AAPG2023	MONI-TREE		PRCE
Coordonné par :	Thomas CORPETTI	48 mois	699 003 €
CES04 : Méthodologies, Instrumentation, capteurs et solutions pour la transition écologique			

MONI-TREE: MONItoring TREE comfort inside cities

Multiscale approach with multimodal remote sensing, physical modeling, deep learning and in-situ data

Partner	Last Name	First Name	Position	Involved WP & responsibilities in the project	months
1- CNRS-LETG	*Corpetti*	*Thomas*	*Senior researcher*	***Scientific coordinator. Resp. WP2,*** *machine learning, physical models*	*18*
1- CNRS-LETG	*Nabucet*	*Jean*	*Engineer*	***Co-resp. WP1*** *; WP3, plant measurements & simulation*	*6*
1- CNRS-LETG	*-*	*-*	*Engineer to hire*	*WP2 - WP4, machine learning*	*12*
1- CNRS-LETG	*-*	*-*	*PhD to Hire*	*WP1 - WP3, plant measurements & simulation*	*36*
2- ONERA-DOTA	*Adeline*	*Karine*	*Research Engineer*	***Resp. WP3****; WP1, plant measurements & optic physical model*	*4.5*
2- ONERA-DOTA	*Roupioz*	*Laure*	*Research Engineer*	*WP4, understanding tree stress*	*2.3*
2- ONERA-DTIS	*Colin*	*Elise*	*Research Engineer*	*WP1 - WP3, optic & radar image processing*	*4.5*
2- ONERA-DEMR	*Everaere*	*Etienne*	*Research Engineer*	*WP1 - WP3, radar physical model*	*4.5*
3- SILVA	*Le Thiec*	*Didier*	*Senior researcher*	***Co-resp WP1****, plant physiology*	*7*
3- SILVA	*Desalme*	*Dorine*	*MCF*	*WP1, plant physiology*	*6*
3- SILVA	*Buré*	*Cyril*	*Technician*	*WP1, plant physiology*	*3*
3- SILVA	*-*	*-*	*Engineer to hire*	*WP1, plant measurements*	*6*
4- ECOBIO	*Sulmon*	*Cécile*	*MCF*	***Resp WP4****, WP1, plant ecophysiology*	*6*
4- ECOBIO	*Gouesbet*	*Gwenola*	*Research Engineer*	*WP4, plant ecophysiology*	*4*
4- ECOBIO	*Le Bris*	*Nathalie*	*Engineer*	*WP4, metabolic analysis*	*1*
4- ECOBIO	*Chorin*	*Marion*	*Engineer*	*WP4, metabolic analysis*	*1*
4- ECOBIO	*Fontaine-Breton*	*Thierry*	*Technician*	*WP1 - WP4, plant culture and sampling*	*2*
4- ECOBIO	*Bodiguel*	*Rémi*	*Technician*	*WP1 - WP4, plant culture and sampling*	*1*
4- ECOBIO	*Le Rouzic*	*Emmanuel*	*Technician*	*WP1, field sampling*	*1*
4- ECOBIO	*-*	*-*	*Engineer to hire*	*WP1 - WP4, plant culture and sampling*	*12*
5- IRISA	*Pelletier*	*Charlotte*	*MCF*	*WP2 - WP3, machine learning*	*5*
5- IRISA	*-*	*-*	*Engineer to hire*	*WP2, machine learning*	*18*
6- AUBEPINE	*El moualy*	*Sabine*	*Research engineer*	***Resp WP5*** *; WP1, WP4, metabolic, final products*	*5*
6- AUBEPINE	*Le Bris*	*Xavier*	*Research engineer*	*WP1, WP4 - WP5, metabolic, final products*	*6*
6- AUBEPINE	*Eigenschenck*	*Emmanuel*	*Engineer*	*WP1, WP4 - WP5, metabolic, final products*	*6*
6- AUBEPINE	*d'Auhtier*	*Nicolas*	*Technician*	*WP1 : VTA acquisitions*	*6,5*
6- AUBEPINE	*Genton*	*Claire*	*Technician*	*WP1 : VTA acquisitions*	*6*

Note on eligibility criteria according to compliance with pre-proposal: The project is fully consistent with the pre-proposal. Nothing has been changed in the consortium/organization in WPs. The total amount requested is 3% higher. This is due to the fact that we have adjusted the costs of the missions to fit exactly the number of required days, and we have added 2 500€ for the drafting of the consortium agreement.

I. Context, positioning, and objective(s) of the proposal

a. Objectives and research hypothesis

Global environmental changes and their consequences in urban areas

According to the World Bank, 54% of the world's population is currently living in urban areas (defined as human settlements with a high population density and manmade infrastructures) and this number is expected to reach 80% in 2050. In France, the same trend is observed since 81.2% of the population are urban citizens according to INSEE (the National Institute of Statistics and Economic Studies) in 2022, with 54.6% living in cities of more than 50,000 inhabitants. But in a context of climate change, unpredictable events (i.e. storms, heat waves, long drought periods) occur and impose critical challenges to cities. These drastic environmental modifications contribute to increase the urban heat island, reduce air quality and thus strongly affect human/animal health, vegetation resilience and biodiversity with hazardous consequences in terms of economy, ecosystem services, well-being or attractiveness. Therefore, it is increasingly important to have policies and approaches that are capable of making cities resilient and adaptable to these sustainable changes.

Role of trees & Scientific barriers

It is well-known that vegetation, and in particular trees, provides very effective solutions for reducing these impacts such as cooling cities and improving air quality **[19]**[1]. However, to play a "green" positive role, trees must survive and maintain a good physiological state in such a hostile context imposed by their environment and anthropogenic pressures (e.g., hydric and thermal stresses, resource limitations, physical constraints). As shown in summer 2022, combined long term hydric stress and high temperatures have caused the death of many trees while others survived despite, *a priori*, unfavorable conditions. These surprising observations disturb city managers who **lack tools for monitoring tree well-being,** able to **alert in case of large stress,** and guide future and **adapted management plans for tree plantations**. This is because we are facing a **complex system with multiple interactions** whose every contribution is not yet well understood.

Physiological responses to stresses induced by environmental changes

Urban-related stresses induce tree physiological responses to regulate water, carbon and nitrogen status, and prevent or limit tissue and organ damages. This translates into changes in evapotranspiration and photosynthesis processes, and in metabolic shifts regarding pigments, leaf structural, and stress response compounds which are species-dependent. Researchers in tree expertise need macro-scale analyses to underline specific survival or dieback mechanisms. However, measuring the internal condition of trees is not an easy task. Several processes exist such as destructive or non-destructive methods, direct or indirect measurements under controlled conditions (in labs) or on real data with remote sensors (spectrometer, images). Thus, it is crucial to have a better knowledge between these measuring processes and the trees' physiological responses to stress factors in order to have a better understanding of the urban tree comfort.

Assessing tree physiology

A variety of physiological parameters can be measured on trees (listed in Table 1 for the project), either locally corresponding to information at the tree scale (with field/lab instrumentation), or globally related to the observation of trees in their context using remote sensors (UAV, airplanes, satellites, cf [11]), and either under controlled conditions (for example in greenhouses, see Figure 1) or in real conditions inside cities. If not measured directly, these parameters can be also retrieved from the electromagnetic spectrum measurement whose variations are induced by changes in specific physiological parameters such as vegetation moisture and pigment contents, among others, which depends on the spectral domain (here optical and radar domains are studied). Then, appropriate simulation codes can help in indirectly estimating these vegetation parameters.

Figure 1: Experiments under controlled conditions (SILVA greenhouse): (left and middle) oaks trees of 24 and 28 months respectively.

Assessing tree stresses

The environmental variables that promote tree stress are of two kinds: climatic and structural. Climatic variables mainly concern the temperature and humidity and are either fixed by the user as input (for experiences in a controlled environment and simulation) or measured by local sensors or field campaigns for information related

[1] References in **[Blue]** involve people of the consortium

to trees in cities. Structural variables concern the neighborhood in which the trees are subjected: density or urbanization, and percentage of green spaces, … Such structural variables have been formalized by the urban climate community with the notion of LCZ: Local Climate Zones [39]. LCZs correspond to coherent urban patterns within which the climate has its own behavior. In the context of tree monitoring, it is reasonable to assume that LCZs may also have their own influence on tree temperature as well as on pollution levels. The table below lists the main source of stresses we expect to assess in this project.

