Impact of forest Management and Climate Change on understory Microclimate (MaCCMic)

Summary table of persons involved in the project

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's total duration
Partner 1 ISPA	OGEE	Jérôme	DR INRAE	Project coordinator and partner's PI; co-responsible for WP0 (with LENOIR and FERRIO) and WP1 (with DURRIEU); physics-based microclimate modelling; supervision of PhD1 involved in WP1-3; microclimate data and analysis; project results dissemination	16 (33%)
	DUPONT	Sylvain	DR INRAE	Physics-based microclimate modelling in complex settings (MuSICA-ARPS); will supervise PhD2 involved in WP2; project results dissemination	10 (21%)
	BIDOT	Caroline	IE INRAE	Physics-based microclimate modelling in complex settings (MuSICA-ARPS)	6 (13%)
	BRUNET	Yves	DR INRAE	Physics-based microclimate modelling (MuSICA); microclimate data and analysis; project results dissemination	5 (10%)
	CHARRU	Marie	MC BSA	Forest management scenarios; microclimate data and analysis; project results dissemination	5 (10%)
	DOMEC	Jean-Christophe	PR BSA	Forest management scenarios; microclimate data and analysis; project results dissemination	5 (10%)
	FANIN	Nicolas	CR INRAE	Microclimate data and analysis (Landes); project results dissemination	5 (10%)
	DEVERT	Nicolas	AI INRAE	Microclimate data and analysis (Landes, urban)	5 (10%)
	KRUSZEWSKI	Alain	TR INRAE	Microclimate data and analysis (Landes, urban)	5 (10%)
	RABEMANANTSOA	Tovo	AI INRAE	Project database management	4.5 (9%)
	ALUOME	Christelle	IE INRAE	Project database management	4.5 (9%)
	LAFONT	Sébastien	IR INRAE	Microclimate data and analysis (Landes, Fluxnet/ICOS); project results dissemination	4.5 (9%)
	WINGATE	Lisa	DR INRAE	Microclimate data and analysis (Landes, urban); project results dissemination	4 (8%)
	WIGNERON	Jean-Pierre	DR INRAE	Satellite-derived forest above ground biomass and fragmentation; project results dissemination	4 (8%)
	FRAPPART	Frédéric	CR CNRS	Satellite-derived above ground biomass and fragmentation; project results dissemination	4 (8%)
	PhD1		PhD UB	Physics-based microclimate modelling (MuSICA, CLM-ml, microclima, NicheMapR); microclimate data and analysis; project results dissemination	36 (75%)
	PhD2		PhD ANR-INRAE	Physics-based microclimate modelling in complex settings (MuSICA-ARPS); project results dissemination	36 (75%)
Partner 2 EDB	CHAVE	Jérôme	DR CNRS	Partner's PI; co-responsible for WP3 (with FISHER); microclimate data and analysis and physics-based modelling (French Guyana sites); project results dissemination	6 (13%)
	FISHER	Rosie	NCAR scientist (visiting)	Co-responsible for WP3 (with CHAVE); physics-based microclimate modelling (CLM-FATES, CLM-ml); supervision of Postdoc1 involved in WP1 and WP3; project results dissemination	12 (25%)
	LABRIERE	Nicolas	Postdoc CNRS	Satellite-derived above ground biomass and fragmentation; project results dissemination	2 (4%)
	Postdoc1		Postdoc ANR	Physics-based microclimate modelling (CLM-FATES, CLM-ml); project results dissemination	24 (50%)
Partner 3 EDYSAN	LENOIR	Jonathan	CR CNRS	Partner's PI; co-responsible for WP0 (with OGEE and FERRIO) and WP2 (with REVERS); microclimate and biodiversity data and analysis (ONF sites); supervision of one PhD (Eva Gril) and Postdoc2 involved in WP2; project results dissemination	12 (25%)
	GALLET-MORON	Emilie	IE UPJV	GIS and LiDAR data analysis (ONF sites)	9.6 (20%)
	LASLIER	Marianne	MC UPJV	Remote sensing and LiDAR data analysis (ONF sites); project results and dissemination	7.2 (15%)
	BRASSEUR	Boris	MC UPJV	Soil microclimate and biodiversity data and analysis (ONF sites); project results and dissemination	4.8 (10%)
	GRIL	Eva	PhD CNRS	Microclimate and biodiversity data and analysis (ONF sites); niche modelling; project results and dissemination	4.8 (10%)
	MARREC	Ronan	MC UPJV	Landscape ecology (ONF sites)	2.4 (5%)
	LEROUX	Vincent	MC UPJV	Biodiversity data and analysis (ONF sites)	2.4 (5%)
	DECOCQ	Guillaume	PR UPJV	Biodiversity data and analysis (ONF sites)	2.4 (5%)
	Postdoc2		Postdoc ANR	Landscape-scale microclimate modelling and data analysis; project results dissemination	24 (50%)
Partner 4 BIOGECO	REVERS	Frédéric	CR INRAE	Partner's PI; co-responsible for WP2 (with LENOIR); supervision of one PhD (Amandine Aclocque) involved in WP2; microclimate and biodiversity data and analysis (Ciron valley); project results dissemination	8 (17%)
	HAMPE	Arndt	DR INRAE	Microclimate and biodiversity data and analysis (Ciron valley and ORPHEE); project results dissemination	2 (4%)

Partner	**Name**	**First name**	**Current position**	**Role & responsibilities in the project (4 lines max)**	**Involvement (person.month) throughout the project's total duration**
	JACTEL	*Hervé*	*DR INRAE*	*Microclimate and biodiversity data and analysis (ORPHEE and Landes sites); project results dissemination*	*2 (4%)*
	CORCKET	*Emmanuel*	*MC UB*	*Microclimate and biodiversity data and analysis (Ciron valley and ORPHEE); project results dissemination*	*4 (8%)*
	MELLERIN	*Yannick*	*TR INRAE*	*Microclimate data (Ciron valley)*	*4 (8%)*
	DUDIT	*Jennifer*	*AI UB*	*Microclimate data (Ciron valley)*	*4 (8%)*
	BODENES	*Catherine*	*IE INRAE*	*Microclimate database (Ciron valley)*	*4 (8%)*
	SEGURA	*Raphael*	*AI INRAE*	*Weather station data (Ciron valley; urban forest)*	*2 (4%)*
	ACLOQUE	*Amandine*	*PhD UB*	*Microclimate and biodiversity data and analysis (Ciron valley); project results and dissemination*	*8 (17%)*
	DELZON	*Sylvain*	*DR INRAE*	*Microclimate and biodiversity data and analysis (urban forest); project results and dissemination*	*2 (4%)*
	PORTE	*Annabel*	*DR INRAE*	*Microclimate and biodiversity data and analysis (urban forest); project results and dissemination*	*2 (4%)*
Partner 5 TETIS	*DURRIEU*	*Sylvie*	*DR INRAE*	*Partner's PI; co-responsible for WP1 (with OGEE); LiDAR data and analysis (ONF sites, Ciron valley and urban forest); project results and dissemination*	*7.2 (15%)*
	ALLEAUME	*Samuel*	*IR INRAE*	*LiDAR data and analysis (ONF sites, Ciron valley and urban forest); project results and dissemination*	*6 (13%)*
	FERET	*Jean-Baptiste*	*CR INRAE*	*Sentinel2 data and analysis in conjunction with LiDAR and microclimate data; co-supervision of PhD3; project results and dissemination*	*7.2 (15%)*
	PhD3		*PhD ANR-INRAE*	*LiDAR- and Sentinel2-derived leaf area profile and functional diversity indices across seasons and landscapes; project results dissemination*	*36 (75%)*
Partner 6 CITA	*FERRIO DÍAZ*	*Juan Pedro*	*ARAID researcher*	*Partner's PI; co-responsible for WP0 (with OGEE and LENOIR); LiDAR and microclimate data and analysis (Moncayo sites)*	*2.4 (5%)*
	SANCHO KNAPIK	*Domingo*	*ARAID researcher*	*LiDAR and microclimate data and analysis (Moncayo sites)*	*2 (4%)*
	GIL PELEGRÍN	*Eustaquio*	*ARAID researcher*	*LiDAR and microclimate data and analysis (Moncayo sites)*	*1 (2%)*
	PEGUERO PINA	*José Javier*	*ARAID researcher*	*LiDAR and microclimate data and analysis (Moncayo sites)*	*1 (2%)*

Changes that have been made in the full proposal compared to the pre-proposal

In response to the panel's assessment of the pre-proposal, we have now put more emphasis on the biotic factors (species composition and diversity) that could influence understory microclimate. This translated into the addition of a PhD project focusing on how canopy functional diversity can be sensed from space using multi-spectral images at high spatial resolution (i.e. Sentinel2). This PhD project will be carried out at partner 5 (TETIS) with Dr. Jean-Baptiste Féret as the main supervisor, who joined the consortium for this reason. This change has no consequence on the overall budget because the requested funding for PhD1 that will be held at ISPA has now been secured independently.

In addition, the project now puts more emphasis on the strong interactions between the projected changes in understory microclimate (in temperature and moisture, but also CO_2 and light) and in the growth dynamics of the understory plant community, potentially leading to major conceptual advances on our understanding of forest resilience in the fate of climate change.

Compared to the pre-proposal, the budget has increased by 15%, mostly (+11%) because of the change of the overhead of INRAE partners (12% instead of 8% in previous years) and the difference of salary grids at CNRS for non-permanent researchers (+30% compared to INRAE or University grids).

I. Proposal's context, positioning and objective(s)[1]

a. Objectives and research hypothesis

Project's objectives

The microclimate in the understory is an essential component of many services provided by forests. This is because forest canopies are able to buffer climate extremes; in particular, the understory microclimate temperature is usually cooler than the macroclimate temperature[2] during the day and in summer, and warmer at night and in winter (De Frenne *et al.*, 2019; Zellweger *et al.*, 2019a). Several recent studies show that this buffering capacity is essential for understanding forest biodiversity dynamics because understory communities (plants, insects, fungi, etc.) respond to microclimate more than macroclimate change (De Frenne *et al.*, 2013; Zellweger *et al.*, 2020; Williamson *et al.*, 2020). This capacity of forest canopies to buffer climate extremes is equally important for explaining the dynamics of forest regeneration and thus their resilience to climate change. It is also important for recreational activities, especially during heat waves in urban areas.

