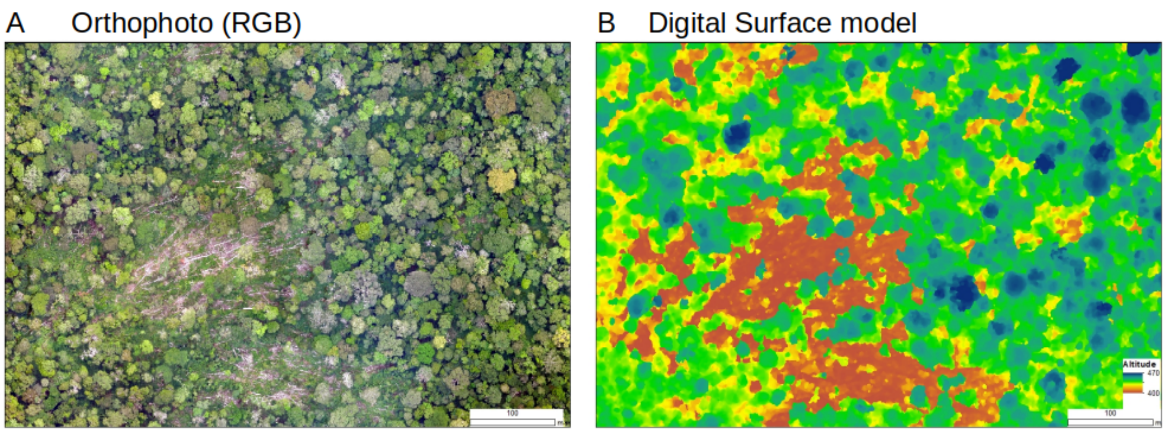


Figure 4: Example of drone acquisition at DynAfFor site on June 2018. A) Orthomosaic in RGB mode illustrating an area where a large natural windthrow recently occurred. B) The corresponding digital surface model (height of the top of the canopy) showing in red the massive windthrow assessed from stereophotogrammetry. Such natural events may also greatly favour the rapid expansion of giant herbs. This area will also be ground-surveyed during the project to assess the effect of large natural disturbances (field observations made in February 2020 indicated both tree and giant herbs recruitment over this area).

1.3.2.2 Fire effects on Marantaceae forests dynamics

The effect of large fire events on the dynamics of giant herbs has never been assessed directly. Between late January and early February 2016, major fires occurred in a Marantaceae forest area, covering ca. 37,800 ha according to the MODIS Burned Area dataset. These fires occurred in the context of a very strong El Niño event[13]. The IFO logging company, that manages the impacted area, conducted surveys to quantify the impact of these fires on tree dynamics. In parallel, 20 transects of 20 m x 250 m will be set in transitional areas to assess the combined effect of fires and logging on tree dynamics as part of the project “paysage Nord Congo” (AFD, accepted in 2020; PI S. Gourlet-Fleury). In the present project, we will additionally measure vegetation cover of giant herbs at a 10-m resolution in these transects, as done in the Loundoungou site, to better understand the impact of fires on Marantaceae forests. We will also mobilize remote sensing data to quantify the area extent where shifts from closed-canopy forests to Marantaceae forests can be observed following the fire events, based on approaches developed in WP2. We will conduct ground survey assessment in the fire-affected areas to assess the regeneration (tree or giant herbs) after five years and to validate our remote sensing classification. Remote sensing time series of WP2 will allow to assess the type of forest (dense or open) before the 2016 fire event. **We expect that open Marantaceae forests were more conducive to fires than dense forests and a dominance of giant herbs in forest areas strongly affected by fires**.

1.3.2.3 Effect of disturbances on giant herb reproduction

Clonality has been suggested to be a key mechanism by which giant herbs propagate through disturbed areas more efficiently than trees[8,9]. We will collaborate with Alexandra Ley (University Halle-Wittenberg, Germany), a specialist of Marantaceae biogeography, to quantify the clonality of giant herbs following logging disturbances in the Loundoungou site. In 2021, we will systematically sample giant herb ramets in the four 9-ha forest plots at different spatial scales, recording individuals at different distance intervals (<2 m; <5 m; <20 m; < 100 m; < 300 m), and geo-located samples in the plots. The sampling design will aim to (i) compare undisturbed and logged plots and (ii) compare areas previously occupied and newly colonized by giant herbs. Alexandra Ley will use already-developed microsatellite markers[21] to spatially quantify the clonal diversity and outcrossing rate of *Haumania danckelmaniana*, the dominant giant herb in our study site. To our knowledge this will be the first direct test of the influence of disturbances on the rate of clonality in a tropical plant population. **We hypothesise that clonality predominates over outcrossing in disturbed areas**.