Family of variable	Acquisition process	Kind of information (local/global)	Measuring instrument	Partner with the instrument or data
Electromagnetic spectrum	C, F, S	Leaf / Tree	spectrometer and camera	LETG / ONERA
Primary production function	C, F, S	Leaf / Tree	spectrophotometer, dualex	SILVA / LETG
Investment in the development strategy	C, F, S	Leaf / Tree	leaf scan, tree height, balance …	SILVA / LETG / ONERA
Water availability	C, F, S	Leaf/Tree	balance, osmometer, gas exchange	SILVA
Metabolic fonctioning	C,F	Leaf/Tree	liquid and gas chromatography, metabolomics	ECOBIO / SILVA
Plants stress expression	C,F	Leaf/Tree	spectrophotometer, polymerase chain reaction	ECOBIO

Table 1: List of physiological variable families used in this project. 1st column: family name; 2nd column: acquisition process with "C" for *controlled environment* (in labs), "F" for *field measurement,* and "S" for *simulation* with models; 3rd column: local measurement (on single trees or leaves) or global measurement (using images); 4th column: instruments; 5th column: availability.

Type of stress	Acquisition process	Type (local/global)	Measuring instrument	Partner with the instrument or data
Thermal	C, F, S	Local	Weather station	LETG / ONERA / SILVA
Hydric	C, F, S	Local	Weather station	LETG / ONERA / SILVA
Thermal	F,S	Global	Available products developed in our labs	LETG / ONERA
Land use	F,S	Global	Remote Sensing	All

Table 2: List of the main sources of stress to which trees are subjected. 1st column: stress type; 2nd column: acquisition process with "C" for *controlled environment* (in labs), "F" for *field measurement,* and "S" for *simulation* with models; 3rd column: local measurement (on single trees or leaves) or global measurement (using images); 4th column: instruments; 5th column: availability.

Assessing tree comfort

Complementary to the measurement of physiological variables, other techniques exist to characterize the comfort of trees based on visual inspection. In particular, VTA (Visual Tree Assessment) approach [17], designed in AUBEPINE, is a non-intrusive method based on the method proposed by Mattheck. C 1994. The visual tree assessment consists of 3 steps: identification of external symptoms expressing internal defects, diagnosis by thorough inspection and evaluation of the failure criteria leading to an overall risk assessment of the tree.

Goals of the project

In order to better **understand the response of trees to extreme solicitations,** to **prevent their senescence at an early stage,** and to **provide maps of the comfort of trees in cities associated with alert systems**, the guideline of this project is to acquire a large number of *physiological* variables (in real, simulated and controlled conditions) associated with their *environment* (urban pattern, climatic conditions), and to exploit machine learning in order to identify links between them and to generate global maps. An important underlying question is to evaluate the **ability of remote sensing data to estimate physiological variables** related to the internal structure of trees. It is indeed recognized that the internal state of trees influences their external properties (photosynthesis capacity, pigmentation in particular) which can be observed through their electromagnetic radiation [45] and thus through images, noting however that the inversion still remains a complicated step, and that the link between some physiological parameters and multispectral imagery is still not understood for some variables (antioxidant for example [22]). Our project is also a contribution in this direction. We will explore learning estimation models able to derive some relations between physiological variables and their counterparts in images. An important originality here is that these methods will be calibrated on the basis of **physical simulations**, which will allow us to i) guarantee a sufficiently large amount of data to train our models and ii) ensure the **physical consistency of our estimators**. These models will then be refined on data acquired in controlled environments to ensure, again, a physical consistency of our models. In a second step, from the models mentioned above, the **application in real conditions** (i.e. using real remote sensing images and *in situ* measurements on trees) will be performed. To this end, the **transferability** of our models in real situations will be studied. To ensure a free reproduction of our processes (more details in "Open science, reproducibility, FAIR principles" paragraph), we will rely on freely available SENTINEL (1 and 2, named S1 and S2 in the rest of the document) images. These complementary data (optical for S2 and radar for S1) enable to observe both vegetation indexes (with optic) and structure (with radar), have a better spatial and spectral resolution than similar products (LANDSAT for example) and are associated with an interesting revisit time (on the same site) of 4-5 days. An illustration of S1/S2 can be seen in Figure 4(b-c). However, these data being acquired at 10m resolution, a **super-resolution** step will be required to improve the spatial resolution at 3m (see for example Figure 4 (d)), more adapted to the scale of cities. From generated maps of physiological parameters at the city scale and internal measurements inside trees, we will develop **methodologies to estimate tree comfort indexes** at the scale of a city. To this end, data issued from the VTA approach will be used on a large number of trees and will be linked to stress factors (urban patterns, temperature). Specific attention will concern the analysis and interpretation of key features, issued from machine learning, connected to tree physiology in order to assess parameters from remote sensing and to help the interpretability of urban patterns connected to tree physiology.

<u>Test Cities & privileged species</u>

Application on real cities will concern Rennes and Toulouse. These two cities have different climates (Toulouse's climate is transitional Mediterranean, with relatively mild winters and hot, sunny summers, while Rennes's climate is sub-oceanic, with fairly mild and rainy winters and fairly hot summers) and are monitored for decades (many existing measures and surveys regarding their climate and their vegetation). In addition, the consortium is used to collaborate with their managers. Our machine learning algorithms will be trained in a sub-part of the city of Rennes and tested both in the other part of Rennes (to evaluate quantitatively our performances) and in Toulouse. This latter experience aims at evaluating the **transferability** of our methods in other contexts. To this end, domain adaptation approaches, able to apply an algorithm trained in one *source* domain (i.e. Rennes) to a different (but related) *target* domain (i.e. Toulouse), will be studied. As for privileged species, since this project is the first in this direction, special attention will be given to plane trees and pedunculate oaks, which are two species found in major European cities and for which simulation models are available.

<u>Open science, reproducibility, FAIR principles</u>

The consortium is particularly attentive to the reproducibility of our processes, both in terms of availability of data, methods, and of application in various urban contexts. To implement this, all data acquired during this project will be made publicly available at the end of the project, under the principles of FAIR data dissemination: Findable, Accessible, Interoperable, Reusable. The algorithms that will be developed, whether they are related to the estimation of physiological variables or to the analysis of tree comfort, will be made available on GitHub. Finally, concerning the reproducibility of our methods of mapping the well-being of trees in cities, access to free satellite data with a good temporal frequency will be favored. Today, to observe the urban environment with precision (at a spatial resolution from 3m to 5m), it is necessary to use satellites providing very high spatial resolution images. Access to such data is on demand (and therefore not continuously over time) and not free, which limits the extension in other study sites. In this project, we rather prefer to rely on freely available SENTINEL-1/2 data. Since 2015 and the launch of the SENTINEL constellation, the community is facing significant changes both in terms of data handling and processing and in terms of potential new monitoring applications. Thanks to its continuous acquisition process, many new use cases have indeed been explored in a wide range of applications. However, this large potential of the SENTINEL data is altered by the limited spatial resolution (at best 10m) that prevents the observation of small objects. For this reason, the remote sensing and artificial intelligence research communities have developed efficient super-resolution algorithms able to exploit the multivariate nature of S2 images to reconstruct precise objects at finer resolutions (from 1m to 5m). Though efficient for generating visually realistic images, when one focuses on the reconstruction of trees or vegetation, associated values suffer from an important lack of consistency. Therefore, one objective will also consist in designing **super-resolution methods with a specific focus on vegetation reconstruction**.

To sum up, the objectives, in terms of **tree understanding** and **city planning**, can be summarized as follows:

- Deriving physiological parameters from remote sensing images
- Understand the warning signs announcing the dieback of trees through short and long term multi-year monitoring with anomaly detection
- Produce global maps at city scale of tree comfort indexes able to make alerts and help city managers
- Identify urban patterns likely to be favorable/unfavorable to tree well-being and compare them with Local Climate Zones [39], known urban patterns connected to local climate

The objectives, in terms of **remote sensing** and **machine learning**, can be summarized as follows:

- Physically consistent processing of heterogeneous data (internal tree parameters, VTA, images) to derive physiological parameters and their links between images
- Super-resolution of SENTINEL1 and SENTINEL 2 data to apply our processes at city scale
- Domain adaptation to evaluate the generalization to other cities.

b. Positioning in relation to the state of the art

Many studies have focused on analyzing the role of trees in improving the environment in urban areas (see for example [19,37,44]) and their benefits are today partly well understood. Concerning the consequences of stress factors on trees, the state of knowledge is not as complete. There have been studies related to the response of trees to external stresses in the forest environment [32], their reaction to drought [36], sudden climatic events [40] or more generally under climate change [2]. In an urban environment, though some studies exist on the adaptation of trees to permanent stress [4], to our knowledge, there are not yet physiological studies analyzing the conditions of well-being and senescence of trees in cities.