Forest management practices impact these different services, for better or worse, by modifying forest structure and composition and thus important factors governing understory microclimate. Today, however, forest managers have a limited toolkit to quantify the impact of their practices on understory microclimate. Recommendations to fight against biodiversity loss (leave stumps and residues in place, create islands of deciduous trees, maintain tree species diversity, etc.) remain rather qualitative. These recommendations are not necessarily well followed because they seem to work against other management objectives such as wood production or fire prevention. To provide better guidance to forest managers, we need tools that can quantify the impact of management on understory microclimate now and in a future climate.

The **objective of this project** is to develop observation-based tools to **identify the main factors influencing forest understory microclimate**, and biophysical and ecological models to **anticipate the impact of forest management** (density, fragmentation, thinning, choice of species, understory removal, etc.) **on forest microclimate and understory vegetation, notably in terms of climate extremes** (drought, heat wave, late frost, flooding, etc.) **under future climate change scenarios**. These tools and models will be key to help forest managers increase the resilience of forests and foster their ecological, recreational and climate services in a warming world.

Research hypotheses

There is currently no consensus on the factors that influence the buffering of forest microclimate and its possible decoupling from macroclimate warming. A recent study indicates a stronger buffering in warmer biomes, with maximum and mean temperatures consistently cooler, and minimum temperatures consistently warmer, compared to macroclimate temperatures (De Frenne *et al.*, 2019). These observed patterns could not be explained by factors such as topography, distance to the coast, forest height or even differences in leaf phenology of the dominant tree species (evergreen, deciduous or mixed) (De Frenne *et al.*, 2019). **Canopy closure and leaf area**, both of which are strongly influenced by forest management, are often considered as key factors influencing the buffering of macroclimate and microclimate in forest understories (Lenoir *et al.*, 2017; Zellweger *et al.*, 2019a). This is because a higher leaf area not only reduces solar energy near the ground during the day, it also reduces radiative losses at night. The effect of canopy closure (or other local stand characteristics) could not be tested by De Frenne et al. (*op. cit.*) but may have explained part of the reported patterns in forest microclimate buffering across biomes.

Another factor that deserves attention is **canopy structure**, and notably leaf area distribution. Indeed, air temperature profiles inside and below vegetation canopies not only depend on total leaf area, they also reflect how this leaf area is distributed, at least vertically. Canopy layers with the highest leaf area will absorb most of the incoming radiation and also release more heat, and because of the high coherence of turbulent eddies inside the canopy (Brunet, 2020), this will translate into hotter air in these layers compared to other layers. Only a handful of biophysical vegetation models

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[1] References in green were produced by scientists from our consortium.

[2] Macroclimate temperature is defined here (and in the cited literature) as the air temperature provided by a nearby (<1-2km) weather station. Following the definition of the world meteorological organisation, this is the air temperature at 1.5m above ground in the centre of a clearing of several tens of metres on each side, with a minimum of slope and covered with low grassy vegetation.

can reproduce these complex air temperature profiles within vegetation canopies (Baldocchi *et al.*, 2002; Ogee *et al.*, 2003) (Fig. 1).

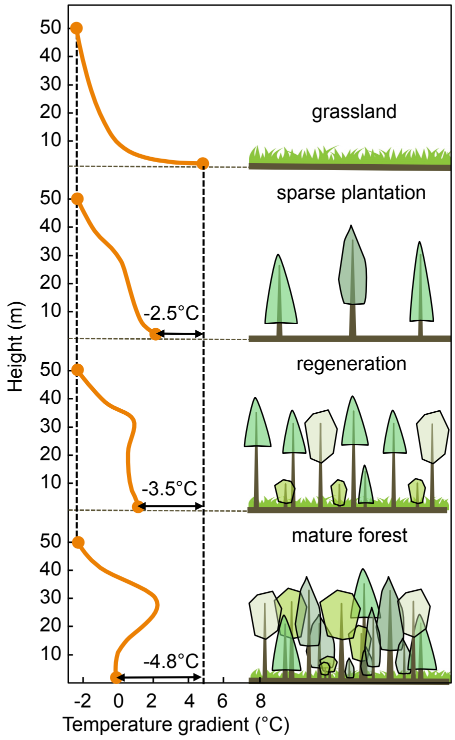

Figure 1 | Vertical profiles of midday air temperature typically observed during a hot summer day in different ecosystems or, here, simulated with the ecosystem model MuSICA (Ogée et al., 2003). The temperature at 1.5m above the grassland is what is defined here (and in the cited literature) as macroclimate temperature.

Besides leaf area and its vertical distribution, **plant functional traits** (maximum stomatal conductance, hydraulic conductivity and rooting depth, leaf size, albedo and phenology, etc.) also influence the biophysical properties of a forest (albedo, coupling with the atmosphere, Bowen ratio) and therefore its microclimate. It is well known that deciduous canopies, because of their lower albedo and higher transpiration rates in summer, are much cooler than coniferous forests (e.g. Anderson *et al.*, 2011). Forest management practices that favour certain tree species or densities can induce an increase in canopy temperature of the same order as that induced by a more radical change in land use (i.e. deforestation) (Luyssaert *et al.*, 2014). The impact of tree species' choice on microclimate is probably more pronounced during summer droughts, as some plants regulate their water use better than others. During a short drought, isohydric species conserve water and thus reduce transpiration, which warms the air more than less conservative (anisohydric) species; but during longer droughts, the effect should be gradually reversed because isohydric species would keep transpiring, albeit at a slow rate. Transferred to a landscape or continental scale, these two extreme hydraulic strategies can even influence the macroclimate, and strongly amplify heatwaves or droughts (e.g., Teuling *et al.*, 2010).

In MaCCMic, we propose to test the **hypothesis (H1) that both canopy structure and plant functional diversity are important factors that influence the buffering capacity of forest understory microclimate and its decoupling from regional macroclimate, and that their relative importance increases with drought severity and duration.**

At the landscape scale, **topographic factors** such as elevation, slope, aspect or topographic convergence have all been recognised as strong drivers of microclimate (Dobrowski, 2011; Maclean *et al.*, 2018). Accounting for these factors is relatively straightforward and likely to be important only in mountain regions. In low land forests, other landscape features are also important. For example, the **distance to water bodies** (lakes, rivers…) has been identified as a key factor influencing microclimate and species distribution in drought-prone regions (Mclaughlin *et al.*, 2017). Other factors such as **patch size** and **forest fragmentation** can also have a strong influence on the understory microclimate: it is well known that the microclimate in the understory varies greatly from the forest edge to the interior (Chen *et al.*, 1993; Davies-Colley *et al.*, 2000), and this led to recommendations to foresters to minimise late frost risk at the regeneration stage (Groot & Carlson, 1996; Aussenac, 2000). Also, because of differences in their biophysical properties (albedo, coupling with the atmosphere…), a forest, a crop or a grassland will have canopy temperature differences of up to 5°C in summer (e.g., Luyssaert *et al.*, 2014; Zhang *et al.*, 2020), therefore modifying the macroclimate of the surroundings (Alkama & Cescatti, 2016; Zhang *et al.*, 2020), and thus the understory microclimate. In summary, besides local canopy structure, the configuration of the land surface at larger scales can also influence understory conditions via mesoscale interactions.

In MaCCMic, we will test a second **hypothesis (H2) that the microclimate in forest understory depends on landscape features such as the amount of forested area of the surroundings and its degree of fragmentation (i.e. woodland fraction within a given radius, average patch size, etc.).** Testing this hypothesis is becoming crucial, given the on-going intensification of forest harvest and fragmentation worldwide (Brinck *et al.*, 2017; Ceccherini *et al.*, 2020; Senf & Seidl, 2021), and the increasing recognition that smaller but numerous forest patches could be beneficial for forest biodiversity conservation programmes (Arroyo Rodríguez *et al.*, 2020) or for enhancing ecosystem services in agricultural landscapes (Valdés *et al.*, 2020).

With climate change, and notably **increasing CO_2 concentrations**, the buffering of understory microclimate and its decoupling with macroclimate conditions are anticipated to evolve, but the direction of this evolution is currently highly uncertain because of several competing effects. First, elevated CO_2 (eCO_2) concentrations generally stimulate an increase in leaf area (Ainsworth & Long, 2005), unless nutrients are limiting (e.g. McCarthy *et al.*, 2007; Norby *et al.*, 2009; Duursma *et al.*, 2016), and this has been proposed as the main explanation for the recent greening of the land surface over the past decades (Zhu *et al.*, 2016). For the reasons evoked above, an increase of canopy closure should reinforce the buffering of understory microclimate. However, long-term eCO_2 treatments tend also to reduce stomatal conductance, especially in young, deciduous trees, and water- or nutrient-limited conditions (Medlyn *et al.*, 2001; Ainsworth & Long, 2005). If this eCO_2-induced reduction in stomatal conductance compensates for the increase in leaf area, we should expect only marginal changes on ecosystem-scale evapotranspiration (e.g. Körner *et al.*, 2007), and therefore on canopy temperature. Although such compensatory effects have been observed in long-term eCO_2 experiments (Tor-ngern *et al.*, 2015), a recent satellite-based study seems to indicate that evapotranspiration has been increasing recently with land surface greening, especially in water-limited regions (Forzieri *et al.*, 2020). If both leaf area (forest shading) and evapotranspiration (forest cooling) are increasing globally, this should enhance the buffering of understory microclimate and potentially its decoupling from macroclimate conditions.