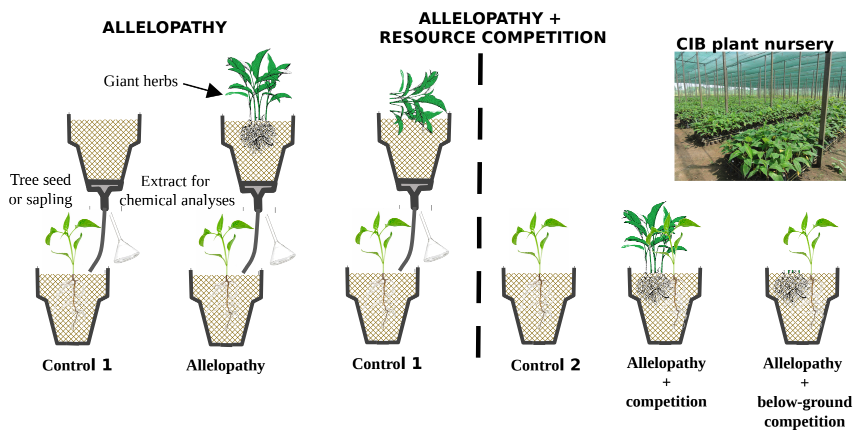


Figure 5: Experiment planned to dissociate resource preemption competition and allelopathic effects of giant herbs on tree germination and growth. Exp. 1: on the left, there are three types of donor pots: (i) with bare soil as control (n = 8); (ii) planted with giant herbs (n =8); and (iii) containing giant herbs leaves (n =8). Leachates from each donor pot will be delivered to the target pots (below) where seeds from four tree species will be planted. Exp. 2: on the center, seed germination and sapling growth of the four target tree species will be monitored in three treatments: (i) tree seeds will be planted alone (n = 8); (ii) with giant herbs (n = 8); and (iii) with cut-leaf giant herbs (n = 8). A 3-ha plant nursery from the CIB company that hosted banana saplings in 2017 (top right).

1.3.2.4 Disentangling competition from allelopathy effects from giant herbs on trees

If competition between giant herbs and tree seedlings was quantified by Brncic[10] and Gillet[9], these two authors, as well as Brugière et al.[8], suspected that the root system of giant herbs can inhibit seed germination through allelopathic effects. This effect has never been demonstrated and, if existing, would strongly influence the stability of Marantaceae forests and the colonizing ability of giant herbs. We will design a "donor-target" experiment[23] to (i) test for an allelopathic effect of giant herbs on tree species and (ii) dissociate direct competition from allelopathic effects (Fig. 5). Seed germination and sapling growth of tree species will be monitored biweekly for twelve months in a plant nursery established near our experimental site (Pokola). Four focal tree species will be selected among the dominant tree species, maximizing difference between species in terms of their ecological behaviour (two pioneers and two shade tolerant species). We consider that four species is a maximum to keep the experiment manageable. All treatments will be replicated 8 times per tree species, resulting in the monitoring of 192 pots. A technician from North Congo will be hired to maintain the experiment during the whole period. The experiment will allow estimating the relative effect of allelopathy and competition through the comparison of the two treatments (i.e., left and right part of Fig. 5). **We hypothesise that, beside competition for resources, giant herbs inhibit tree regeneration through allelopathy**.

1.3.2.5 Local perception of Marantaceae forests

Through a collaboration with Solen Le Clec'h (Wageningen University, Netherlands), ethnobotanical surveys will be undertaken by a master student (hire on our own funds and co-supervised by S. Le Clec'h and M. Réjou-Méchain) to analyse the perceptions of Marantaceae forests by the local populations, focusing on different linguistic groups. These surveys will be critical to understand how Marantaceae forests do differ from dense forests in terms of the services they provide. These surveys may also raise important hypotheses on the origins of Marantaceae forests and give insights on the heterogeneity of Marantaceae forests composition and their associated ecological functions, ecosystem services and uses.

1.3.3 WP2 Contemporary and long term spatio-temporal dynamics of Marantaceae forests

(Co-leaders: N. Barbier, UMR AMAP & L. Bremont, UMR ISEM)

Assessing spatiotemporal dynamics of Marantaceae forests is pivotal to understand whether these systems are stable over time and/or if they are expanding with ongoing global changes. A better understanding may further validate or invalidate some hypotheses on the origin of Marantaceae forests (e.g., whether they are intermediate successional stages between savannas and closed-canopy forests or whether they are colonizing new areas through the effect of human or natural disturbances). In WP2, we will (i) build a time series of remote sensing images covering a period of 60 years to characterize the recent spatiotemporal dynamics of Marantaceae forests and (ii) test the long term (> 500 years) stability of Marantaceae forests through historical ecology approaches.

1.3.3.1 Spatiotemporal dynamics of Marantaceae forests from the 1950s to today

Information on the past distribution of Marantaceae forests can be extracted from aerial photographs taken by the French national geographic institute (IGN) in the 1950s and 1960s over the whole territories of the Congo Republic. These panchromatic black and white argentic photographs were acquired in stereo pairs (see example on Fig. 6). Over some extensive areas, concomitant surveys were conducted with infrared cameras. These rare historical data have been poorly leveraged so far for large-scale analyses[4,24], although they represent a unique source of information on tropical forest state as far as 60 years ago. Using such old photographs over rather small areas, White[18] and Rollet[19] demonstrated that Marantaceae forests could be easily distinguished visually from closed-canopy forests and savannas. The CERGEC (Centre de recherche géographique et de production cartographique, Congo, Brazzaville), the national institute in charge of these historical images, already granted access to the archives and a collaboration is established with this institute.

We will thus build a geodatabase where these historical photos will be assembled, georeferenced and orthorectified over large areas (~10,000 km²) in North Congo. This time-consuming task will be performed by an engineer to be hired through the present project (see Human resources). Focal study areas will be selected in (i) protected areas, such as in the Odzala National Park, and (ii) areas with records of human disturbance during the last decades (in areas where logging activities and/or human-induced fires occurred). Areas that benefited from infrared acquisitions will be prioritized as giant herbs have a clear signature in the infrared spectrum (Fig. 7), providing information that is complementary to the one inferred from panchromatic images (i.e., forest structure and canopy texture). Marantaceae forests will thus be mapped at large scale through a visual stereo-photo interpretation of old photographs[25] combined with infrared information when available. Over smaller areas, photogrammetric approaches will be applied to these old images to derive dense point clouds of forest structure that will be quantitatively compared with already acquired drone-based point clouds (see WP1). Photogrammetric analyses on such old images were already and successfully compared to airborne laser scanning data in French Guiana (Viennois, in prep).