For the past few decades, remote sensing has been an important tool to measure the physiological state of plants on a large scale. However, inverting the signal data to derive physiological variables is a complicated step and a number of studies have tackled this task. Today, though it is possible to derive some vegetation indexes (the best known being the NDVI, Normalized Difference Vegetation Index) from spectral information, the estimation of biophysical variables is more tricky. Depending on the source of data, efficient approaches exist either to retrieve bio-geophysical properties [30,38,42,45] or biomass [5,29] using for example prior physical models (see [6,12,21]) but applications mainly concern agricultural or forest areas. This information is rarely at the scale of a single tree, due to the limited spatial resolution of the images. Recently, drones have enabled to assess higher resolutions and some studies have been designed for retrieving biophysical information from UAVs (see [10,11]). In an urban context, today the detection of trees and possibly species can be performed (see [25,28,33,41]) but as far as access to physiological information is concerned, there is still a gap that this project proposes to fill. Complementary to UAV (whose acquisition cost is high and whose regulations prevent regular monitoring in urban areas), access to free S1/S2 images is an interesting alternative for regular observation of the urban environment. However, as mentioned above, the associated spatial resolution (at best 10m) is limited and super-resolution techniques must be used [43]. Today mature techniques exist and can be applied, but when focusing on trees, the validity in terms of biophysical parameters computed from such images is limited despite being visually plausible. In this project, we will continue our first works **[46]** to develop super-resolution techniques able to reconstruct with consistent tree physiological parameters.

Finally, it should be noted that in the last ten years, spectacular progress in data analysis has been made thanks to artificial intelligence (AI) and deep neural networks [24], with significant gains in various image processing and earth observation tasks, using in particular convolutional neural networks [1]. Roughly the main idea consists in learning, from a stack of layers (i.e. an elementary transformation of the data with some parameters to train), some features from the input data. These features, also named *encoded* information, feed a new stack of layers (decoded part) whose goal is, from the encoded information, to learn the best combinations to estimate the output variables. Several teams are specialized in AI for earth observation, in partir IRISA and LETG. Different variants of neural networks, for time series **[34]**, heterogeneous data **[27]** or adapted to physical models have been developed **[8]** but tree physiology has not been studied yet under this angle.

As for research programs, up to now, many ambitious research projects have been funded to understand the role of trees inside cities and their influence in terms of urban heat island (see ANR DIAMS, ANR H2C, ANR ECOVILLE, ANR COOLTREES and then TIR4sTREEt) or of air quality (ANR sTREEt). Other projects have also been focused on the identification of tree species (ANR HYEP et VEGDUD), of a specific stress (hydric, temperature, …) and on the connection between trees and their ecosystem (UE-biodiversa UEBANMYCOSERVE). However, no project considers the stress in a global way despite the fact that in general, a combination of all these stresses (hydric, thermal, pollution, …) is responsible for sudden dieback. Furthermore, projects scarcely integrate comparison with field data collected by tree technicians, which is yet an essential feedback of the real state of the tree compared to remote data. Last but not least, few projects explore the application of local modeling strategies (e.g. canyon and neighborhood scale) at larger scales such as the city, which is achievable by combining in-situ, physical modeling and remote sensing data.

c. Methodology and risk management

Apart from a **coordination WP (WP0)**, to implement this project, we will focus on **data (WP1):** collecting existing ones, simulating and acquiring new data. Data collection and dissemination will be conducted under FAIR principles. Then, the **estimation of physiological variables from optic/radar informations** will be studied using machine learning on data acquired under **controlled conditions (WP2)** i.e. using as input tree physiological parameters measured on trees grown in greenhouses under monitored conditions [10] associated with spectral measurements on these trees, and their numerical counterpart in the optical and radar ranges using simulations from DART **[18]** and EMPRISE **[23]** respectively. The controlled condition analysis is more suitable to calibrate the set of methods before moving on to the twin experiment on real cities. The application in **real cities (WP3)** will require the design of innovative super-resolution of S1/S2 data to ensure continuous production (one map every 5 day). Finally, the **identification of stress factors** and the definition of **tree comfort indexes will be designed in WP4,** with the identification of urban patterns favorable/unfavorable to trees, in relation with their temporal history. Qualitative data based on VTA method (Visual Tree Assessment, [17]) will be used to assess qualitative information. Application in the **cities of Rennes and Toulouse with the generation of maps and alert tools** will finally be made in WP5. This is summarized in Figure 2 with a Gantt chart in Figure 5.

Note on ethical and regulatory considerations

No crucial ethical nor regulatory points emerge from this project. No personal information will be exploited. In the unlikely event that names are noted (e.g. persons responsible for the field measurement), the project will guarantee anonymity and that no individual data will be the subject of any study (only aggregated data). The project has no implication on issues of gender/minorities, … The ratio of male/female is exactly 0.5 (among the 22 people involved in this project, 11 are men/women) and among the five WPs, three are headed by women.

The project is gender-neutral since there is nothing specific that either promotes or denies inclusion. Partners will be sensitive to equally integrate male/female in this project (in particular when hiring new staff).

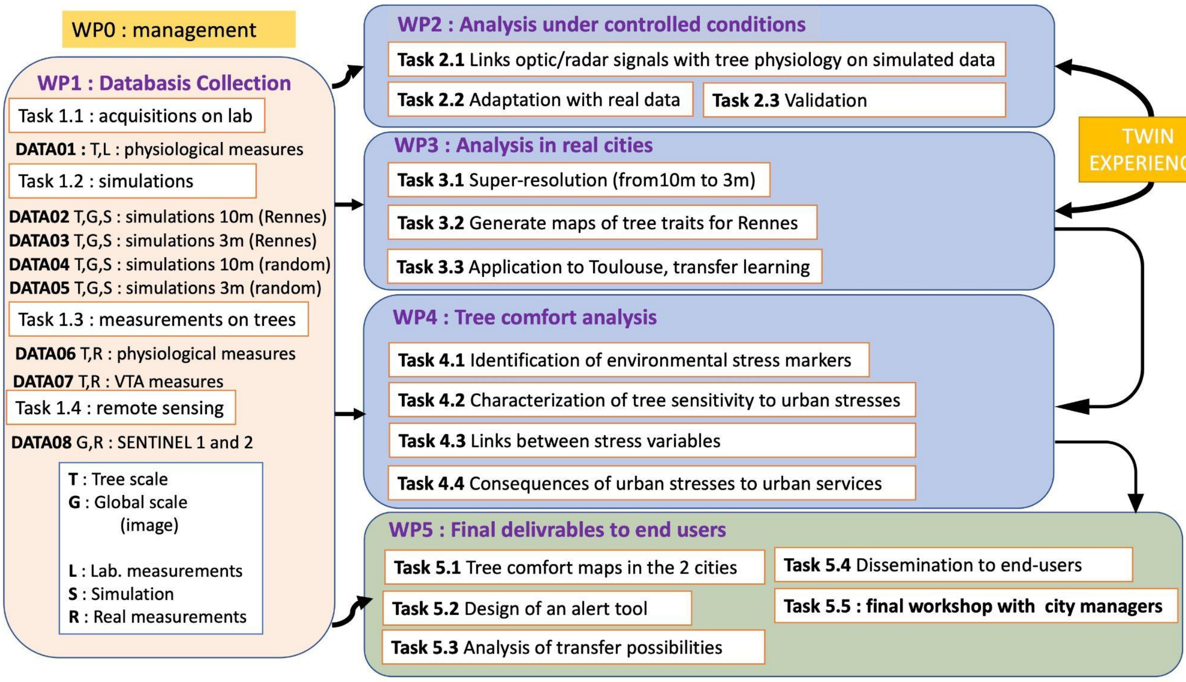

Figure 2: overall organization of the project in work packages.

WP0 : Project management (M1 - M48). **Leader** : **T. CORPETTI (LETG)** **Partners** : All

Objectives:

This management WP aims at monitoring the progress of the project and taking remedial action when required. This WP plans and coordinates bi-annual meetings, compiles all scientific and financial materials for reporting issues as required, and ensures information exchange within the project and the dissemination of results.