Besides changes in canopy cover and physiology, the rapid rise of atmospheric CO_2 levels should also lead to modifications in understory dynamics and composition (e.g., Kerstiens, 1998; Hättenschwiler & Körner, 2000; Lloyd & Farquhar, 2008; Chave *et al.*, 2008), with potentially strong impacts on understory microclimate and forest regeneration. Several studies on tree seedlings in eCO_2 understory environments (e.g., Kerstiens, 1998; Hättenschwiler & Körner, 2000; Mohan *et al.*, 2007) reported that slow-growing, late-successional, shade-tolerant species usually exhibit larger CO_2-induced growth rate enhancements than fast-growing, early-successional, shade-intolerant species. Theoretically, it can be shown (Lloyd & Farquhar, 1996) that plants with high respiratory costs and/or low-nutrient availability (i.e. slow-growing species) will respond *proportionally* more to an increase in CO_2 than fast-growing species. This stimulation of deep shade plants with increasing CO_2 levels is therefore coherent with theory, and has been proposed (Granados & Körner, 2002; Körner *et al.*, 2007) as an explanation for the accelerating growth of lianas in the neotropics (Phillips *et al.*, 2002). This difference in eCO_2-induced growth rate enhancements between early- and late- successional tree seedlings is also predicted by the latest generation of process-based vegetation demography models in US temperate forests (Miller *et al.*, 2016), in good agreement with observations (Mohan *et al.*, 2007), and suggests an acceleration of secondary forests' regeneration in the future. Canopy closure enhances the build-up of CO_2 concentrations in the understory (+15-20% those outside the forest in tropical forests, even during daytime, Lloyd *et al.*, 1996), reinforcing the eCO_2-induced stimulation of understory growth. As CO_2 levels continue to rise, we should therefore expect a progressive increase in understory vegetation growth rates, which should stimulate transpiration and evaporative cooling in the understory, and further enhance the buffering of understory microclimate from macroclimate warming. Following this set of arguments, we propose to test in MaCCMic the **hypothesis (H3) that on-going climate change, and especially the rapid rise in atmospheric CO_2 levels, favours understory species and enhances the buffering of the understory microclimate from the regional macroclimate**.

Scientific and technical barriers to be lifted

To test the above hypotheses is a real challenge both experimentally and theoretically. For example, testing H1 and H2 will require detailed observations not only of understory microclimate, but also of canopy structure, plant functional diversity and landscape features. These observations are not extremely challenging technically, albeit very demanding in terms of manpower and computation time. **What is truly challenging is to deal with the fact that the different factors, unless specifically tested with expensive and time-consuming experiments, will co-vary with one another**. For example, in a recent study on understory microclimate variations along a riparian forest corridor (Ciron river in the Southwest of France), we found that canopy deciduousness (which we quantified as the canopy gap fraction difference between summer and winter, and took as a functional index of the canopy) is strongly correlated with summertime canopy gap fraction, because deciduous canopies are in dense riparian woodlands in the river gorges, while evergreen canopies are in pine plantations on the plateau. Similarly, the fraction of woodland area of the surroundings is anti-correlated with the distance to the river, because more open lands (crops, clear cuts) are present on the plateau. Testing H3 is also extremely challenging as it requires gathering datasets from long-term experiments, covering at least the last 2 or 3 decades.

Keeping in mind that our main objective is to provide guidance to forest managers, we will try to tease apart the impact of these potentially confounding factors in the context of management practices currently established (understory removal, thinning, coppicing, clear cutting) or being tested (species mixtures, natural regeneration). This will be done by **designing specific experiments where only one factor is tested at a time**.

We will also gather several campaigns of airborne and drone-based LiDAR measurements to characterize precisely canopy structure and how it varies in the landscape (Soma *et al.*, 2018) as well as remote-sensing, multi-spectral data from Sentinel2 to characterize not only land cover at high resolution (https://labo.obs-mip.fr/multitemp/la-vectorisation-du-produit-oso-comment-ca-marche/) but also its functional diversity (Feret & Boissieu, 2019). This will allow us to **explore a more diverse range of situations, even in locations where ground-based observations of canopy closure or plant diversity are not available, and identify new locations where to install microclimate sensors to best tease apart the impact of the different factors we want to test**.

The use of **process-based (biophysical) microclimate models will also be of great help to tease apart confounding factors**. Compared to statistical (empirically-trained) models, process-based microclimate models predict all microclimate variables comprehensively, even those that have not been measured, and they allow to change one confounding factor at a time and perform sensitivity analyses on each of these microclimate variables. For example, using the ecosystem model MuSICA, we recently tested the effect of understory removal on air and soil temperature in the understory of a mature pine plantation during the 2003 heatwave. At midday (solar radiation > 350 W m^{-2}), the understory removal created an average soil surface temperature increase of +2.8°C during the first heatwave in June 2003, that rose to +6.3°C during the second heatwave in August 2003 because the soil surface had dried out (Ogée, unpublished results). Validating such results on specific test cases and experiments will allow us to estimate confidence intervals in the model predictions, and explore rapidly the impact of multiple climate change and management scenarios.

Another big challenge will be to synthetize and translate the various results into clear recommendations and easy-to-use tools for forest managers. This will be addressed by implementing a range of actions, from regular meetings with forest owners and managers of the experimental sites to disseminate our results, to continuing education courses at forest engineer schools, to web applications based on near-real-time microclimate datasets or model simulations. All these actions are detailed below (notably in §III. Impact and benefits of the project).

b. Position of the project as it relates to the state of the art

Currently, to predict how forest management impacts understory microclimate, we mostly rely on statistical (correlative) models trained on microclimate measurements, often of short duration, using landscape and (sometimes) canopy features as explanatory variables (e.g. Zellweger *et al.*, 2019a, 2020). These models are instructive and will be very useful in MaCCMic to identify the local and landscape factors most influencing microclimate variables in a given context. However, the reliability of these statistical models for making predictions outside their calibration conditions is questionable, as is their ability to distinguish between the functional impacts of different hydraulic strategies, which is a problem for studying the effect of global warming or innovative management.

Physics-based (biophysical) microclimate models also exist (Baldocchi *et al.*, 2002; Ogee *et al.*, 2003; Kearney & Porter, 2017; Maclean *et al.*, 2018; Kearney *et al.*, 2019) and have the advantage of simulating coherently all the components of the microclimate: temperature, humidity, radiation, wind, etc. The problem is that most of these models are only suitable to open landscapes (deserts, grasslands), thus not applicable to the forest environment because they do not account for the specificity of turbulent flows within vegetation canopies, nor for differences in plant traits between understory and overstory species. Only a small handful of biophysical models can simulate turbulence and energy transfers within structurally complex, mixed vegetation canopies (e.g., Ogee *et al.*, 2003). These models rely on *a priori* knowledge of structural parameters to describe canopy architecture (leaf area density, species height, etc.). Today, with the emergence of LiDAR data, refined information on canopy architecture over large areas is becoming readily available (e.g., Soma *et al.*, 2018), bringing our ability to predict variations of forest microclimate to a new level (Lenoir *et al.*, 2017; Tymen *et al.*, 2017; Zellweger *et al.*, 2019b). In MaCCMic we will combine this LiDAR-derived information on canopy architecture across the landscape with in-house biophysical models of microclimate inside complex, mixed vegetation canopies (Ogee *et al.*, 2003; Dupont *et al.*, 2011) to test our two hypotheses H1 and H2.

Unlike for statistical models, microclimate datasets are not needed to develop biophysical models; such datasets are however required to evaluate the ability of biophysical models at simulating the influence of different canopy and landscape features on understory microclimate. Also, to test our hypothesis H3, long-term records of microclimate measurements in forest interiors are required. Such long-term microclimate measurements exist in forests, notably as part of the observation network Fluxnet (Baldocchi *et al.*, 2001; Friend *et al.*, 2007), which the lead PI has been involved in since its beginning almost 30 years ago, and continues to participate in through his involvement in the ICOS research infrastructure. Because Fluxnet was primarily designed to focus on measurements of carbon, water and energy fluxes, microclimate data – of air or soil temperature and humidity at different heights or depths in the soil – are still poorly catalogued and undervalued. In preparation of this proposal we have already gathered long-term microclimate records from 13 Fluxnet forest sites in Europe, North America, Australia and the Amazon (mostly around *ca.* 20yr-long but sometimes up to nearly 30-yr long, see Fig. 2). These long-term records will allow us to test the effects of the "natural" increases in CO_2 concentration and temperature on forest understory microclimate. With on-going international efforts such as ICOS, more of these datasets should become increasingly available: monthly updates of microclimate data are already available from 6 sites in Finland and Sweden on the ICOS database.

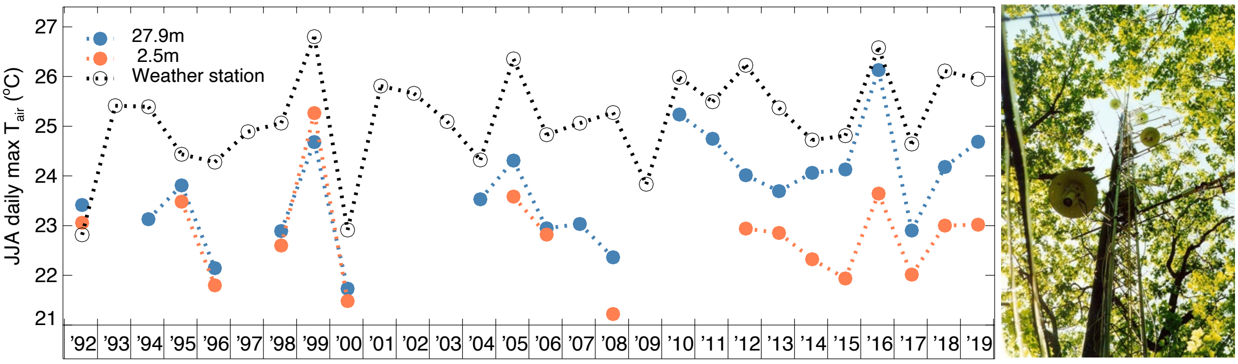

Figure 2 | The Harvard forest environmental measurements tower, maintained since 1990 provides the world's longest continuous measurement of mass and energy exchange between a forest and the atmosphere. Here the summertime (JJA) maximum air temperature at 27.9m and 2.5m above the forest floor, and at a weather station nearby (<1km) from 1992 to 2019. Canopy height is about 25-26m.

Beyond Fluxnet and ICOS, and with the emergence of big data science, other international ambitious database initiatives are also emerging to compile soil and near-surface temperature datasets from all over the world into a global geospatial database (De Frenne *et al.*, 2019; Zellweger *et al.*, 2019a; Lembrechts *et al.*, 2020). For example SoilTemp (Lembrechts *et al.*, 2020) brings together over 15000 years of understory temperature data at a sub-hourly time step, with some records up to 40-yr long. Our consortium is strongly involved in these initiatives. The work proposed in MaCCMic will not only help to continue contributing data to these international efforts, it will also benefit from these large databases to test our hypotheses and evaluate our models.