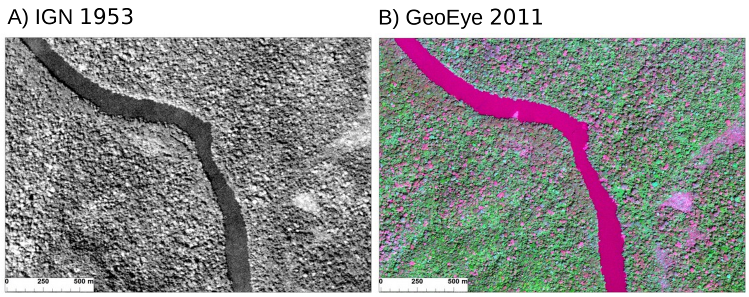


Figure 6: Comparison between an old IGN photography from 1953 and a recent very high resolution multi-spectral image acquired in 2011 in south-east Cameroon (14.2°N 2.6°E). (©Gaelle Viennois).

Recent high-resolution, multi-spectral cloud-free images will be superimposed on the old photographs to assess the spatio-temporal dynamics of Marantaceae forests. We will give priority to data already acquired by our team over central African forests (3,000 km² of recent very high resolution (VHR) images in North Congo) or freely available through the OSFACO project. We will also use Sentinel 2A data (10-m resolution), freely available from the European Space Agency, and complete data archive from Landsat sensors since the 1970s. Combining radiometric, multi-spectral, temporal signatures (leveraging Sentinel 2A and Landsat capabilities) and VHR-based texture features (FOTO methods[26]) provide a great potential to identify Marantaceae forests from adjacent closed-canopy forests (Fig. 7). In another approach, time series will be analysed through recent methodological developments allowing to characterize break-points and trends[27]. An ongoing partnership with Airbus Defense and Space (initiated during the 'FOREST' EIT KIC project in which N. Barbier and G. Viennois participated) will give us access to improved pre-processing tools (Overland processing platform) to scale up this approach over large areas. The main advantage of this approach is to provide, along with the temporal depth, an improved temporal resolution in order to better characterize the timing of events such as fire frequency and recovery speed after disturbance[28].

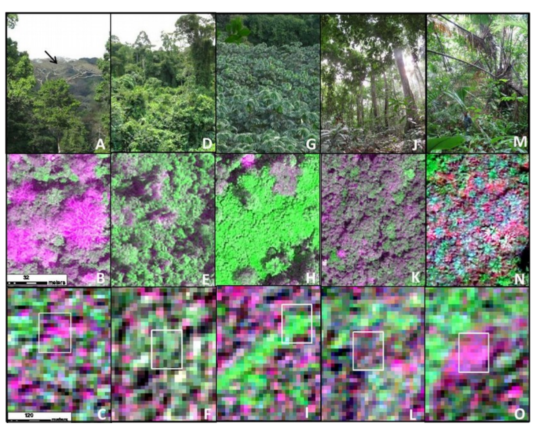


Figure 7: Detection of Marantaceae forests from remote sensing data. Comparison of five forest types from ground photographs (first row), Red/Near Infrared/Green very-high-spatial-resolution GeoEye (second row) and high-spatial-resolution composites (third row). Forest types correspond from left to right to a mixed closed-canopy forest, an open Marantaceae forest, a young secondary forest, a *Gilbertiodendron dewevrei* forest and a swamp forest. Figure taken from Viennois et al.[29].

This will be one of the first attempts to directly assess forest dynamics from historical images (>60 yrs) over such a large extent in tropical forests (> 1000 km^2). This WP will generate critical insights into the contemporary dynamics of Marantaceae forests. It will also provide an important baseline for the optimization of field sampling design (e.g., effect of fires in WP1) and to calibrate/validate the spatialized theoretical models to be developed in WP3. **We expect that Marantaceae forests expanded during the last decades, especially in human-disturbed areas, and that no shifts from Marantaceae forests to closed-canopy forests occurred in the same time.**

1.3.3.2 Long term spatio-temporal dynamics of Marantaceae forests

Some Marantaceae forest patches may have originated from very old human disturbances, i.e., > 1000 yr. ago[9–11]. This assumption is based on results obtained from charcoals and pottery abundances, which give information on fire and/or human activities and potentially on tree composition (through charcoal identification[9]). These approaches however do not give direct information on the presence/absence or abundance of giant herbs through time and thus do not provide direct evidence for the long-term stability of Marantaceae patches.