Description:

The project will be monitored by a steering group composed of the coordinator and the WP leaders. This group will also be responsible for the provision of all required reports. It will ensure smooth communication between the consortium, including the integration of early career scientists (PostDoc, PhD, master students) hired during the project. The primary management will also be through biannual meetings / workshops, to maintain contact between all participants. Smaller meetings will also be organized between sub-groups during the project.

Deliverables*:*

D0.1 : Consortium Agreement – **D0.2 :** Data plan management – **D0.3 :** Intermediate report – **D0.4 :** Final report

Milestone:

M0.1 Project meetings (at the begining and then at approximately 6 months intervals)

WP1 : Database collection (M 1 - M 24). **Leader** : **J. NABUCET (LETG) & D. LE THIEC (SILVA)** **Partners** : All

Objectives:

This WP collects all data and ensures internal dissemination (during the project) and open diffusion (in the end)

Description:

Four kinds of data will be used: measurements on trees in controlled conditions, simulations of optical and radar images, measurement on trees in real cities (physiological measurements, VTA) and remote sensing images.

Task 1.1 Acquisition under controlled conditions

The objective is to implement scenarios under controlled hydric and thermal conditions of the plant, following an experimental plan constrained by the conditions of the urban environment. Two tree species will be studied: the plane tree, a species very present in urban environments because of its great capacity of adaptation, and the pedunculate oak, more restrictive in its tolerance to stress. This experimentation includes measurements presented in Table 1 to ensure a hydric and spectral ecophysiological follow-up of the plant. The cuttings will be grown in two fully automated greenhouses at INRAe-Nancy (SILVA partner, Figure 1). The environmental conditions are controlled and the daily hydric, thermal and spectral monitoring of the plant are ensured by an autonomous robot. The variables measured in the different scenarios will be realized at the leaf and plant scale to allow the scaling up for WP2. They constitute the dataset named **DATA01** in Figure 2.

Task 1.2 Optical and radar image simulations

Optical images will be simulated from the 3D canopy radiative transfer code named DART [18], embedding the leaf radiative transfer code, PROSPECT-D **[14]**, while radar images will be simulated with the scene model of the EMPRISE framework **[23]**. Both codes require as inputs the parameterization of 3D mock-ups which aim to represent the scene that is observed by a single or several pixels inside a remote sensing image. Their design necessitates assigning the (i) electromagnetic and (ii) geometrical properties of the modeled 3D elements (i.e. tree, building with wall/roof) and ground topography (i.e. road, grass). As much as possible, these properties will be shared or selected in a coherent way for optical and radar simulations to ensure future comparisons and synergies. Mock-up and simulation examples are given in Figure 3 and studied variables in Table 1. There are two different objectives for data simulation. First, we aim to simulate images as accurately as possible with respect to reality (controlled conditions or real city) for validation purposes. Such data will be simulated at 10m (**DATA02**) and 3m (**DATA03**) resolutions. Second, we aim at generating a large number of plausible (but not necessarily related to a real city) situations under various Local Climate Zones (LCZ), with a large range of input parameters. Such datasets, built at 10m (**DATA04**) and 3m (**DATA05**), can provide a large number of simulations under various conditions, and be useful for the training and inversion tasks (see WP2 and WP3).

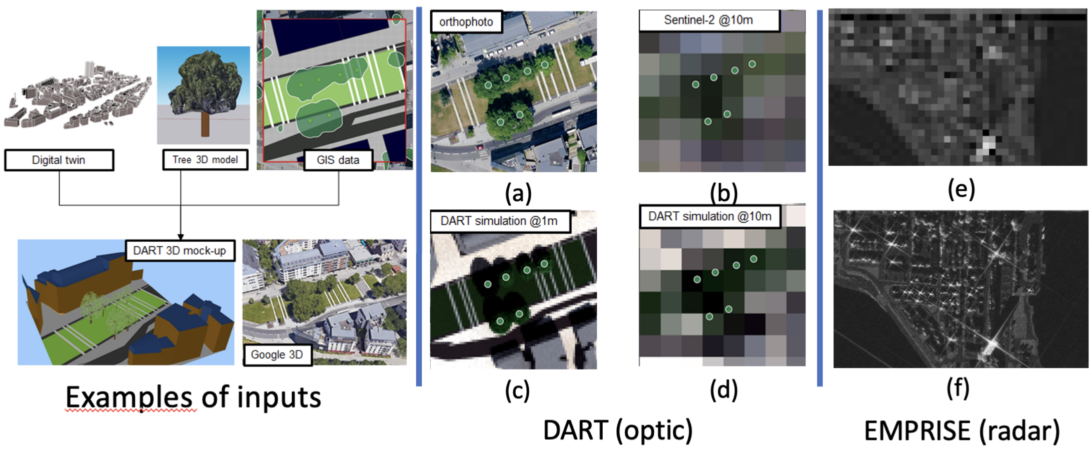

Figure 3: Examples of use of DART and EMPRISE models. Left: selection of inputs to build the DART 3D mock-up used to simulate (c) 1m and (d) 10m S2 images that can be compared to (a) orthophoto and (b) real S2 image, Right: EMPRISEsimulation over an urban harbor area at (e) 10m and (f) 20cm resolution.

Task 1.3 On field measurements

In situ measurements will be performed on the two tree species considered in task 1.1 along an urbanization gradient from the center to the periphery of the two study sites (Rennes and Toulouse). Four stations of 10 trees/species will be sampled according to the urban morphology, the degree of soil sealing and the intensity constraints of the Urban Heat Island. For each individual, 2 leaves per cardinal face of the tree will be taken at a height between 6m and 8m and then analyzed. Depending on the nature of the variable to be measured, the samples will be processed on site (measurement of dualex, fresh weight, gas exchanges...) and the other analyses will be carried out in the laboratory with appropriate conditioning of the biological samples (liquid nitrogen, ice,...). All the variables in Table 1 will be carried out to ensure comparison with the data obtained in task 1.1 and the simulated data of task 1.2 (the samples can be frozen for the duration of the project for further analysis if needed). This is the dataset **DATA06**. At the scale of each individual, a visual analysis of the tree will be carried out by the partner AUBEPINE using VTA technique [17] in order to specifically study the expression of stress & comfort of trees. This dataset, named **DATA07**, will help us in WP4 to derive tree comfort maps and their links with urban patterns.

Task 1.4 Remote Sensing data

The SENTINEL-1 (with C-band synthetic aperture radar imaging) and SENTINEL-2 (with optical of 13 spectral bands) data used in this project are provided with atmospheric corrections by the THEIA Pole's continental surface data hub (https://www.theia-land.fr/). As the two satellites do not have the same optical properties and acquisition orbits, a correction of the geometry of the data by coregistration will be carried out using the GeFolki **[3]** software developed by ONERA. In order to spectrally validate the products of the super-resolution produced by WP2, specific campaigns of spectro-radiometric measurements (ASD Fieldspecpro4) will be performed. These measurements will be collected on different types of materials present on the territory of the Rennes (mineral and vegetal surfaces). Depending on the quality of the evaluation of the products from WP2 on super-resolution, we may eventually resort to the use of PlanetScope data with a spatial resolution of 3m and a spectral resolution close to S2. Finally, we will use existing tools for estimating / simulating air temperatures **[16]** to access air temperature maps. These spatial data constitute the dataset **DATA08**.

Deliverables

D1.1 Open databasis of simulations using DART and EMPRISE at 10m and 3m (from **DATA02 to DATA05**)

D1.2 Open databasis on physiological tree measurements under controlled/real conditions (**DATA01 & DATA06**)

D1.3 Open databasis on tree comfort using VTA/AVA (**DATA07**)

D1.4 Databasis of processed SENTINEL1/2 images and air temperatures on Rennes and Toulouse (**DATA08**)

Milestones

M1.1 All data required for the rest of the project **M1.2** Internal website for sharing data

WP2 : Analysis in controlled condition (M 1 - M 24). **Leader** : **T. CORPETTI (LETG)**

Partners : LETG, SILVA, ONERA, IRISA

Objectives: The thematic objectives are to establish links between optical/radar data and physiological variables. The methodological objectives are to develop artificial intelligence methods able to deal with heterogeneous data and to ensure a physical consistency in the estimation. The methods will be calibrated by extracting information on pixels associated with trees of the two species on images issued from simulations (**DATA05**, cf for example Figure 3 (c-f)) and measurements under a controlled environment (**DATA01**).