To test hypothesis H3, we would need also to represent how forest dynamics is likely to evolve under climate change. The newest generation of vegetation demography models (VDMs) now resolve in great detail the dynamics of forest regeneration that shape canopy and understory structure and composition (Fisher *et al.*, 2018; Fisher & Koven, 2020). As already stated, these VDMs also predict, at least qualitatively, the eCO_2-induced acceleration of forest regeneration observed in eCO_2 experiments (Miller *et al.*, 2016), and are now being coupled to land surface schemes that describe the biophysical processes that shape water and energy transfers at the surface in climate models (Fisher *et al.*, 2015; Koven *et al.*, 2020). Developments have also started to integrate in these land surface schemes a multilayer description of the turbulent transfer of heat and moisture to simulate vertical gradients of microclimate between understory and canopy (Chen *et al.*, 2016; Bonan *et al.*, 2018). All these developments are opening avenues to simulate forest microclimate at continental and global scales, and to study potential feedback on forest regeneration and the climate system. To do so, however, a step is still missing: the integration of these in-canopy turbulent transfer descriptions into the VDMs. In MaCCMic, we will do this next step, and will also include in-canopy turbulent transfer of CO_2 in the vegetation canopy (Baldocchi *et al.*, 2002; Ogee *et al.*, 2003). This will allow us to study *in silico* how a climatically-buffered, CO_2-rich understory environment impacts plant growth and phenological stages, with the expectation that this will improve our predictions of forest regeneration and resilience in a changing climate.

c. Methodology and risk management

Methodology and its relevance to reach the objectives

The project will integrate **existing and comprehensive datasets of forest microclimate from several other on-going projects (Table 1)**. While spatially comprehensive datasets will be instrumental to identify local and landscape factors influencing forest understory microclimate and test our hypotheses H1 and H2, long-term datasets will be needed to evaluate the ability of biophysical models at simulating the combined influence of these factors and of climate change, and test our hypothesis H3.

Site or network name	Period with microclimate data	Type of microclimate data	Ancillary data	Designed to study local effects of management on microclimate
Fluxnet/ICOS (range of forest stands and biomes)	Since the mid 90's for most sites	Vertical profiles of air temperature, humidity, CO_2 and windspeed (inside and above canopy) and of soil temperature and moisture (down to 1m)	Ecosystem-scale water, CO_2 and energy fluxes; wood production; leaf area index; soil texture; leaf gas exchange; management dates; forest disturbance history	Only over time (e.g. after thinning or understory removal)
Ciron (riparian mixed forest and maritime pine plantations)	Since December 2016 (some since 2013)	1.5m air temperature and humidity	Gap fraction (winter and summer 2017); LiDAR data (2019); woodland fraction of surroundings (2017); regeneration (beech saplings); biodiversity (vascular plants and lichens, ground beetles, wild bees…)	Mostly in terms of forest type (e.g. riparian mixed deciduous vs. pine plantation)
Moncayo (restored Med. oak coppices)	Since April 2020	Below-canopy air temperature and humidity, sunlight and windspeed, soil temperature and water potential	Gap fraction; wood production; biodiversity (fungi, soil microbes); LiDAR data (2021)	Yes (i.e. 8 co-located plots with a range of management practices)
ORPHEE (mixed stands of maritime pine, poplars and oaks)	Since June 2020	Below-canopy sunlight and soil temperature and humidity	Gap fraction; wood production; biodiversity (vascular plants, soil microbes)	Yes (species mixture), but only on soil microclimate (plot size too small otherwise)
Mormal, Blois, Aigoual (mixed beech and oak forests)	Since July 2020	1m air temperature and soil surface temperature	Gap fraction (2020); LiDAR data (2021); wood production; woodland fraction of surroundings (2021); biodiversity (vascular plants, arthropods) (2021-2022)	Mostly in terms of tree density, stand age and size (i.e. coppice with standards vs. high stand only in Aigoual)
Nouragues (seasonally-dry tropical forest)	Dec 2013-June 2015	Below-canopy sunlight and air temperature and humidity	LiDAR data (2016); biodiversity (flora and micro-fauna)	Mostly in terms of forest fragmentation
Landes (maritime pine stands) (*)	Since 2021 (at 2 sites)	Below-canopy sunlight, windspeed and soil and air surface temperature and humidity	Gap fraction; wood production; soil texture; biodiversity (vascular plants, soil microbiota)	Yes (co-located plots with different management practices)
Urban forest (Floirac, Bordeaux) (**)	Not yet	Below-canopy sunlight and soil and air surface temperature and humidity	Gap fraction; wood production; soil texture; LiDAR data (not yet)	Mostly in terms of forest type (collocated coppices and irregular high forests with different understories)

Table 1 | General overview of the different microclimate and ancillary datasets that will be available and used for MaCCMic, and their relevance to explore specifically the impact of forest management.
(*) For the Landes sites, only 2 sites are equipped at the moment, spread over a soil fertility gradient (2 treatments per site, with and without understory vegetation). Within MaCCMic, we propose to equip 6 other new sites, 4 sites along a chrono-sequence of pine plantations, and 2 sites currently experiencing natural regeneration.
(**) The urban forest sites will be equipped with microclimate sensors and characterised by LiDAR as part of MaCCMic.

Long-term microclimate datasets will be gathered from the international Fluxnet/ICOS network where rich, although undervalued, records of vertical profiles of temperature and humidity in the soil and the air below and above the forest canopy are being collected, often covering several decades (Fig. 2). Temperature and (sometimes) air humidity at 1-1.5m, and their variations with vegetation cover and topographic properties, are also monitored in the Ciron Valley and in several national forests in France (Mormal, Blois, Aigoual), Spain (Moncayo) and French Guiana (Nouragues, Paracou) and in the ORPHEE experimental site (Gironde, France). Airborne LiDAR measurements have also been performed (or they will be before the start of the project) in order to characterise the structure of the canopy very finely (height, gap fraction, plant density profiles), as well as biodiversity surveys for different taxa (see ancillary data in Table 1). In most of these sites, plots with different management practices are being monitored; for example the Moncayo site gathers different silvicultural trials spread over the last 20 years for the restoration of over-aged Mediterranean oak coppice forests (conversion to regular "high" forest, conversion to forest coppice with standards, conversion to pastoral forest), and in the ORPHEE experimental site, tree species mixtures are manipulated (between one and five tree species per plot), with or without water limitations. Atmospheric CO_2 and windspeed profiles are also routinely collected as part of Fluxnet/ICOS, which will be instrumental to test our biophysical models at simulating these important microclimatic variables.

To best provide guidance to forest managers from the Landes de Gascogne in southern France (over 800 000 ha, >70% of which are maritime pine plantations), we will also design new, specific experimental plots to test the effect of specific management practices currently established (understory removal, thinning, clear cutting) or being tested (natural regeneration). In total, 8 stands will be equipped, 2 in natural regeneration and 6 along a chronosequence and fertility gradient (2 fertility levels and 3 stand ages). Each of these plantations will be monitored in two different blocks and along edges, and each intervention (thinning, understory removal) will be done on one block at a time, in coordination with the forest managers.

Finally, given the increasing recognition that urban forests and woodlands can mitigate urban heat island effects, especially during heatwaves, we propose as part of MaCCMic to also monitor microclimate, floral and faunal biodiversity and canopy structure in university-owned urban woodlands within the Bordeaux metropole (Floirac experimental forest). A weather station has recently been installed in an open field on the university premises adjacent to the woodlands. Within MaCCMic, we will equip the site with a spatial network of microclimate sensors in different understories and at different distance from the forest edge. LiDAR flights will also be performed in order to characterise precisely the canopy architectures of the different woodlands. This urban forest site will then be integrated within other international efforts to characterise microclimate variations in urban forests of European cities (coll. Pieter Defrenne, University of Ghent, Belgium).

Apart from the maritime pine and urban sites that will be set up as part of MaCCMic, all the data sets already exist (some covering several years, see Table 1) and will be accessible from the start of the project. As part of MaCCMic, we will also use LiDAR and Sentinel2 data from the Ciron to try to identify new locations where to install microclimate sensors to best tease apart the impact of local and landscape factors, and this effort may lead to the deployment of more sensors in this riparian corridor during the course of the project.

To tease apart confounding factors and test our hypotheses, biophysical microclimate models will also be used in MaCCMic. More specifically, we will use the open access R package *microclima* (Maclean *et al.*, 2018) and its coupled version with the other R package *NicheMapR* (Kearney & Porter, 2017; Kearney *et al.*, 2019), as well as the multilayer surface models MuSICA (Ogee *et al.*, 2003) and CLM-ml (Bonan *et al.*, 2018), also available for the project (MuSICA is developed by partner 1 and CLM-ml by Dr. Gordon Bonan at NCAR and by partner 2). This high number of physics-based models is justified by their diversity of approach and level of complexity. In particular, while *microclima* can describe topoclimatic variations of temperature in complex landscapes (from altitude, slope, aspect and topographic convergence), it still requires calibration with local observations of temperature "at the height of interest" (Maclean, 2019). Coupling *microclima* and *NicheMapR* resolves this issue and includes other microclimate variables besides air temperature such as soil temperature and moisture but only in bare soil or single-layered canopies (i.e. grasslands); vertical gradients of air temperature or humidity within tall, complex vegetation canopies are not possible (or only in a very rudimentary, non-biophysical manner). MuSICA and CLM-ml on the other hand are well-equipped to predict microclimatic variations in tall, complex vegetation canopies, although only MuSICA is capable of reproducing "counter-flow" air temperature and humidity profiles commonly observed in forest canopies, as well as in-canopy CO_2 vertical profiles. Another strong advantage of CLM-ml is that it uses the same core platform to couple the land surface to the atmosphere as the vegetation demography model CLM-FATES.