We will sample ten sites along a gradient of giant herbs abundance and canopy openness in North Congo, from large monodominant giant herb patches with almost no trees to closed-canopy forests without giant herbs in the understory. This gradient will be preliminary identified thanks to the previous task and will ideally match some of the long-term transects that will be established in transitional areas (see the fire effect section). We will sample seven 1.5-m soil cores per site (n=70 cores in total). Four cores per site will be used for phytolith, soil organic carbon isotope (^{13}C and ^{14}C dating) and charcoal mass quantification. Phytoliths from giant herbs can often be identified at the genus level, and sometimes at the species level[30]. The analysis of organic carbon isotope ratios along soil profiles is an accurate method to determine past fluctuations of forest openings[31] and charcoal concentration in tropical soils is often considered as a good proxy of ancient disturbances[32,33]. The depth interval sampling step will be adjusted according to the dating and profile dynamics recorded by the phytoliths. We plan to analyze ten levels per core, i.e., around 40 per site and therefore 400 samples for the entire study. This large number of samples is realistic because we will not carry out complete phytolithic counts on all levels but ratios between the phytoliths produced by giant herbs and an exogenous marker (silica microballs), which will save time and allow us to obtain precise concentrations of phytoliths[34]. At least 10% of the samples will be counted in full to quantify more precisely if there have been changes in tree cover independently from giant herbs[35]. The other three cores will only be used for charcoal mass quantification. While charcoal abundance may validate the higher occurrence of historical fires in Marantaceae forests compared to closed-canopy forests, phytolith analyses combined with radiocarbon dating will allow quantifying the occurrence and abundance of giant herbs through time. Here we thus aim to test the long-term stability of some Marantaceae forest patches and to assess whether closed-canopy forests have been covered by giant herbs in the past (it would indicate, contrary to our expectations, possible shift from Marantaceae forests to closed-canopy forests). Furthermore, by combining phytoliths and ^{13}C we will be able to detect if some sites were previously covered by savannas as a test of the hypothesis formulated by White[18] and de Foresta[14], i.e., that Marantaceae forests originate from savannas. This work will be conducted through the supervision of a technician (see Human resources). **We hypothesize that large Marantaceae forest patches originated a long time ago (>500 yrs) and that only shifts from closed-canopy forests to Marantaceae forests occurred in the last millennia**.

1.3.4 WP3 Modeling tree-giant herbs interactions

(Co-leaders: C. Favier, UMR ISEM & P. Couteron, UMR AMAP)

The dynamics of Marantaceae forests most likely operates over long periods of time in scattered patches. Both local observations/experiments (WP1) and large-scale monitoring (WP2) are necessary to grasp this complex dynamics, but models are needed to bridge the scale gap and evaluate how local processes propagate into broad spatiotemporal patterns. To improve our theoretical and predictive understanding of the condition of stability of Marantaceae forests, we will develop a theoretical model, calibrated with empirically-derived parameters to ensure consistency among multi-scale data interpretations. Our model of tree and giant herbs dynamics will be mathematically-tractable and mechanistic. This model will allow identifying the conditions in which the system (i) steadily displays both a limited biomass of trees and large biomass of giant herbs (i.e., Marantaceae forest) or (ii) potentially shifts to a large tree biomass (closed-canopy forests). This work will allow (i) testing the conditions under which Marantaceae forests may be stable or only transient states, and (ii) what are the individual and joint roles of logging and fire disturbances in Marantaceae forest dynamics.

1.3.4.1 Adaption of the IFAC model to tree-giant herb dynamics

Over the last years, the AMAP team has developed a mathematical framework using impulsive differential equations to model asymmetric tree-grass interactions in a context of disturbances[36–38]. This work was primarily designed to understand the conditions of stability of forests, grassland and savanna states, but it can easily be transposed to study the interactions between trees and giant herbs. Contrary to most previous works that expressed state variables (e.g., tree and grass) in terms of relative cover[39], the model uses biomass as state variable to account for the fact that plant categories (tree and grass) are not mutually exclusive at a given point in space. Our framework models the dynamics of three "types" of plants: tree saplings, adult trees and grasses, similarly to Staver et al.[39]. The Impulsive Fire model of Asymmetric tree–grass Competition (IFAC) accounts for the asymmetric nature of tree-grass competition and for the role of fires in savanna dynamics, implementing fires as periodic impulsive events[37]. This way of modelling fires is more realistic than assuming a time-continuous fire effect[39], significantly modifies the condition of multi stability and provides more realistic long term behaviours[37]. A spatio-temporal version of the IFAC model has been recently developed assuming that spatial propagation of woody and grass components can be approximated as local biomass diffusion through Laplace operators[38]. Thank to this assumption, it was possible to derive conditions of boundary steadiness vs. movement for which diffusion coefficients proved pervasive.

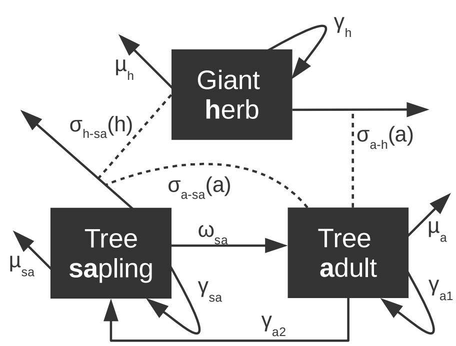


Figure 8: Model outline illustrating the three compartments that will be considered with the main relationships to be accounted for between compartments. Symbols γ and μ express biomass growth and decay, respectively, ω represents the transfer rate between plant stages and σ represents negative effects such as competition or allelopathy. The biomass residence time is thus expressed by $1/(\omega + \mu)$.

We will adapt IFAC to the case of trees and giant herbs. The asymmetric nature of trees vs. giant herbs interactions warrants the use of these models as a basis for the development of a Marantaceae forests-specific model. The first step will thus be to incorporate the processes that are specific to Marantaceae forests using both findings from the literature (WP0) and results from WP1 and WP2. In Figure 8, we provide a compartment diagram that summarizes the main relationships expected between plant "types". We will use this general framework to understand the conditions for stability of Marantaceae forests, defined here as conditions with high biomass in giant herb compartment and relatively low biomass in tree compartments.

1.3.4.2 Model sensitivity and calibration

We will model the biomass of each plant type as state variable varying through time. To define the range of biomass values that the model should account for, we will first estimate the biomass of the three plant types along a gradient of giant herbs density. The above- and below-ground biomass of giant herbs will be estimated through destructive sampling of leaves, petioles and root system in quadrats of 3 x 3 m^2. Shoots and roots will be then oven-dried and weighed. This sampling will be conducted in collaboration with the CIB logging company using excavators in logged areas. The above- and below-ground biomass of adult trees and saplings will be estimated through a non-destructive approach, using allometric equations[40,41].