Description:

When one desires to develop a learning model reproducing physical behaviors (i.e. physiology here), an interesting solution consists in pre-training models on simulated data (simulation has the advantage of defining a large number of data under various contexts and thus improving the genericity of the models) and refining them on real ones. These two aspects are defined in this WP

Task 2.1 Designing fusion networks to link optical / radar signal with physiological parameters on simulated data

In this task, we plan to design three neural networks capable of estimating physiological variables. The three variants concern the input data: we will develop a network taking spectral values in the optical domain, another in the radar domain and finally, a specific network that will take these two data simultaneously. These networks will be trained on data issued from WP1 and acquired under simulated conditions (**DATA05**). Concerning the third neural network, we will develop particular architectures (fusion networks **[27,35]**) which consist in processing in a parallel way the information coming from each source and to combine the information once encoded (and not from the beginning). It has been proven that such approaches are generally more efficient. We also plan in the cost function (allowing to drive the learning process towards a reliable solution) to put physical constraints from plant growth information (i.e. prevent from impossible values / behaviors).

Task 2.2 Adapting the network to real situations

In a second step we aim to adapt the three pre-trained networks on simulated data to real data (**DATA01**). Several strategies will be designed : i) fine tuning the entire network (i.e. re-estimate all the parameters); ii) fine tuning the entire network with different weights (i.e. the first layers which correspond to the encoding of the data are only slightly modified, and the last layers which correspond to the adaptation to the output are modified with more weights) and iii) freeze the entire network and add in the end several layers to estimate. These three strategies are the main alternatives when using pre-trained models and will be compared. Lastly, depending on the quality of the results, some adaptation strategies able to transform with consistency real data to network trained on simulated ones, will be studied [7].

Task 2.3 Validation / interpretation

Of course, during the whole process, we will exchange between the teams to evaluate / validate / adapt the techniques on dataset **DATA03**. This one will be based on classical quantitative criteria (estimation error) but also on physical criteria (temporal evolution consistency, interaction between variables).

Deliverables

D2.1 Three variants of neural networks for the identification of physiological variables depending on inputs

Milestones

M2.1 Estimators of physiological variables from optic and radar observations

WP3 : Analysis in real cities (M 6 - M 36). **Leader** : **K. ADELINE (ONERA)** **Partners** : ONERA, *LETG, IRISA*

Objectives: From WP1 and WP2, mapping of tree physiological variables from in situ, simulated and remote sensing data by means of super-resolution, physically-based inversion and transfer learning methods

Description:

This work-package aims at 1) preparing the optical-radar remote sensing dataset at the tree scale (3m-5m) and 2) target a more accurate estimation of selected tree physiological variables by applying algorithms of WP2.

Task 3.1 Spatial downscaling of satellite imagery by developing super-resolution methods

As the objective is to use the freely available S1-S2 data and their spatial resolution is at best 10m (too limited to work at the tree scale since pixels are “mixed”, see Figure 4(b)), we plan to target the tree scale (3-5m, close to “pure pixels”) by using deep learning super-resolution methods. In particular, we will start from an existing approach that especially focuses on vegetation and tree reconstruction **[46]**. Networks will be trained between simulated databases **DATA04** (10m) and **DATA05** (3m) from WP1. Though methodological literature can be found for S2 [43], nothing exists for S1 and this constitutes a challenge to be tackled. To this end, fusion networks (also mentioned in task 2.1) will be adapted to super resolution. The trained super-resolution methods will be validated with **DATA02** and **DATA03** datasets. Quality will be assessed with common and perceptual metrics (mean square error, spectral angle mapper, peak signal to noise ratio, structural similarity, mean opinion score).

Task 3.2 Generate maps of tree physiological variables for the reference city

The estimation of these variables will use a physically-based inversion method based on previous work performed for forest ecosystems and imaging spectroscopy data **[31]**, as no work has been done so far for urban environments for S1/S2 sensors (due to the “mixed pixels” issue). This method relies on the training of machine learning methods between optic/radar signals and tree traits from **DATA04** and **DATA05** simulated data. Based on a recent sensitivity analysis **[26]**, only leaf area density and leaf chlorophylls content can be retrieved from S2 at 10m. Same analysis will be carried out for S1. Their application on S1/S2 images (**DATA08**) on which super-resolution (from the task 3.1) is performed will then be performed. The outputs will be maps of tree physiological variables for the considered Sentinel time series. Validation will be performed with *in situ* vegetation traits measured close to the sensor overpasses with classic accuracy metrics. These estimations will be limited to the selected tree species of the project thanks to the tree plantation designs from the green space departments of Rennes and Toulouse cities[2]. First optic inversion results are visible in Figure 4(e) and will be extended to the radar one. In the last step, multi-modal synergies will be explored such as the addition of inversion constraints.

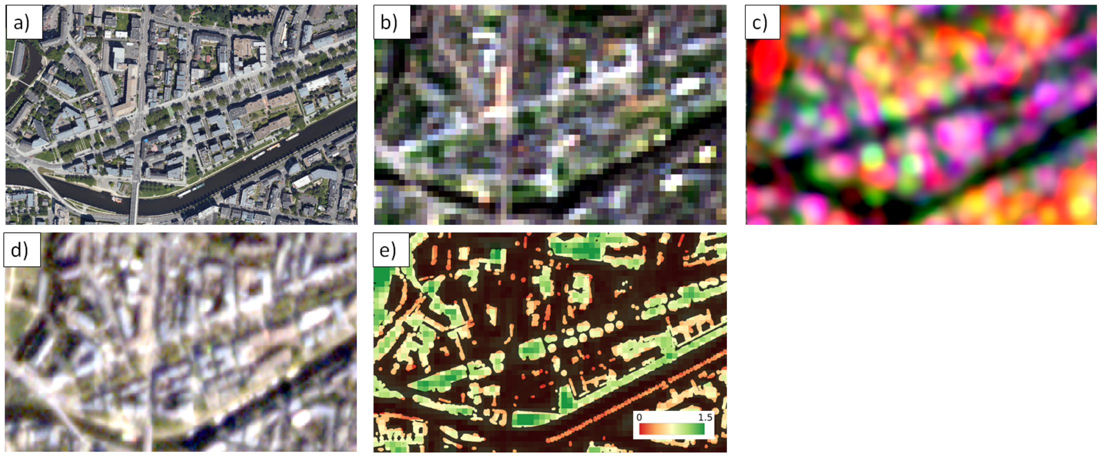

Figure 4. **Remote sensing data and first product over a subarea of Rennes**: a) 1m orthophoto, b) RGB composite 10m S2 image, c) VV ascending/VH ascending/VH descending composite 10m S1 image, d) 3m super-resolution product, e) 10m leaf area density [m2.m-3] estimated from inversion with the partial least square regression **[26]** (non vegetated areas masked in black).

Task 3.3 Use of transfer learning methods for multi-scale and multi-city application

From the conclusions of previous tasks, the most relevant key remote sensing and key physiologic parameters will be defined, as well as the most efficient regressions between these last two. The first goal will be to use these regressions for the inversion process in task 3.2 and to optimize them compared to the previous machine learning achieved performances or eventually evaluate how to combine all methods. This is part of the multi-scale transfer learning from WP2 to WP3 work. The second goal will be to assess the transferability of the best inversion method tested on the reference city in task 3.2 to the second one and target the robustness in terms of city structure synergies for similar urban patterns and tree species but in different climate contexts.

Deliverables

D3.1 Super-resolution training model parameterization (task 3.1), best inversion method parameterization (task 3.2) and transfer learning model parameterization (task 3.3)

D3.2 Downscaled Sentinel images (task 3.1) and maps of tree traits for Rennes and Toulouse (task 3.2 and 3.3)

[2] see for example https://data.rennesmetropole.fr/explore/dataset/vegetation_fine_2017/information/

Milestones

M3.1 Generated super resolution of S1/S2 and maps of physiological parameters (as entries of WP4)

M3.2 Uncertainty analysis of our products

WP4 : Tree comfort analysis (Month 24 - Month 42). **Leader** : **Cécile SULMON (ECOBIO)**

Partners : *ECOBIO, LETG, SILVA, ONERA, AUBEPINE*

Objectives:

From results of WP2 and WP3, this WP aims at identifying key urban patterns that generate stress for tree vegetation, ecophysiology and sensitivity/tolerance markers. It also aims at characterizing links between ecophysiological markers and remote sensing tree traits to select relevant variables for end users and characterize the consequences of urban patterns on tree services. Prototypes will be generated on Rennes data (easier to go on field for the WP leader) and the reproducibility on Toulouse will be analyzed in WP5.