While CLM-ml and MuSICA will be readily available from the start of MaCCMic to test our set of hypotheses, during the course of the project, we will progressively incorporate biophysical theories from CLM-ml and MuSICA into both CLM-FATES (in order to explore *in silico* how a climatically-buffered, CO_2-rich understory environment impacts plant growth and phenological stages) and the R packages *microclima* and *NicheMapR* (in order to provide forest ecologists with the necessary tools to estimate microclimate variations in topologically-complex forest landscapes). Nonetheless, even the most complete process-based formulations (i.e. MuSICA) are only valid at a distance from the forest edge several times the canopy height and on gently sloping terrain. To simulate spatial variations of the microclimate in small forest patches, or complex terrains, a version of MuSICA coupled to the 3-dimensional atmospheric flow model ARPS, developed by partner 1 (e.g. Lagouarde *et al.*, 2015), will be used. Using this model, and microclimate measurements along transects (from forest edge, or in river canyons) performed in different sites (Landes, Ciron, Floirac), will allow us to develop simple correction factors (e.g. based on the forest height-to-edge ratio) that we will try to incorporate into the other biophysical microclimate models mentioned above (i.e. MuSICA, CLM-ml, etc.).

Scientific programme

We structured the scientific programme within MaCCMic around three rather independent *scientific* work-packages (WPs 1-3, Table 2), each focusing on a different research hypothesis, while a fourth work-package (WP0) is devoted to project coordination and dissemination. We believe that this organisation of the project will facilitate collaborations between partners (rather than an organisation by discipline or sites, or split between experimentalists and modellers), while keeping the focus on our research hypotheses and overall objective. This organisation is such that all partners are involved in at least 2 of the 3 scientific WPs, although this is not true at the individual level. For each WP, we will aim to have one meeting every month, for work-in-progress discussions, and meetings with the entire consortium only once a year, to give an overview of the work carried out in all WPs and write the yearly reports. Actions for the dissemination of the project results will be coordinated between partners and are described in section III. A more detailed description of the *scientific* work-packages (WPs 1-3) is provided below.

AAPG2021	**MaCCMic**		PCR
Coordinated by:	Jérôme OGEE	48 months	646k€
CE32 Dynamics of socio-ecosystems and their components for sustainable management			

Work packages, Tasks or Non-permanent personnel to be hired (*)	**2022**				**2023**				**2024**				**2025**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
WP0 | Project cordination and outreach																
0.1 - Kickoff and annual meetings	🟩					🟩				🟩				🟩		
0.2 - Individual WP meetings	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
0.3 - International day of forests (High schools)					D0.3				🟩				🟩			
0.4 - Training course building (Masters)			D0.4					🟩				🟩				🟩
0.5 - Web apps and web trackers (general public)					D0.5a				D0.5b					🟩	D0.5c	
0.6 - Continuing education (Foresters)						D0.6					🟩				🟩	
MSc student - educational quizz for international day (D0.3)					🟥	🟥										
MSc student - web app "management and energy budget" (D0.5a)					🟥	🟥										
MSc student - web app "management and extreme climate events" (D0.5b)									🟥	🟥						
IT engineer - web tracker (D0.5c)															🟥	
WP 1 |Impact of canopy structure and functional diversity on understory microclimate																
1.1 - Microclimate data and analysis	🟩	D1.1a		🟩	D1.1b		🟩	▨	D1.1c		🟩	▨	▨	▨	🟩	▨
1.2 - Remotely-sensed (LiDAR and Sentinel2) forest structure	D1.2a		🟩		🟩	D1.2b		D1.2c								
1.3 - Microclimate model evaluations and sensitivity analyses	🟩	D1.3a		▨	▨	D1.3b										
1.4 - Remotely-sensed canopy functional diversity and comparison against ground data									🟩	D1.4a		🟩	D1.4b			
1.5 - PhD2 defence															D1.5	
MSc student - microclimate in co-located managed forests (D1.1b)					🟥	🟥										
MSc student - microclimate in urban forests (D1.1c)									🟥	🟥						
MSc student - LiDAR LAI and LAD (D1.2a)	🟥	🟥														
PhD1 - microclimate modelling (MuSICA and intercomparison)	🟥	🟥	░	░	░	🟥	🟥	░	░	░	░	░				
PhD2 - LiDAR and Sentinel2 data analysis				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
PDRA1 - microclimate modelling (CLM) and forest regeneration	🟥	🟥	🟥	░	░	░	░	░								
PDRA2 - statistical modelling, model intercomparison, plant biodiversity									🟥	🟥	🟥	░	░	░	░	░
WP 2 | Impact of landscape features on understory microclimate																
2.1 - Impact of distance to river and associated topographic convergence	🟩	🟩	🟩	D2.1a		🟩	D2.1b		🟩	🟩	🟩	D2.1c		🟩	🟩	
2.2 - Impact of distance to forest edge and fragmentation	🟩	▨	▨	🟩	D2.2a		D2.2b		🟩	D2.2c						
2.3 - Microclimate in riparian corridors of various widths									🟩	🟩	D2.3a		🟩	🟩	D2.3b	
2.4 - PhD3 defence															D2.4	
MSc student - microclimate variations with distance to forest edge and tree age and density (D2.2a)	🟥	🟥														
PhD1 - microclimate modelling (MuSICA and intercomparison)	░	░	░	░	░	░	░	░	░	░	🟥	🟥				
PhD3 - microclimate modelling (MuSICA-ARPS)				🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
PDRA2 - statistical modelling, model intercomparison, plant biodiversity									░	░	🟥	🟥	🟥	🟥	🟥	🟥
WP 3 | Impact of climate change on understory microclimate buffering and decoupling																
3.1 - Decadal-scale changes in understory microclimate and legacy effects of disturbance	🟩	🟩	🟩	D3.1		🟩	🟩									
3.2 - CO_2-induced change in understory microclimate and impact on forest resilience/regeneration			🟩	🟩	🟩	🟩	🟩	🟩	D3.2							
3.3 - PhD1 defence												D3.3				
PhD1 - microclimate modelling (MuSICA and intercomparison)	░	░	🟥	🟥	🟥	░	░	🟥	🟥	🟥	░	░				
PDRA1 - microclimate modelling (CLM) and forest regeneration	░	░	░	🟥	🟥	🟥	🟥	🟥								

(*) PhDs or PDRAs may appear in several instances if involved in several WPs

Table 2 | Gantt chart detailing the timeline and scientific programme that will be carried out in MaCCMic.

WP1 | Impact of canopy structure and functional diversity on understory microclimate

(resp.: J. Ogée and S. Durrieu; involved partners: all)

WP1 will focus on the impact of **canopy structure and functional diversity** on understory microclimate, in particular **during drought**, to **test hypothesis H1**. It involves all partners and will consist in two initial and independent tasks (Tasks 1.1 and 1.2) and two more dependent ones (Tasks 1.3 and 1.4), with possible feedbacks on the other initial tasks (notably for the deployment of new sensors in specific locations).

Task 1.1 – Microclimate data and analysis

Task 1.1 has three sub-tasks: (1) setting up microclimate sensors and drone measurements (infrared cameras) in the Landes (maritime pine) and Floirac (urban) sites; (2) microclimate data collection and data management over the different experimental sites and; (3) data analysis, with a special focus on co-located, diversely managed sites, and drought events. Expected deliverables are: (1) **a shared platform** that links the different microclimate databases at each site (D1.1a); (2) **two master reports** on data analysis (and literature review) of microclimate in pine plantations of different ages and tree densities (MSc4, pre-PhD3 work) and in urban woodlands (MSc5) and; (3) **two peer-reviewed articles** on the impact of canopy structure and forest management on the buffering of understory microclimate and canopy temperature during drought events, one on production forests (in a forestry journal, PhD3, D1.1b), and another one on recreational/urban woodlands (in a biometeorology or ecology journal, MSc5, D1.1c).

Task 1.2 – Remotely-sensed forest structure retrieval and comparison against ground data

Task 1.2 has four sub-tasks: (1) LiDAR flights at the urban site; (2) retrievals of site-level leaf area index (LAI) and distribution (LAD) from LiDAR data at all sites, and their validation against ground-based measurements (e.g. winter/summer gap fractions, LAI2000); (3) comparison of LAI retrievals from LiDAR and Sentinel2 and site-level LAI seasonality at all sites and; (4) LiDAR- and Sentinel2-derived seasonal changes in LAI and LAD and their influence on microclimate data. The rationale behind subtasks (3) is that LiDAR-derived LAI and LAD retrievals are reliable but with no seasonal evolution (one flight per site, at peak season) while Sentinel2 data has a good temporal coverage. On the other hand, Sentinel2-derived LAI in complex and dense canopies needs investigation, because it is well known that saturation of the signal in the visible and near-infrared range prevents the retrieval of LAI greater than 5 or 6. By taking advantage of the multi-spectral range of Sentinel2 data (and eventually combining it with radar products, see Risk analysis) we are confident that such problems could be minimised (Feret *et al.*, 2015). Expected deliverables are: (1) **a dataset** and **a master report** on LiDAR-derived LAI and LAD at the different sites (MSc6, pre-PhD2 work, D1.2a); (2) **a dataset** of seasonal variations in LAI at the different sites (D1.2b) and; (3) **one peer-reviewed article** on the comparison between LiDAR and Sentinel2 LAI retrievals (PhD2, D1.2c).

Task 1.3 – Microclimate model evaluations and sensitivity analyses

Task 1.3 has two sub-tasks: (1) biophysical microclimate model evaluation (MuSICA) and sensitivity analysis on contrasted forest managements with focus on drought events and; (2) biophysical microclimate model inter-comparison (MuSICA, *microclimate*/*NicheMapR*, CLM-ml) and evaluation on contrasted forest types and climate events. This second sub-task is a necessary step before the merge of biophysical theories (from MuSICA and/or CLM-ml) into the R landscape-scale microclimate package *NicheMapR* and the global-scale vegetation demography model CLM-FATES. Expected deliverables are mainly **two peer-reviewed articles** (D1.3a and D1.3b) one from each sub-task (PhD1 and PDRA2).

Task 1.4 – Remotely-sensed functional diversity and comparison against ground data

Task 1.4 has three sub-tasks: (1) Sentinel2-derived functional diversity and comparison against vascular plant (canopy and understory) biodiversity data; (2) relationships between Sentinel2-derived functional diversity and forest structure and understory microclimate buffering capacities; and (3) identification of locations in the landscape with contrasted factors (in terms of functional diversity and forest structure) where microclimate sensors could be installed. Expected deliverables are mainly **two peer-reviewed articles** (D1.4a and D1.4b), one for each of the first two sub-tasks (PhD2).