Mathematical parameters modeling the interactions between plant types will be calibrated with results obtained in WP1 and from previous works. For instance, we will use the results obtained by Brncic[10] on the survival of tree seedlings in presence or absence of giant herbs (Fig. 2) to calibrate the functions $\sigma_h - sa(h)$ and $\sigma_a - sa(a)$ (Fig. 8). A sensitivity analysis on these parameters will be conducted to identify the most important processes involved in the long-term dynamics of Marantaceae forests. **We expect that stability may simply occurs through negative feedback mechanisms against tree regeneration (e.g., competition, allelopathy)**.

1.3.4.3 Testing the effect of fire and logging disturbances on Marantaceae forest dynamics

We will test the effects of disturbance on the conditions of stability of Marantaceae forests through two types of disturbances differing by their intensity and frequency. First, the effect of fires will be modelled as random pulse events, highly destructive for the tree and tree sapling compartments (similar to existing versions of the IFAC model). Fires are known to be stochastic by nature (i.e., non periodic), following climatic anomalies for instance[13], strongly reducing the biomass of trees and being devastating for saplings. The observations that we will make on the effect of the recent large-scale fire events in the IFO forest concession (WP1) will help to formulate relevant model settings and approximate tree biomass loss following a large fire event in the study area. In particular, the probability of fire outbreak will be assessed from the remote sensing diachronic survey. Second, we will model the effect of logging activities as periodic pulse events having a moderate effect on adult trees. In the Congo basin, industrial logging is generally highly selective, with less than two trees extracted per hectare with on average a 30-year rotation period[42]. **We hypothesize that the separate or combined effects of fire and logging disturbances enhance the expansion and stability of Marantaceae forests, bringing important information for management practices**.

1.3.4.4 Spatializing processes

Following the recent work by Yatat et al.[38], we will implement spatially-explicit processes in the model to better understand the spatial dynamics of Marantaceae forests. To this aim, we will use diffusion operators[38] on biomass growth dynamics (γ) to represent seed dispersal or clonal vegetation propagation. We will calibrate and validate these diffusion operators using the results from both the logging effect on giant herbs encroachment (WP1) and the observed contemporary dynamics (WP2). The abilities and rapidity of trees and giant herbs to recolonize bare areas will also be assessed by observing the temporal dynamics of abandoned wood storage areas, where giant herb rhizomes are generally destroyed[9]. **Ultimately, simulations will be run through cellular automata in order to assess whether our model produce realistic long-term spatio-temporal dynamics as observed in WP2**.

1.3.5 Project agenda

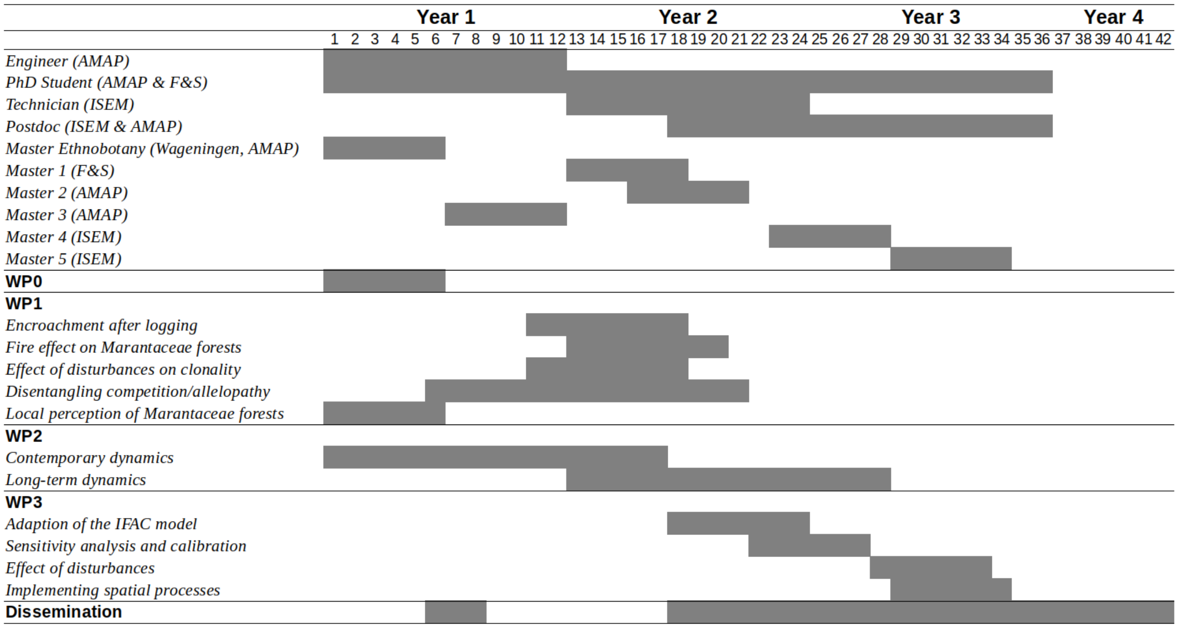


Figure 9: Project shedule planning.