Description:

Task 4.1 Identification of environmental stress markers in tree species

Data related to tree ecophysiological state quantified under stress exposure in controlled greenhouse conditions (**DATA01**) will be analyzed in order to identify relevant variables indicating stress in plants. For these variables, the pattern of response to the different stress tested will be compared in order to classify them into generic and specific (e.g. either thermic or hydric) stress markers. Stress markers will be then analyzed for their responses to *in situ* urban contexts (using field data, **DATA06**) where abiotic environmental parameters will have been characterized, in order to validate these markers for field studies. In addition, the calibration of marker responses with the intensity and type of stress both in the field and controlled conditions will be coupled with S2 images (**DATA08**) to establish a link between urban patterns and risk for tree vegetation.

Task 4.2 Characterization of tree sensitivity or tolerance/resilience to urban-related stresses

Based on both controlled conditions and field data, stress response patterns of trees will be analyzed by taking into account temporal scale. Variables related to the different tree biological functions such as growth, stress responses, *in planta* water management, primary metabolism and carbon allocation will be analyzed individually and in association (e.g. clustering analysis, correlation tests) in order to characterize different patterns of responses (sensitivity *vs* tolerance/resilience) and identify physiological trade-offs between functions. The project using two tree species and different populations (several sites per city, two cities) for each species, this will allow to estimate inter and intraspecies variability of stress response patterns. Moreover, index of tree visual assessment (**DATA07**) will be used as an additional variable to determine the impact of tree health on stress sensitivity. Finally, exploration of temporal response profiles of trees from weeks to interannual timesteps will allow to identify early markers of sensitivity and senescence, and to determine whether the responses of some variables to stress one year can at least partly explain tree responses observed the following years. Temporal series of tree traits and optic/radar images from WP3 can be used and combined with phenological anomaly detection methods **[9,15]**.

Task 4.3 Characterizing the links between the different types of variables

Tasks 4.1 and 4.2 will identify relevant stress-related variables from different acquisition methods. As described in [13] about trait concept in ecology, among these variables, some of them will represent hard traits due to the difficulty to acquire the data (cost, time-consuming complexity) whereas others will be considered as soft traits (easy to measure). As soft traits may represent a response related to the expression of hard traits, the links between hard (variables needing lab measurements) and soft traits (among which remote sensing variables) will be investigated through multivariate and regression analysis.

Task 4.4 Analyzing the consequences of urban stresses on urban tree services

As datasets **DATA01** and **DATA06** embed variables related to primary production (e.g. leaf surface or mass, chlorophyll content, photosynthesis activity) and evapotranspiration (e.g. leaf humidity, water usage efficiency), the effects of urban stress conditions identified in the field (**DATA06**) will thus be tested on variables acquired under controlled conditions (**DATA01**) in order to evaluate the consequences of urban stress on key tree services associated with the questions of urban heat island and carbon sequestration.

Deliverables

D4.1 Identification of stress markers and stress sensitivity/tolerance patterns

D4.2 Characterization of the effects of tree characteristics (species, heath state) on their responses to stress

D4.3 Identification of relevant soft variables with physiological mechanistic meaning

Milestones

M4.1 Validation of stress markers, characterization of urban patterns and temporal history likely to stress trees

M4.2 Validation of relevant variables in the field to develop the deliverables for end users

WP5 : Final deliverables to end users (Month 30 - Month 48). **Leader** : **Sabine EL MOUALY (AUBEPINE)**

Partners : AUBEPINE, LETG, SILVA, ONERA

Objectives:

The objectives of this final WP are, using results of WP4, to generate comfort maps of trees for Rennes and to evaluate the reproducibility of the process on Toulouse. Results will be integrated in GIS softwares to be transferred to city planners. All the processes will be analyzed in order to favor a transfer and possibly optimized. Finally, this WP will concentrate on communication and diffusion of our results.

Description:

Task 5.1 Generation of tree comfort maps in Rennes and Toulouse

From the results of WP4 (M4.1), comfort index maps of the two selected species (plane trees and pedunculate oak) will be generated for the city of Rennes and Toulouse using super-resolved S2 images (M3.1). Apart from classical validation criteria, results will be analyzed by applying the methods on past images where it is known that there have been modifications on trees (before and after the summer of 2022 in particular). Reproducibility will also be assessed by applying methods of WP4 (mainly learned on Rennes's data) on Toulouse.

Task 5.2 Design of an alert tool

Again from the results of WP4 (M4.1) related to links between temporal history and stress, alert maps can be designed by identifying the formation of critical temporal patterns. Evaluation will also be performed on past image time series and reproducibility will also be assessed by applying methods on Toulouse.

Task 5.3 Analysis of transfer possibilities

Through an iterative process proven in the company, the engineers of AUBEPINE will evaluate the obstacles to the transfer of the solutions on the market of the follow-up and the management of the tree heritage. Beyond the reliability of the results, the aim will be to observe the benefit/cost ratios for the user and the accessibility of the tools. For this purpose, each potential result obtained from the health status of trees will be the subject of a summary sheet including the necessary source data, the necessary equipment and its cost, the skills required to reproduce the work, and for which uses. AUBEPINE will submit these results and analyses to a network of communities and tree diagnosis professionals in order to approve the possible economic models and the added value of MONI-TREE's results. We also plan to exchange with international networks that are interested in the issue of urban sustainability and more specifically in the preservation and enrichment of urban woodlands. For example, the metropolis of Montreal and the Soverdi structure which manages the Canopé Action Plan, or the QTRA Network (Quantify Tree Risk Assessment), also the development and sales companies of professional equipment such as Rinntech or IML in Germany. Feedback will be made to the whole team to confirm the TRL level and thus the possibility of innovation transfer, to propose adjustments or additional research operations.

Task 5.4 Dissemination to end-users

Two main software will be experimented as potential receivers of innovations for end-user we collaborate with (Rennes Metropole and Toulouse Metropole in particular). The first one is developed by AUBEPINE and is dedicated to the monitoring and management of trees (BOOM software, www.boom.coop). In this software, the visual analysis of the tree is still completed manually. The task of the developers will be to evaluate the possibility of integrating the tools developed by MONI-TREE to make them available to users. The second is the Qgis software. It will be necessary to understand whether the development of a "tree health" plug-in is possible, either to access the calculation tools, or to access the existing data, as is the case with the GeoBretagne plug-in[3].

Task 5.5 Final workshop with city managers

Apart from dissemination through the usual channels of the peer-reviewed scientific press, articles in popular and industry publications, the dissemination plan also includes communications towards end-users (e.g., city planners, the letter of the SFA, Lien Horticole, or the Pollutec exhibition, the magazine "Construction 21", etc). The organization of a final workshop with invited international researchers will be considered during the last year of the project. Apart from these pure scientific aspects, we also plan to locally inform society about our results in general conferences (fête de la science, café des sciences, journées en jeune public, …).

Deliverables

D5.1 SWOT synthesis with end-users feedbacks

D5.2 Development of additional functionalities on the BOOM software

D.5.2 Organization of a the final workshop, participation in trade fairs (Pollutec, Salon des Maires de France)

Milestones

M5.1 Validation of potential uses - **M5.2** Innovation transfer on the BOOM software

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Risks, and associated contingency plans

In general risks are small given that groups of the consortium have already multidisciplinary collaboration experiences (in particular LETG with ONERA, ECOBIO and AUBEPINE). Risks for each work package have been identified and mitigation actions have been proposed and integrated to the workplan. They are listed below:

WP	Risk	Probability	Severity	*Mitigation Plan*
1	Inability to deliver data	Low (all data and measurement tools are available in respective labs)	High	Work on existing synthetic data instead
2	Unability to reuse deep networks between partners	Low (several computer scientists of the consortium are used with transfer)	High	Work on existing alternative techniques (older and less efficient)
3	Super-resolution does not have the desired quality	Medium (though super resolution is known to be a tricky task, we have experience on this)	Medium	Use PLANET data (3m resolution) or state-of-the-art techniques (in the optic domain only) and TerraSarX radar data (3m resolution, available in ONERA)
4	We do not identify significant markers of stress	Low (It is reasonable to assume that stress variables identified in Table 1 are consistent)	Medium	At least simple regressions between temperature, hydrology and VTA can be explored
5	Too High complexity of our algorithms	Low (we have a good idea of the potential complexity of our processes)	Medium	Work together to simplify our process and get a relevant ratio between quality and complexity. Weave a partnership with local companies able to host our solutions (as Alkante, a SME in Rennes)