Risk analysis

The independence of WP1 with the other WPs, notably WP2, is somewhat relative. Analyses conducted in Tasks 1.1 or 1.3 could be affected by yet-unknown, landscape-scale factors that we will aim to identify in WP2. However, by comparing only forest stands with similar topographic and edaphic situations, and focusing on the difference between these nearly co-located stands and how they differ in canopy and understory composition and structure, we should minimise the role of these landscape-scale factors. Another risk is that Sentinel2-derived LAI retrievals do not agree with LiDAR estimates, because of saturating signals. To address this potential issue, we will also use (MSc7) other satellite products, such as the Sentinel1 C-band synthetic aperture radar (SAR) images, with a 10m resolution every 6-12 days, or the L-band SAR images (JERS-1, PALSAR): these radar products are already used to retrieve aboveground biomass and water content even in very dense canopies (Frappart *et al.*, 2020), and characterise globally forest fragmentation and deforestation/afforestation.

WP2 | Impact of landscape features on understory microclimate

(resp.: J. Lenoir and F. Revers; involved partners: ISPA, EDYSAN, BIOGECO, TETIS, CITA)

WP2 will focus on the impact of **landscape features** on understory microclimate, in particular **forest fragmentation** and **distance to water bodies**, to **test hypothesis H2**. It involves nearly all partners and will consist in two initial and independent tasks: Task 2.1 will study the impact of the proximity of water bodies in the context of river canyons and the associated effect of topographic convergence (Fig. 3a), while Task 2.2 will focus on the impact of the proximity of a forest edge in the context of fragmented forest landscapes. A third task (Task 2.3) will look at possible interactions, in the context of riparian corridors of varying width (Fig. 3b). In the two examples shown in Fig. 3, variations in canopy structure and functional diversity are minimal. In the case of the Ciron data, all 6 air temperature sensors are located along a 120m-long transect underneath similar deciduous mixed broadleaf canopies with similar gap fractions (15%±6%) and similar woodland areas in a 300m radius (95%±0.5%); only differences in the co-varying distance to the river (16-70m) and site elevation (43-51m) seem to explain the observed air temperature differences, although site elevation variations seem too small to explain the microclimate variations. In the study from Oldén *et al.* (2019), all sensors were located at the same distance from the river (7.5m) and underneath canopies dominated by even-aged (>80yr) *Picea abies* trees; only the width of the riparian corridor, and sometimes its logging intensity, seem to explain the observed variations.

Task 2.1 – Impact of distance to river and associated topographic convergence

Task 2.1 has three sub-tasks: (1) data analysis and literature review on the effect of the proximity of a river on understory microclimate; (2) development and evaluation of terrain-informed biophysical models on complex terrains (*microclima*, *NicheMapR*, MuSICA-ARPS) in the context of riparian corridors and (3) derivation and validation of simplified parameterisations for its implementation in R packages and MuSICA. For this task, we will mostly work on the Ciron site where 3 transects like the one shown on Fig. 3 are installed since 2017. In MaCCMic, we will install 6 more transects, with varying widths of the riparian woodland. In a preliminary study, we implemented in MuSICA a simple but physically-sound representation (Maquin *et al.*, 2017) of how the distance from the river impacts the water table depth and soil moisture profile at one given location, with the idea that this could have repercussions on soil evaporation and plant transpiration rates, and thus on the temperature in the understory. We concluded that the influence of the water table depth seems too small to explain the large variations in air temperature shown in Fig. 3a. This is why, in MaCCMic, we propose to use the 3-dimensionnal atmospheric model MuSICA-ARPS that can simulate turbulent flows in complex terrains to better understand microclimatic variations across riparian corridors at such a small scale. Expected deliverables from Task 2.1 are: (1) **a dataset** of understory microclimate variations in the Ciron riparian corridor (D2.1a); (2) **two new software developments and their technical reports**, one describing the implementation of MuSICA in-canopy turbulent features in terrain-informed microclimate R packages *microclima*/*NicheMapR* and one describing the parameterisation in MuSICA of the effect of fine-scale topographic variations in river canyons (derived from MuSICA-ARPS simulations); (3) **two peer-reviewed articles**, each associated to these new developments (PhD1/PDRA2 and PhD1/PhD3), and including evaluation against microclimate data from the consortium (D2.1b and D2.1c).

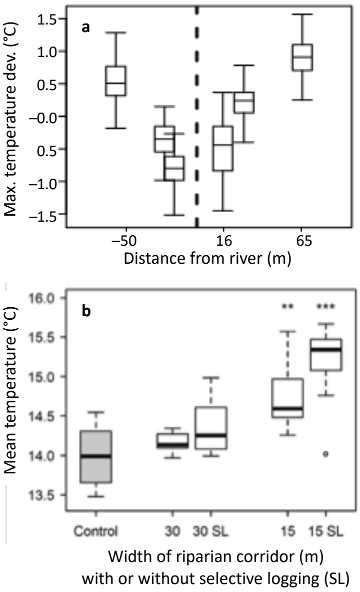

Figure 3 | Examples of microclimate variations with distance to water bodies and riparian strip widths. (a) 2016 summertime (JJA) maximum daily temperature deviations along a transect in the Ciron riparian forest. (b) Mean summertime air temperature in riparian corridors of different widths and management (redrawn from Oldén *et al.* 2019).

Task 2.2 – Impact of distance to forest edge and forest fragmentation

Task 2.2 has three sub-tasks: (1) data analysis and literature review on the role of forest patch size and fragmentation on understory microclimate (transects in the Landes and urban sites will be installed, and the shortest distance to forest edge will be informed in all datasets from the consortium); (2) evaluation of biophysical microclimate models (MuSICA-ARPS) on fragmented landscapes in the context of low-land production forests and; (3) development and evaluation of simple parameterisations in MuSICA to account for the impact of the vegetation type upwind (based on MuSICA-ARPS simulations and a simple 1-dimensional atmospheric boundary-layer model with patchy vegetation at the surface). Expected deliverables from Task 2.2 are: (1) **one master report**, (2) **one new software development and its technical report** and; (2) **three peer-reviewed articles** associated to each sub-task (2 from PhD3 and 1 from PhD1, D2.2a, D2.2b and D2.2c).

Task 2.3 – Microclimate in riparian corridors of various widths

Task 2.3 will combine results from Tasks 2.1 and 2.2 and will mostly consist in exploring the combined effect of topographic convergence associated with river canyons and edge effects associated with the width of riparian forest strips on understory microclimate in the riparian corridor. Expected deliverables are: (1) **one peer-reviewed publication** on the comparison of statistically-trained (GLMM) and process-based (*microclima*, *NicheMapR*, MuSICA) models to simulate understory microclimate variations in riparian forests (PDRA2, D2.3a) and (2) **one expertise report for policymakers** summarizing the main results in the context of the Ciron (D2.3b).

Risk analysis

The main risk for this work package is that the proposed model developments will not lead to good agreement with observations (e.g. Fig. 3). However, given the diversity of approaches, including the 3-dimensionnal model like MuSICA-ARPS, we are confident that we will at least gain understanding of why simplified approaches are difficult in some situations. Also, by including a statistically-trained approach in our terrain-informed microclimate models we are confident that we will be able to produce the expertise report that we envisage in Task 2.3.

WP3 | Impact of climate change on understory microclimate buffering and decoupling

(resp.: J. Chave and R. Fisher; involved partners: ISPA, EDB, EDYSAN, BIOGECO)

WP3 will focus on the impact of **climate change** on understory microclimate, in particular **CO_2**, to **test hypothesis H3**. It involves nearly all partners and will consist in two tasks. Task 3.1 will investigate decadal-scale changes in the buffering of understory microclimate and its possible decoupling from macroclimate, focusing on the legacy effects of disturbances such as management (thinning, understory removal) or extreme events (windfall, biotic attack, drought, etc.). Task 3.2 will investigate how climate change, and particular the rise in atmospheric CO_2, further modifies understory microclimate buffering and decoupling, and how this may translate in terms of forest regeneration and resilience.

Task 3.1 – Decadal-scale changes in understory microclimate and legacy effects of disturbance

Task 3.1 has two sub-tasks: (1) microclimate data analysis at Fluxnet/ICOS sites and other long-term sites with a focus on how forest disturbance impacts the buffering and/or decoupling from macroclimate; (2) microclimate (MuSICA, CLM-ml) model analysis on legacy effects of disturbance on understory microclimate. Results from WP1 will be key for this task, as disturbance here will mostly affect forest structure (management, windfall, biotic attack) or physiology (drought). The use of biophysical models MuSICA and CLM-ml will allow to tease apart the effects of CO_2 and macroclimate warming from the legacy effects of these disturbances. Expected results from this task are: (1) a **dataset** on long-term understory microclimate buffering and decoupling, (2) **two peer-reviewed articles** (D3.1a and D3.1b), one for each subtask (PhD1 and PhD1/PDRA1).

Task 3.2 – CO_2-induced changes in understory microclimate and consequences for forest resilience and regeneration

Task 3.2 has two sub-tasks: (1) microclimate (MuSICA, CLM-ml) model analysis of the effect of CO_2 and climate change on understory microclimate buffering and decoupling under future climate scenarios and; (2) consequences of microclimate buffering/decoupling on predicted forest regeneration dynamics in future climate (using CLM-FATES). Expected results from this task are: (1) a **software update and associated technical note** (D3.2a) describing the implementation of MuSICA and CLM-ml in-canopy turbulent features into CLM-FATES (PDRA1) and; (2) **two peer-reviewed** publications (D3.2b and D3.2c), one for each sub-task (PhD1/PDRA1 and PDRA1).

Risk analysis

The main risk for this work package is that the proposed model development into CLM-FATES is more difficult than initially envisaged. However, after initial exchanges with Dr. Gordon Bonan (NCAR, Colorado) who developed CLM-ml, we concluded that such model development was technically very feasible. Also, we planned a specific budget to facilitate scientific exchanges and meetings with him during the course of the project, that should increase our chances of success.