1.3.6 Risks associated with the project

The overall risk associated with the project is low as the proposed work is strongly grounded on previous studies and methodologies developed by our teams and collaborators. The project will benefit from the momentum set by previous (e.g., COFORTIPS) and ongoing (3DForMod, P3FAC and "paysage Nord Congo") projects that have set an efficient collaboration with central African stakeholders and foresters. Thanks to our extensive experience and close collaborations with forest stakeholders in central Africa, and to our active experimental sites, we are very confident that the different experiments of WP1 will be successfully implemented, as illustrated by ongoing experimentations. Remote sensing data for WP2 are readily available and preliminary analyses demonstrated that Marantaceae forests have a clear structural and spectral signal in remote sensing data (Fig. 7). WP3 will benefit from the strong efforts led by AMAP over the last years to develop mathematical models on tree-grass interactions[36–38] and by the theoretical works developed by ISEM[43,44]. Finally, our collaboration with external experts on genetics (A. Ley) and local institutions (CERGEC and University of Marien Ngouabi) will enable us to bring our work further.

2 Organisation and implementation of the project

2.1 Scientific coordinator and its consortium

The leader of the project is Maxime Réjou-Méchain (IRD, AMAP; Google scholar). His research aims at understanding the spatio-temporal organization of the composition and structure of tropical forests and mostly relies on analyses and models combining extensive field and remote sensing data in central Africa, French Guiana and South-Asia. He led the Geomatic laboratory (team of 11 people) of the French Institute of Pondicherry (India) from 2014 to 2016 where he acquired human and project management skills. He then led a WP in the LongTime project (LabEx CEBA) and will be co-leader of one of the research themes in AMAP from 2021. He supervised ten master students, one postdoc and co-supervised three PhD students. In the project, he will participate to fieldwork and data collection, remote sensing analyses, statistical analyses and the implementation of the modelling approach in collaboration with the consortium members. As the project leader, he will coordinate the consortium on a day-to-day basis, and organize every six months a meeting with external experts invited in Montpellier. He will also be in charge of project communication, reporting and financial management. He will coordinate the scientific outcomes of the project through participation to international conferences and writing of publications in high-ranked scientific journals. A data management plan, opening up data, will be produced within the first six months of the project and updated over the course of the project.

The consortium is composed of three highly complementary laboratories based in Montpellier (France), which regularly collaborate with African partners. UMR AMAP has a longstanding interest in (i) monitoring forest dynamics in permanent forest plots in the tropics; (ii) developing methods to characterize forest structure and dynamics using remote sensing data and; (iii) developing theoretical models to study ecosystem stability. UR "Forêts and Sociétés", which has two staff members permanently present in Congo, has a deep expertise on (i) forest management, ecology and conservation in central Africa; (ii) large scale experimental designs with various logging regimes and; (iii) biostatistics. UMR ISEM lab is well-known for (i) their proficiency in historical ecology, including phytolith and charcoal analyses and (ii) for their theoretical background on ecosystems multi-stability.

The present project is part of long-term research efforts conducted on the ecology of central African forests by the consortium. It will notably build on the experience acquired within the completed COFORCHANGE (ERA-NET BioDivERsA; 2009-2012) and COFORTIPS (ERA-NET BioDivERsA2; 2013-2016) projects. Both projects aimed at better understanding the history, dynamics and resilience of central African forests. The present project will also build on the experience and data obtained in the completed FOREST (EU-EIT - Climate KIC; 2014-2016) project, a carbon-focused project aiming at extrapolating field-based carbon estimates through remote sensing data in central Africa. In addition, the ongoing 3DForMod project (ERA-GAS; 2017-2020) aims at developing new approaches to remotely sense the above-ground biomass of tropical forests in the Guiana shield and in central Africa, and will also offer promising synergies with the present project. Finally, we will also strongly benefit from the P3FAC project (FFEM/ATIBT), a sequel to the DynAfFor project, and from the upcoming project "paysage Nord Congo", which both aim to improve our understanding of the effect of industrial logging on the dynamics of central African forests. Thus, our consortium has a great experience in conducting research projects in collaboration with tropical countries, in particular central Africa. We will be able to cover all the aspects of the projects and partners outside our group will be entrusted with specific actions.

Table 2: Implication of the scientific coordinator and partner's scientific leaders in on-going projects.

Name	Person month	Call, funding agency, grant allocated to the lab	Project's title	Scientific coordinator	Start-End
M. Réjou-Méchain	4	ERA-GAS (200 k€)	3DForMod	R. Pélissier (AMAP)	2017-2020
M. Réjou-Méchain	5	European Space Agency (20 k€)	FOS	D. Schepaschenko (IIASA)	2018-2020
S. Gourlet-Fleury	20	FFEM/AFD (823k€)	P3FAC	S. Gourlet-Fleury	2018-2022
L. Bremond	2	CNRS-INSU (28k€)	PaléoMAD	L. Brémond	2020-2023

2.2 Implemented and requested resources to reach the objectives

2.2.1 Staff expenses

Our project involves 14 researchers and 2 research engineers having permanent positions and one postdoctoral researcher hired by IRD in december 2019 for two years (R. Pouteau). It thus represents a total of

105 person.months (Table 1). The project additionally needs the following human resources:

1) **AMAP/F&S**: A PhD student will start working on the WP1 at the beginning of the project for three years. She/he will conduct both field works and advanced statistical analyses. She/he will co-supervise 2 master students (Table 3). The PhD student will be co-supervised by S. Gourlet-Fleury and M. Réjou-Méchain but will interact closely with other researchers involved in WP1 for specific aspects (Table 1). She/he will spend half her/his time in F&S and AMAP so as to ensure a high level of communication and co-ordination among the supervisors and, more generally, among the teams. **100,311 €**.