[3] see https://cms.geobretagne.fr/content/plugin-geobretagne-pour-qgis

Organization over 4 years, Gantt chart

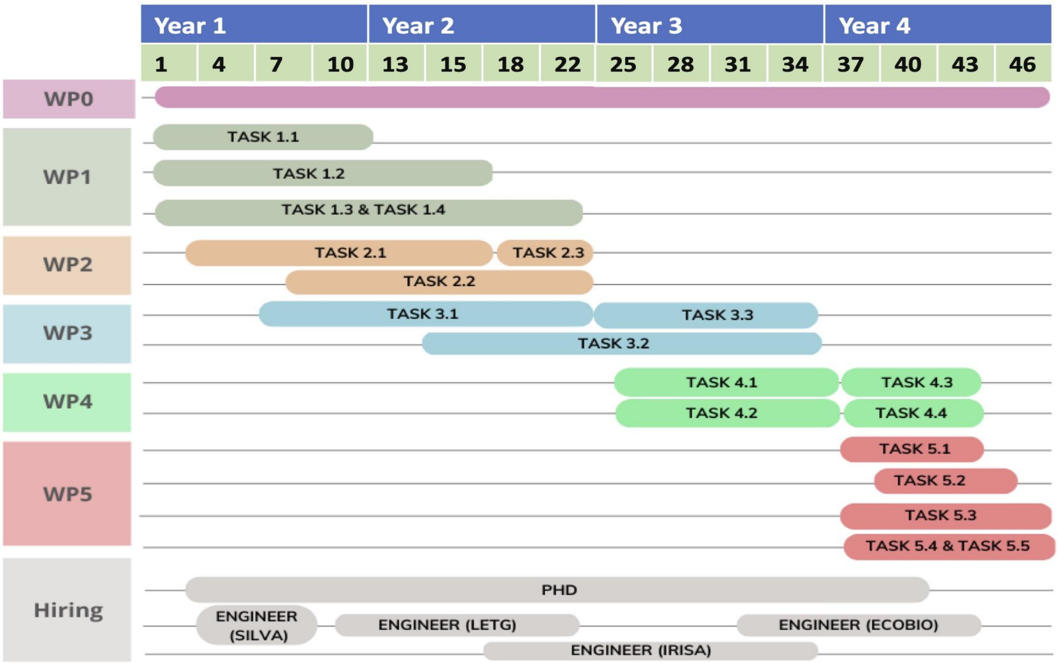

Figure 5: GANTT Chart of MONI-TREE

II. Organization and implementation

a. Scientific coordinator and its consortium / team

MONI-TREE project is coordinated by Thomas Corpetti, a senior researcher with CNRS in LETG lab (UMR 6554). His main research topics concern data science and machine learning for earth observation. For more than 15 years, he has conducted all his research projects in an interdisciplinary framework where his work aims at coupling data science with physical data/models to improve the understanding of the environment (with applications in agriculture, vegetation, pollution or urban temperature). He will be involved in all WP with more scientific contributions to the ones related to machine learning (WP2-WP3-WP4).

- **LETG** is a lab from CNRS-InEE generally working on the impacts, in terms of climate, risk and soil quality, of human activities (urban occupation, intense agriculture, deforestation, ...) on earth. To this end, remote sensing is a privileged source of observation and these last years, the exploitation of S1/S2 data has drastically changed the way LETG designs its processes and analyses. The most important efforts in recent years have been in the analysis of vegetation in urban areas. LETG is equipped with a drone platform and Jean Nabucet, engineer in this laboratory, is conducting all his research on the role of urban vegetation and will be mainly involved in the tasks of measurement/data collection (WP1) and measure and analysis of physiological parameters from them (WP2-WP3-WP4). He is in particular in charge of SNO Observil (https://sno-observil.fr/), a multi-institutional platform dedicated to the observation of the urban environment.
- **ONERA** is a EPIC research center whose mission is to carry out research activities in the aeronautics, space, and defense sectors. MONI-TREE project will benefit from the combined expertise of 3 departments (DOTA dedicated to the optical domain, DEMR to the electromagnetism and radar domain and DTIS to the information processing and systems) to lead multi-modal, multi-scale and multi-temporal work from remote sensing and modeled data. Karine Adeline and Laure Roupioz work on the physics of measurement, modeling, and estimation of surface properties (bio-physical-chemical and structural variables, temperature, emissivity) of both manmade materials and tree vegetation in urban environments from passive optical remote sensing (respectively, they are co-leading with LETG one thesis on tree health monitoring from S2 [26] on urban air temperature estimation

[16]). Etienne Everaere works on the radar simulation of large scenes with asymptotic electromagnetic models as well as the modelization of vegetation. In the Image Vision leArning unit (DTIS-IVA), Elise Colin conducts research on AI and unconventional Earth Observation data and belongs to the AI4GEO (https://www.ai4geo.eu) consortium. They will contribute mainly in WP1-WP2-WP3.

- **SILVA**, is a joint research unit (UMR 1434 AgroParisTech, INRAE, and Lorraine University), carries out multidisciplinary research on wood, trees and forest ecosystems. The missions and scientific objectives of UMR SILVA are twofold; on the one hand, to improve the fundamental understanding of the functioning of trees and their ecosystems and on the other hand to respond to the questions and expectations expressed by society and professionals on the impacts of the evolution of environmental conditions (climate change, resources in water, biodiversity, sustainability, land use) and the emergence of new needs and challenges (bioeconomy). Silva is internationally recognised for its work and Didier Le Thiec and Dorine Desalme will mainly contribute in all WPs for questions related to plant physiology (main investment in WP, WP2, WP4).
- **ECOBIO** is a joint research unit (UMR 6553, CNRS-University of Rennes) that carries out multidisciplinary research in the field of ecology from evolutive ecology to functional and landscape ecology. ECOBIO analyzes the dynamics of biodiversity and ecosystem functioning in the face of ongoing global changes with the aim of sustainable development and maintenance or development of ecosystem services. ECOBIO integrates several technical platforms among which the Experimental Ecology (Ecolex), the Ecochimie (Ecochim), and the Molecular Ecology (PEM) platforms that have the equipment necessary for the planned analyses in particular for ecophysiological and molecular measurements. ECOBIO will be involved in various WP but mainly in WP4 for questions related to plant ecophysiology (Cecile Sulmon and Gwenola Gouesbet), metabolic analysis (Nathalie Le Bris, Marion Chorin) and plant samples (Thierry Fontaine-Breton, Rémi Bodiguel, Emmanuel Le Rouzic)
- **IRISA** is a joint research unit (UMR 6074) supported by universities (including Univ. Bretagne Sud), public higher education institutions, CNRS and INRIA. The OBELIX team (observation of the environment by complex imagery) conducts its research in machine learning and computer vision for earth-observation. It is nationally and internationally recognized for its work. Charlotte Pelletier is a researcher specialized in time series analysis and super-resolution. She will contribute in all WP where machine learning is present, and mainly to WP3.
- **AUBEPINE** is a tree specialist engineering office. Created in 1999, this cooperative company provides counsel to both public and private sector on managing and preserving trees. Its Engineers and researchers have a long experience on tree diagnosis in multiple situations. The challenges and questions about trees they face daily give them a collective expertise to provide solutions for preserving tree heritage and considering their futur. Aubepine's members are referent trainers for professionals, communities about Visual Trees Assessment. For 5 years, Aubepine has been working with LETG to développ and intégrate 3D technologies in expertise practices. AUBEPINE, through Sabine El Moualy, Xavier Le Bris and Emmanuel Eigenschenck, will contribute mainly in WP4 for tree stress identification and in WP5 devoted to applications, dissemination, transfer. In addition, 2 technicians (Claire Genton, Nicolas D'Authier) will contribute to VTA measures in WP1.