Summary of deliverables

Overall, MaCCMic should deliver a shared platform that links the different microclimate databases at each site, 1 web tracker (see III.), 2 web applications (see III.), 3 new teaching materials (see III.), 4 original datasets, 4 software updates and technical notes, 1 expertise report, 8 master reports, 3 PhD theses and up to 17 peer-reviewed articles.

II. Organisation and implementation of the project

a. Scientific coordinator and its consortium / its team

Past experience (in project coordination, on the topic) and implication of the PI

The PI of the project (J. Ogée) has a strong experience in project management: over the last 10 years, he has coordinated 5 collaborative projects (including 2 ANR) and several small single-partner projects. His latest ANR project (3 partners, 2013-2018) resulted in 20 publications and one declaration of invention. The PI has also a strong expertise in modelling microclimate in forests: MuSICA (https://www.bordeaux.inra.fr/ispa-ecofun/wordpress/index.php/musica-model/) is currently the only ecosystem model that can simulate belowground and intra-canopy microclimate variations in tall mixed vegetation canopies; the model has also been coupled to the 3-dimensional atmospheric model ARPS (Dupont *et al.*, 2011; Lagouarde *et al.*, 2015) to simulate microclimate in complex landscapes (canyons, hills, etc.), and some features of the in-canopy transport are now being implemented in global land surface models (Chen *et al.*, 2016). The PI will commit 33% of his time to MaCCMic.

Complementarity of the consortium

A consortium of micrometeorologists, forest ecologists, remote-sensing image analysts and modellers from 6 complementary research units was created to achieve the objectives of the project. Together, the consortium gathers all the facilities required to conduct the experiments and modelling envisaged in this project:

- Partner 1 (ISPA) brings expertise in micrometeorology, microclimate modelling, forest management and remote sensing, and will provide existing and new microclimate and ancillary datasets from the ICOS/Fluxnet network and the Landes and urban sites, as well as the biophysical models MuSICA and MuSICA-ARPS;
- Partner 2 (EDB) brings expertise in large-scale dynamic vegetation modelling and tropical forest ecology, and will provide the biophysical and vegetation demography model CLM-FATES (in particular, Dr. Rosie Fisher is the external co-chair of the CLM-FATES model working group);
- Partner 3 (EDYSAN) brings expertise on statistical microclimate and niche modelling and temperate forest ecology and biodiversity, and will provide microclimate and ancillary datasets from several ONF sites (Mormal, Blois, Augoual);
- Partner 4 (BIOGECO) brings expertise in temperate and urban forest ecology and biodiversity, and will provide microclimate and ancillary datasets from the Ciron, ORPHEE and urban sites;
- Partner 5 (TETIS) brings expertise in LiDAR data, satellite image analysis and forest ecology, and will provide remotely-sensed products of canopy structure and canopy biodiversity at the partners' sites;
- Partner 6 (CITA) brings expertise in Mediterranean forest ecology and management, and will provide microclimate and ancillary datasets from the Moncayo sites.

Besides being complementary, this consortium has also proven to be able to work closely together (partners TETIS-EDYSAN and TETIS-BIOGECO-ISPA have been involved in past projects), as well as being at the forefront of several research fields related to MaCCMic (demonstrated by the large proportion of cited literature that has been co-signed by scientists from the consortium).

Implication of scientific coordinator and partners's scientific leader in on-going project(s)

Name of the researcher	Person month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start - End
OGEE Jérôme	4	Labex COTE, 180k€	An integrated approach to understand the contribution of leaf shedding in tree responses to drought (LEAFSHED)	BURLETT Régis	2019-2021
LENOIR Jonathan	33.6	ANR JCJC, ANR-19-CE32-0005, 300k€	IMpacts des PRocessus mIcroclimatiques sur la redistributioN de la biodiversiTé forestière en contexte de réchauffement du macroclimat (IMPRINT)	LENOIR Jonathan	2019-2023
REVERS Frédéric	16.8	LabEx COTE, 146k€	Study of roles of socio-economic and ecological factors on forest socio-ecosystem functioning: example of the Ciron Valley (SEEFOREST)	REVERS Frédéric	2019-2022
REVERS Frédéric DURRIEU Sylvie	4 6	CNES, 143k€	Added-value of fusing multisource LiDAR and optical data to better understand relationships between forest structure, biodiversity and microclimate (FRISBEE)	REVERS Frédéric	2019-2021
DURRIEU Sylvie	3.5	ADEME, 350 k€	PROspective TErritoriales forestière SpaTialisée (PROTEST)	MONNET Jean-Matthieu	2018-2021
DURRIEU Sylvie	10	CNES, 250 k€	Space Lidar for Improved Multisource Forest Inventory (SLIM)	DURRIEU Sylvie	2020-2023
FERRIO DÍAZ Juan Pedro	18	Spanish Research Agency, 230k€	PID2019-106701RR-I00. La gestión forestal como herramienta revitalizadora del monte bajo de quercíneas: reactivación de sumideros de carbono y otros servicios ecosistémicos (CO2PPICE)	FERRIO DÍAZ Juan Pedro	2020-2023
FERRIO DÍAZ Juan Pedro	2	H2020, 2017 Call, 725k€	MSCA-RISE-2017-777803. A global initiative to understand gypsum ecosystem ecology (GYPWORLD)	PALACIO BLASCO Sara	2018-2022

b. Implemented and requested resources to reach the objectives

As mentioned above, several existing experimental sites will be accessible and the associated datasets will be available from the start of the project, together with the different modelling codes that we plan to use as part of this project, as well as the computing facilities and data servers required to store and analyse datasets and perform model simulations. Financial support is however requested to maintain the running cost of those experimental sites and computing facilities, and also to equip new sites (called Landes and urban sites in Table 2). A detailed breakout of this requested funding is detailed below for each partner.

Partner 1: ISPA

Staff expenses

Staff expenses at ISPA related to MaCCMic are spread as follows:

- 743k€ for permanent staff (87 person.months);
- 153k€ for non-permanent staff with *no* funding requested [1 full PhD (PhD1) to work on WP1-2-3 and 0.5 PhD (PhD3) to work on WP3];
- 75.5k€ for non-permanent staff with funding requested [0.5 PhD (PhD3) to work on WP3, 3 months of IT and communication engineer to work on WP0, as well as 4 master-level internship allowances: 1 MSc to work on WP1-3 (pre-PhD3), 1 MSc to work on WP1 (in collaboration with PhD1) and 2 MSc to work on WP0].

Instruments and material costs

Instrument and material costs at ISPA related to MaCCMic are 68k€, spread as follows:

- 15k€ of small equipment and consumables to equip new sites with microclimate sensors [6 pine plantations (Landes sites), including 2 with microclimate gradients, 1 urban forest with microclimate gradients as well] and reinforce the density of sensors on a few existing sites (notably the Moncayo site);
- 20k€ of small equipment and consumables to perform model simulations and remote-sensing image analysis [10k€ for computing time on computing facility centres from Bordeaux and Toulouse universities, 6k€ for on-site data servers, 4k€ for modelling computers for PhD1 and PhD3];
- 18k€ of equipment, for the acquisition of two 3D sonic anemometers and their datalogger (for WP3);
- 14k€ of equipment, for the acquisition of 1 infrared camera and its protection case (for WP1).

Building and ground costs

None.

Outsourcing / subcontracting

Outsourcing costs include 1k€ for two Intel Fortran compilers.

General and administrative costs & other operating expenses

Other operating expenses at ISPA related to MaCCMic are 48.4k€, spread as follows:

- 6k€ of travel expenses for field data installation and acquisition (Landes sites, urban forest, Moncayo site);
- 10k€ of travel expenses for attendance to international conferences (notably for PhD1 and PhD3 and their supervisors);
- 12k€ of travel expenses for consortium meetings (2k€ per year over 4 years) and outreach activities (4k€);
- 20.4k€ of general and administrative costs (12% of total requested funding).

Partner 2: EDB

Staff expenses

Staff expenses at EDB related to MaCCMic are spread as follows:

- 62.5k€ for permanent staff (6 person.months);
- 80.4k€ for non-permanent staff with *no* funding requested [14 person.months, visiting researcher] and;
- 137.8k€ for non-permanent staff with funding requested [2-year postdoc (PDRA1) to work on WP1-2].

Instruments and material costs

Instrument and material costs at EDB related to MaCCMic are 8k€ to perform model simulations and remote-sensing image analysis [6k€ for computing time on computing facility centres from Toulouse university, 2k€ for modelling computer for PDRA1].

Building and ground costs

None.

Outsourcing / subcontracting

None.

General and administrative costs & other operating expenses

Other operating expenses at EDB related to MaCCMic are 24.6k€, spread as follows:

- 4k€ of travel expenses for visiting CLM-ml main developer Gordon Bonan at NCAR (USA);
- 4k€ of travel expenses for attendance to international conferences (notably for PDRA1);
- 4k€ of travel expenses for consortium meetings (1k€ per year over 4 years) and;
- 12.6k€ of general and administrative costs (8% of total requested funding).

Partner 3: EDYSAN

Staff expenses

Staff expenses at EDYSAN related to MaCCMic are spread as follows:

- 265.5k€ for permanent staff (40.8 person.months);
- 13k€ for non-permanent staff with *no* funding requested [4.8 person.months, PhD Eva Gril] and;
- 88.8k€ for non-permanent staff with funding requested [2-year postdoc (PDRA2) to work on WP0-3].

Instruments and material costs

Instrument and material costs at EDYSAN related to MaCCMic are 8k€ [3k€ for maintenance of existing microclimate networks (ONF sites), 3k€ for data servers to perform niche model simulations and remote-sensing image analysis, 2k€ for computing model for PDRA2].

Building and ground costs

None.

Outsourcing / subcontracting

None.

General and administrative costs & other operating expenses

Other operating expenses at EDYSAN related to MaCCMic are 25k€, spread as follows:
- 2k€ of travel expenses for field data acquisition over 3 years (ONF sites);
- 4k€ of travel expenses for attendance to international conferences (notably for PDRA2);
- 6k€ of travel expenses for consortium meetings (1.5k€ per year over 4 years) and;
- 13k€ of general and administrative costs (12% of total requested funding).

Partner 4: BIOGECO

Staff expenses

Staff expenses at BIOGECO related to MaCCMic are spread as follows:
- 241.7k€ for permanent staff (32 person.months);
- 22.8k€ for non-permanent staff with *no* funding requested [8 person.months, PhD Amandine Acloque];
- 10.2k€ for non-permanent staff with funding requested [3 internship allowances on WP0, WP1 and WP3].