2) **AMAP**: An engineer will be hired at the beginning of the project for a period of one year to manage and analyse the remote sensing data (WP2). She/he will have a strong background in geomatics and remote sensing analysis. The engineer will build a database of old aerial photographs, which includes time-consuming georeferencing and orthorectification works. She/he will closely interact with R. Pouteau on the detection procedure of Marantaceae forests combining spectral and textural information, in collaboration with G. Viennois, N. Barbier and M. Réjou-Méchain. **41,472 €**.

3) **ISEM/AMAP**: A post-doctoral researcher will be hired for a period of 18 months to work on WP3, two to three years after the beginning of the project. The postdoc will have a strong background in applied mathematics, and in ecology if possible. Based on the development of WP1 and WP2, she/he will develop the mathematical framework described in WP3 and co-supervise one master student (Table 3). She/he will be co-supervised by C. Favier (ISEM) and P. Couteron (AMAP) and will closely interact with I. Maréchaux (AMAP), V. Dakos (ISEM) and S. Kéfi (ISEM). She/he will spend half her/his time in ISEM and AMAP as to ensure a high level of communication and coordination among teams. **78,803 €**.

4) **ISEM**: A technician will be hired for a period of 12 months, one year after the beginning of the project, to prepare and analyse the phytoliths (WP2). She/he will be supervised by L. Bremond (ISEM) and will closely interact with one master student (Table 1). **34,584 €**.

5) Five Master students will be (co-)supervised during the project on five subjects: i) **F&S**: Understanding the fire effects on Marantaceae forests dynamics (WP1; Supervisors: C. Doumenge, E. Forni, V. Rossi & PhD student); ii) **AMAP**: Disentangling competition from allelopathy effects from giant herbs on trees (WP1; Supervisors: C. Fortunel, Z. Mao & PhD student); iii) **AMAP**: Spatiotemporal dynamics of Marantaceae forests from the 1950s to today (WP2; Supervisors: R. Pouteau, G. Viennois & N. Barbier); iv) **ISEM**: Assessing the long term ($>$ 500 yrs) dynamics of Marantaceae forests through phytoliths and carbon dating (WP2; Supervisors: L. Bremond & M. Réjou-Méchain) ; v) **ISEM**: Testing the theoretical effect of disturbances on Marantaceae forest dynamics and integrating spatially-explicit processes in the model (WP3; Supervisors: C. Favier, P. Couteron & postdoc). **17,595 €**.

2.2.2 Total requested resources

The total requested amount to the ANR is of 546 k€. Details are providen in the Table 3.

3 Impact and benefit of the project

3.1 Relevance for sustainable socio-ecosystems

There is currently an important concern that Marantaceae forests are increasing in area throughout the semi-deciduous forests of central Africa. This results in an unprecedented demand from forest managers and conservationists to better understand the dynamics of these forests to adapt forest management practices accordingly. Logging activities have been widespread in central African countries for over five decades, covering today 32% of the *terra firme* forests, i.e., almost twice the forested area under protection[45]. Logging activities often constitutes the largest private employment sector in central African countries and a very large proportion of local population directly or indirectly relies on logging activities.

For instance, according to a survey conducted by the CIB-OLAM company, over the nearly 60,000 people living in their forest concessions (13,000 km^2), half of them financially benefit from logging activities (950 direct employees, 2,500 including laborers and contractors and ca. 30,000 including families and businesses). Apart the potential local economic benefits, forest certified concessions are often committed, or engaged by states or environmental certification, to have educational, cultural and health programs. For instance, the CIB company involved in this project, which holds a Forest Stewardship Council (FSC) certification, manages four hospitals (43,624 consultations and 256 chirurgical surgery in 2019; 250 patients in long-term HIV prophylactic treatment), a local radio for Pygmies populations (Biso na biso), a free and open sport hall with several sports federations and distribute freely drinkable water through public fountains. The company also created a local development fund (receiving 200 Fr CFA per cube meter of marketed wood), managed by local authorities and NGOs, to support local initiatives related to food security (e.g., farmed fishes and animals and agriculture). Thus, non-sustainable forest management practices would constitute both socio-economic and ecological disasters in central Africa.

If central African countries have made strong efforts toward a more sustainable forest harvesting through integrated management plans, more research is needed to fully understand the impact of logging activities and then to minimize it. It is commonly accepted that logging damage is relatively limited in central Africa, affecting 7 to 20% of the areas dedicated to production and consisting in harvesting only a few trees per ha[42]. However, after logging activities, canopy opening is estimated to be of ca. 10% per rotation and thus potentially conducive to the long-term establishment of giant herbs. The long-term effect of multiple rotations and the lack of forest resilience once giant herbs colonize logged areas may thus seriously compromise the sustainability of forest logging in central Africa. **The project thus responds to a strong societal demand and may have a direct impact on management practices**.

3.2 Scientific impact of the project

Devising a dialogue between extensive spatio-temporal observations, local experiments and theoretical models is a major strength in ecology. Such a complementarity in approaches will allow us to provide predictions at different spatial and temporal scales, and thus to improve our ability to manage, protect or restore tropical forests at appropriate operational scales. This is especially important in a context where tropical forests from central Africa will face an increase in annual temperature and rainfall seasonality, with higher frequency in El Niño events[46] and in anthropogenic activities in the future[47].

Focusing on an original but understudied ecological model will bring new insights on the conditions of stability of coexisting forest states, which so far have remained elusive. Other widespread forest types may be similar alternative stable states within a matrix of mixed and closed-canopy forests, such as the liana-infested forests from Amazonia[6], the bamboo-dominated forests both occurring in Amazonia and Asia[48] and the monodominant *Gilbertiodendron dewevrei* patches from central Africa[25]. The general framework that we want to develop here may thus serve as a basis for the study of numerous other tropical forested systems, contributing to a better understanding of the dynamics and history of tropical ecosystems.