Instruments and material costs

Instrument and material costs at BIOGECO related to MaCCMic are 40k€, spread as follows:
- 25k€ of small equipment and consumables to reinforce or maintain the density of microclimate sensors on a few existing sites (Ciron, ORPHEE) and equip new ones (1 urban forest);
- 10k€ for biodiversity monitoring at existing sites (Ciron, ORPHEE) and at new ones (urban forest);
- 5k€ of small equipment and consumables to replace on-site data servers and field computers;

Building and ground costs

None.

Outsourcing / subcontracting

None.

General and administrative costs & other operating expenses

Other operating expenses at BIOGECO related to MaCCMic are 19.5k€, spread as follows:
- 4k€ of travel expenses for field data acquisition over 3 years (Ciron, ORPHEE and urban forest);
- 4k€ of travel expenses for attendance to international conferences;
- 4k€ of travel expenses for consortium meetings (1k€ per year over 4 years) and;
- 7.5k€ of general and administrative costs (12% of total requested funding).

Partner 5: TETIS

Staff expenses

Staff expenses at TETIS related to MaCCMic are spread as follows:
- 189.2k€ for permanent staff (20.8 person.months);
- 51.9k€ for non-permanent staff with *no* funding requested [0.5 PhD (PhD2) to work on WP1 and WP3];
- 55.3k€ for non-permanent staff with funding requested [0.5 PhD (PhD2) one MSc allowance to work on WP1-3 (pre-PhD2)].

Instruments and material costs

Instrument and material costs at TETIS related to MaCCMic are 14.5k€, spread as follows:
- 13k€ of small equipment and consumables to perform LiDAR and Sentinel2 data analysis [5k€ for computing time on computing facility centre from Montpellier university, 6k€ for on-site data servers, 2k€ for modelling computers for PhD2];
- 1.5k€ of equipment, for the maintenance of the portable LiDAR and its drone (for WP1).

Building and ground costs

None.

Outsourcing / subcontracting

None.

General and administrative costs & other operating expenses

Other operating expenses at TETIS related to MaCCMic are 21.8k€, spread as follows:
- 2k€ of travel expenses for field data acquisition (LiDAR data at urban site);
- 4k€ of travel expenses for attendance to international conferences (notably for PhD2 and his/her supervisors);
- 6k€ of travel expenses for consortium meetings (1.5k€ per year over 4 years);
- 9.8k€ of general and administrative costs (12% of total requested funding).

Requested means by item of expenditure and by partner

		ISPA	EDB	EDYSAN	BIOGECO	TETIS	CITA
Staff expenses		75.5k€	137.8k€	88.8k€	10.2k€	55.3k€	0k€
Instruments and material costs (including the scientific consumables)		68.0k€	8.0k€	8.0k€	40.0k€	14.5k€	0k€
Building and ground costs		0.0k€	0.0k€	0.0k€	0.0k€	0.0k€	0k€
Outsourcing / subcontracting		1.0k€	0.0k€	0.0k€	0.0k€	0.0k€	0k€
General & admin. costs & other operating expenses	Travel costs	28.0k€	12.0k€	12.0k€	12.0k€	12.0k€	0k€
	Admin. management & structure	20.4k€	12.6k€	13.0k€	7.5k€	9.8k€	0k€
Sub-total		**192.0k€**	**170.4k€**	**121.8k€**	**69.7k€**	**91.6k€**	**0k€**
Requested funding							**645.5k€**

III. Impact and benefits of the project

a. Impact and benefits in scientific, economic, social or cultural fields

Impact for the global change terrestrial ecology community

The results of MaCCMic will be closely followed by the community of terrestrial ecologists interested in how climate change impacts forest biodiversity (a science community that a large part of the consortium belongs to). In particular, our results will help to tease apart the ecological and biophysical factors that drive the change of plant community composition in forest understories. Using factorial manipulation experiments, it has been shown that light availability, independently of warming, was driving the change in understory plant communities to more warm-adapted species (a process called 'thermophilisation') (De Frenne *et al.*, 2015). Long-term floristic surveys also showed that this rate of thermophilisation of understory plant communities was lagging behind macroclimate warming, and best followed changes in understory microclimate (De Frenne *et al.*, 2013; Zellweger *et al.*, 2020). Compared to statistical microclimate models, the biophysical models that will be used and developed in MaCCMic will allow more confident predictions of the future of the microclimate warming in forest understories, and the associated change in understory plant communities. Biophysical models will also be instrumental in refining current estimates of thermophilisation rates of understory plant communities. Currently, those rates are estimated by averaging species-level "indicator values" (IVs) for temperature at the community level and inferring their rate of change over time for a given location based on floristic surveys. This approach is often criticised because each species IV is taken from the spatial mean (over the species range) of the long-term average macroclimatic temperature, and thus rather reflects the macroclimatic niche of a given species. By using the biophysical models of microclimate buffering from MaCCMic, we could refine these species IVs by estimating the mean annual temperature conditions as experienced in the forest understory and throughout the entire species range. This should provide revised, and more accurate, thermophilisation rates to global change terrestrial ecologists.

Impact for the carbon cycle and climate change research community

As part of MaCCMic, we will integrate state-of-the-art biophysical descriptions of below-canopy CO_2 concentration build-up and buffered microclimate into CLM-FATES, one of the large-scale vegetation demography and biophysical model that is used to inform the Intergovernmental Panel on Climate Change (IPCC) (Arora *et al.*, 2020). Developments in these models are very strongly followed in the scientific community with large model inter-comparison projects or model benchmark initiatives. Currently, there is a heated debate in climate change research about the fate of the land carbon (C) sink, often quoted as the second largest uncertainty in future climate projections after clouds (Friedlingstein & Prentice, 2010). Some studies, based on forest inventories (Pan *et al.*, 2011), as well as atmospheric CO_2 observations and eCO_2 experiments (Ciais *et al.*, 2019; Liu *et al.*, 2019) argue that the land C sink has increased over the past decades and will most likely continue to do so in the future. Other studies on the contrary, based on centennial-long dendrochronological records (Büntgen *et al.*, 2019; Brienen *et al.*, 2020) and ecological theories (Bugmann & Bigler, 2011; Körner, 2017), argue that the current CO_2-induced increase in forest productivity and growth that drives the land C sink is only transient, because of growth-lifespan trade-offs that will inevitably lead to an increase in tree mortality rates, albeit with some time lag. Currently, models do not predict such a strong weakening trend in the land C sink, but their ability to represent ecological processes such as recruitment, sapling growth and mortality is limited. The model development that we propose to CLM-FATES will allow us to explore how CO_2 build-up and buffered microclimate in the understory of closed canopies impacts growth rates of late- and early-successional saplings, potentially leading to new understanding of the biophysical and ecological mechanisms behind the fate of the land C sink in a changing climate.

Impact for the forest sector

It is also expected that MaCCMic will have a strong impact on the forest sector by providing new tools to help forest managers increase the resilience of forests and foster their ecological, recreational and climate services. At least two sets of tools are envisaged: (1) a **web application** with an interactive virtual forest that will show, based on a biophysical model (MuSICA), how forest management (species, density, etc.) can influence the energy and water balance and the understory microclimate during specific past and future extreme events and; (2) a **web "tracker"**, that is, a website that will summarise, based on near real-time data, how understory microclimate is buffered and decoupled from its macroclimate, for a set of typologies of forests or tree plantations in a given region.

Forest typologies will be defined based on fixed topographic and edaphic factors of the region, and potentially evolving management practices, eventually including patch size and fragmentation of the surroundings (see H2). These tools will allow foresters to monitor specific climate events and identify which existing or new forest typology can best buffer climate extremes.

To best design these tools and disseminate their use, regular meetings with forest owners and managers of the experimental sites studied in MaCCMic will be organised. The consortium has already a strong experience for this type of interaction, and the interest of forest owners and managers to interact with the research community on questions related to climate change is very high. We are therefore confident that this type of interaction will be very successful.

b. Science-society initiatives

General public outreach

The consortium has a long experience in communicating to the general public, notably *via* the regular writing of science communication articles in web-based journals (e.g. The Conversation), notably in the framework work of the yearly "Fete de la Science" event. The web application and web tracker described above will also be an excellent opportunity to communicate our work to the general public.

International day of forests (Middle schools)

The project will integrate well into the education and outreach activities of the applicants. It will be part of the aspiration to broaden participation of middle school students in science. In particular a seminar course and educational Quizz on forest microclimate and climate change will be designed and proposed to middle school in France, notably in the framework of the "International day of Forests" (March 21st). A master student (most probably from the "Science communication and mediation" university of Bordeaux-Montaigne master programme) will help in the design of the teaching material and Quizz. This educational outreach is a natural continuation of the current activities of JC Domec who has been organizing the International Day of Forests at Bordeaux Sciences Agro since 2018. He has also invited five middle schools from disadvantaged areas (zones d'éducation prioritaire, ZEP) to interact with foresters to talk about trees, biodiversity, and climate change.

Training course building (Masters)

We will also incorporate findings from MaCCMic into our teaching materials for undergraduate and graduate programs at Bordeaux Sciences Agro (Engineering degree in Forestry coordinated by JC Domec and M Charru) and at the University of Bordeaux (Master program "Biodiversity, Ecology and Evolution" in which several applicants are currently teaching). The core of the project will be an excellent example of complex systems behaviour, feedback processes, and the need for a more holistic view on ecosystems.

Continuing education (Foresters)

To disseminate our findings to forest managers beyond those directly involved in the experimental sites studied in MaCCMic, we plan to design and teach a two-day short-course on the "Impact of forest management on the Earth's climate and microclimate". The course will include lectures, discussion, and experience with some existing tools, including the web app and tracker described above. We will make ample use of examples and will draw from the expertise among the participants.

We plan to offer the course through Bordeaux Science Agro's Outreach Education Office in association with the French national forest service (ONF). JC Domec is also already working with ONF, where two "apprentices" from the Bordeaux ONF office are enrolled in his forest engineer continuing education program each year.

VI. References related to the project

(references in green were produced by scientists from our consortium)

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