Finally, by investigating the long-term effect of anthropogenic activities on the structure and composition of tropical forests, our project will contribute to a better understanding of the long-standing effect of human disturbances in the tropics. Several studies showed that human activities occurred throughout central Africa, as evidenced by charcoal/pottery abundances in most soils[49] but whether these activities have left a signature in the structure and/or composition of contemporary forests is unclear. A recent study suggested that current composition of many central African forest areas may be a legacy of human activities from the 19th century[50]. In this project, we will evaluate if anthropogenic disturbances have a strong impact on forest dynamics and composition over a much longer period, i.e., potentially over millennia.

Table 3: Summary of the resources requested in the project.

Type	Description	Unity cost	AMAP	F&S	ISEM	Total cost
Travel/missions*						
3 weeks in North Congo	Field works WP1-2	3,000 €/trip	8	-	6	42,000 €
2 weeks in North Congo**	Field works WP1	4,000 €/trip	-	7	-	28,000 €
2 days in Montpellier (France)	Monitoring committee meetings (one per year)	700 €/expert	12	-	-	8,400 €
5 days in a foreign country	International conferences	3,000 €/trip	2	2	1	15,000 €
Service delivery						
^{14}C analyses	WP2 Long term dynamics (L. Bremond)	250 €/sample	-	-	50	12,500 €
^{13}C analyses	WP2 Long term dynamics (L. Bremond)	15€/sample	-	-	100	1,500 €
Phytoliths and charcoal analyses	WP2 Long term dynamics (L. Bremond)	10 €/sample	-	-	150	1,500 €
Field campaign tree measurements	5 congolese technicians for 10 months (WP1)	500 €/month	-	42	-	21,000 €
Experimental help	1 congolese technician for 20 months (WP1)	500 €/month	20	-	-	10,000 €
Genetic analyses	Clonality assessment (WP1; A. Ley)	9,000 €	1	-	-	9,000 €
Data storage	Secured data storage for aerial photographs	300 €/year/To	6	-	-	1,800 €
Publication fees	Open access fees of scientific journals	1,500 €	2	2	2	9,000 €
Conference fees	International conferences fees, e.g., ATBC	800 €	2	2	1	4,000 €
Drone acquisition	Drone acquistion over 800 ha (WP1)	15,000 €	1	-	-	15,000 €
Instruments and material						
Fieldwork equipment	Miscellaneous equipment (< 500 €)	-	8000	6000	4500	18,500 €
Informatics	Laptop + Screen and other satellites	1500 €	2	0	1	4,500 €
Aerial photographs	Historical photographs	18 €/image	600	-	-	10,800 €
Satellite images***	Very High Resolution images (e.g., SPOT)	2 €/km2	10000	-	-	20,000 €
Human resources						
PhD student	See description above	2,786.4 €/month	36	-	-	100,311 €
Remote sensing engineer	See description above	3,456 €/month	12	-	-	41,472 €
Technician	See description above	2,882 €/month	-	-	12	34,584 €
Post-doc	See description above	4,378 €/month	-	-	18	78,803 €
Masters	See description above	577.5 €/month	12	6	-	10,395 €
Masters	See description above	600 €/month	-	-	12	7,200 €
Management fees (8%)						40,421 €
Total Requested to ANR			290,858	74,590	180,238	**545,686€**
Consortium contribution	Salary		554,823	143,526	112,216	810,565 €
TOTAL AMOUNT			**845,681**	**218,116**	**292,454**	**1,356,251 €**

*Additional missions will be undertaken by the three labs;
**Include expatriate costs;
***Additional images will be bought on other projects by AMAP.

3.3 Dissemination strategy

The project will have three main components in its communication strategy:

1) *Communication to scientists*: Our findings will be published in international peer-reviewed journals and presented at international conferences. Specialized journals in the fields of environmental monitoring and ecology will be targeted for intermediate results. A first review paper on Marantaceae forests, invited by *American Journal of Botany*, is already under preparation (WP0), which will raise the visibility of the project from its beginning. A wide-audience journal will be targeted at the end of the project to publish a synthesis combining the results obtained from the three main WP. We will target open access options in order to make papers reachable to a wide community, including African researchers and students who usually have a limited access to the scientific literature. Active collaborations and/or communication with research institutes from Congo, such as the CERGEC, the Marien Ngouabi University and the National Forest Research Institute (IRF, Brazzaville) will be conducted throughout the project.

2) *Communication to forest stakeholders and policy makers*: Because our results will have strong implications in terms of forest management, we will continuously interact with forest stakeholders, notably because we will jointly monitor their logging impacts on the forest, and thus update them on our progresses. As already done for each of our missions in the CIB company, we will give public talks to present our preliminary results and to get feedbacks. For other stakeholders and policy makers, we will broadcast at the end of the project a booklet providing the key results of the project and the main recommendations for forest management. For this, we will strongly rely on the P3FAC project, whose aim is to mobilize public and private actors in the sector around scientific results in favour of more sustainable forest policies.

3) *Communication to the general public*: A website will be set up from the beginning of the project, with a synthesis of our knowledge on Marantaceae forests as a first content. Then, the first series of vegetation maps generated in WP2 and some photographs from the field and from our experimental design will be published online and commented. Project news will be communicated through Twitter messages. The final results will be communicated on the website and the abovementioned booklet will be free for download. We will also create Wikipedia pages in French and English on the Marantaceae forests at the beginning of the project and prepare press releases as much as possible to communicate our progress to the general public. Lastly, communications through the local Biso na biso radio will be made as much as possible during our field missions.

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