Implication of the scientific coordinator and partner'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
Thomas Corpetti	16	ANR (580 k€)	HIATUS	A. Le Bris (IGN)	2019 - 2023
Thomas Corpetti	6	ANR France - Turkey (190 k€)	MULTISCALE	L. Chapel (IRISA)	2019 - 2023
Thomas Corpetti	8	Labex CominLabs (250 k€)	DynaLearn	N. Courty (IRISA)	2020 - 2023
Jean Nabucet	10	Rennes Métropole, 230k€	ASTRESS	J. Nabucet (LETG)	2021 - 2024
Didier Le Thiec	6	Labex Arbre ANR (50k€)	NSICC	D. Le Thiec (INRAE)	2022 - 2024
Didier Le Thiec	3	Labex Arbre ANR (60k€)	DONUTS	D. Le Thiec (INRAE)	2023 - 2024
Karine Adeline	23	ANR JCJC (321 k€)	CANOP	K. Adeline (ONERA)	2023 - 2026
Cécile Sulmon	4	Rennes Métropole, 230k€	ASTRESS	J. Nabucet (LETG)	2021 - 2024
Cécile Sulmon	4	EC2CO, CNRS (25 k€)	RESI-ADAPT	C. Sulmon (ECOBIO)	2023
Cécile Sulmon	8	ECOPHYTO, OFB (465k€)	EXPOTROPHIQ	C. Sulmon (ECOBIO)	2023 - 2025
Charlotte Pelletier	4	GDR ISIS (7 k€)	SESURE	C. Pelletier (IRISA) / N. Audebert (CNAM)	2021 - 2023
Charlotte Pelletier	4	PNTS (9 k€)	PASTEIS	C. Pelletier (IRISA) / S. Valero (CESBIO)	2023 - 2024

b. Implemented and requested resources to reach the objectives

Partenaire 1 : LETG

Staff expenses: 258 592 € (complete costs): Costs for T. Corpetti (18 pers.month) and J. Nabucet (6pers. month), Justifications in II.a section.

Non-Permanent staff without ANR funding: 28 435 € : Participation of an engineer for 6 months to help during field campaign (WP1 and WP4).

Non-permanent staff with ANR funding: 174 518 €: The project plans to hire one PhD (ONERA / LETG) on topics related to WP1 (dat acquisition/simulation) and WP3 (application in real cities), one engineer (12 months, LETG) on machine learning tasks in WP2 for links between physiological variables and optic/radar signals. They will be supervised by T. Corpetti and J. Nabucet.

Instrument and material costs: 5 000€: Computer with GPU card for deep neural networks and machine learning (mainly used in WP2 and slightly in WP4)

Outsourcing / subcontracting: 10 000€: Academic publication fees (journals, conferences)

Overheads costs: 9 000€: Final meeting & international conferences (6 k€), intern project meetings (3 000€)

Partenaire n°2 : ONERA (-DOTA, -DEMR, -DTIS)

Staff expenses: 181 917 € (complete costs): This corresponds to a total of 15.8 pers.month including the 4 permanent researchers for the work dedicated to WP1, WP2, WP3, WP4 and WP5 and the co-supervision of the PhD student with LETG dedicated to the work of WP1 and WP3 (more justifications in II.a section)

Outsourcing / subcontracting: 6000 €: Cost for 2-3 publications in high impact factor journals such as Remote Sensing of Environment, including the valorization of the PhD student work realized on 3D modelling, radiative transfer simulations, inversion and remote sensing, and optical-radar synergies.

Overheads costs: 2500 €: Cost for travel expenses of 4 permanent researchers during annual project meetings and eventually participation to new field data collection on Rennes/Toulouse.

Partenaire 3 : SILVA

Staff expenses: 129 853 € (complete costs): This corresponds to the participation of D. Le Thiec (7 pers.month), D. Desalme (6 pers.month) and Cyril Buré (3 pers.month, technician) in all WPs for questions related to plant physiology (main investment in WP1 and WP2).

Non-permanent staff with ANR funding: 25 648 €: The project plans to hire one engineer (6 months) and one Master 2 student (6 months) for physiological plant measurements, mainly in WP1.

Instrument and material costs: 20 000 €: Materials for field sampling, consumables for robot in greenhouses, consumables for ecophysiological measurements in greenhouses and in cities.

Outsourcing / subcontracting: 10 000 €: Metabolites analysis and other analyses (Platform Silvatech INRAE Nancy), publication fees (journals, conferences)

Overheads costs: 10 000 €: cost for travel expenses to field campaign on Rennes/Toulouse, Intern project meetings (2 500€)

Partenaire n°4 : ECOBIO

Staff expenses: 80 100,00 € (complete costs): Costs for C. Sulmon (6 pers.month); G. Gouesbet (4 pers.month), N. Le Bris (1 pers.month) ; M. Chorin (1 pers.month), T. Fontaine (2 pers.month) & R. Bodiguel (1 pers.month). Justifications in II.a section.

Non-Permanent staff without ANR funding: 2 500 € : Ecolex platform staff: E Le Rouzic 2 500 € (1 pers.month)

Non-permanent staff with ANR funding: 51 900€: We plan to hire one engineer (12 pers.month, 48 000€), on plant culture sampling and treatments (from morphological traits to metabolic and molecular traits, WP4) and one student scholarship (6 months, 3 900€), on measurements of ecophysiological variables (WP1)

Instrument and material costs: 14 000€: Materials for field sampling: 2 000€, consumables for ecophysiological measurements and molecular biology: 12 000€

Outsourcing / subcontracting: 16 500€: Metabolomic analysis: 8 000 € (analyses conducted by Ecochim platform of Ecobio and submitted to internal pricing), Publication fees (journals, conferences) : 6 000€, agreement of consortium fees : 2500€[4]

Overheads costs: 5 500€: Field campaigns, missions (3 000 €) & intern project meetings: 2 500€

Partenaire 5 : IRISA

Staff expenses: 36 681 € (complete costs): This corresponds to the participation of C. Pelletier (5 pers.month) in all WPs for questions related to machine and deep learning (main investment in WP3).

Non-permanent staff with ANR funding: 74 477 €: The project plans to hire one research engineer for 18 months, especially devoted to the optical and radar super resolution task in WP3 since this part is the most challenging from artificial intelligence point of view.

Instrument and material costs: 2 500€: Computer for the engineer adapted to machine learning tasks

Outsourcing / subcontracting: 6 000€: Publication fees (journals, conferences) : 6 000€

Overheads costs: 2 500€: Intern project meetings (2 500€)

Partenaire 6 : AUBEPINE

Staff expenses: 93 584 € (complete costs): This amount corresponds to the engineers (S. El Moualy, X. Le Bris E. Eigenschenck, 17 pers.month in total) who will be mobilized for tree stress identification (WP4), generation of global maps and transfer technology (WP5). In addition, 2 technicians (12,5 pers.month) will be devoted to VTA surveys on trees in the cities of Rennes and Toulouse (WP1) help with the organization of the final workshop (WP5).

Instrument and material costs: 6 500€: Field equipment is required for the VTA experiments (1 resistograph : 4000 €, 2 dendrometers: 1000 €, 2 field tablets: 1000€).

Requested means by item of expenditure and by partner

	Partner 1 LETG	Partner 2 ONERA	Partner 3 SILVA	Partner 4 ECOBIO	Partner 5 IRISA	Partner 6 AUBEPINE
Staff expenses	461 545 €	181 917 €	155 501 €	134 500 €	111 158 €	93 583 €
Instruments and material costs	5 000 €	0 €	20 000 €	14 000 €	2 500 €	6 500 €
Building and ground costs	0 €	0 €	0 €	0 €	0 €	0 €
Outsourcing / subcontracting	10 000 €	6 000 €	10 000 €	16 500 €	6 000 €	0 €
Overheads costs (including missions expenses, general and administrative costs & other operating expenses	9 000 €	2 500 €	10 000 €	5 500 €	2 500 €	0 €
Administrative management & structure costs**	26 799 €	124 298 €	8 863 €	11 866 €	11 539 €	0 €
Sub-total	512 344 €	314 715 €	204 364 €	182 366 €	133 697 €	100 083 €
Requested funding	**225 317 €**	**157 357 €**	**74 511 €**	**99 766 €**	**97 016 €**	**45 037 €**

III. Impact and benefits of the project

Consequences of such a project are important in a context of **adaptation and reducing the effects of climate change**. These latter being accelerated inside cities, and knowing that 70% of the world population will live in urban areas within 30 years, developing global tools to monitor trees (the first of the elements on which play to control the quality of the environment in the city), **understand their survival conditions, alert of a sudden perturbation of their physiological state** and **help city planners** in the design of more favorable conditions for trees have strong scientific, societal and environmental impacts.

[4] It was agreed between all members of the project that the consortium agreement will be carried out by the service partnership valorization of the CNRS and that ECOBIO will support the associated charges (2 500€)

As for methodological issues, the use of **multivariate satellite data** (optical, radar, thermal) associated with a large set of **physiological variables** both in real and controlled situations is a new and challenging issue. Related methodology to process such data will couple **artificial intelligence & physical models** of plants which is a hot topic for which few operational solutions exist at the moment.

We wish to take advantage of the results of this project to **target international projects/partnerships**, in particular to transpose our methods to other cities with different characteristics and on other species.

The consortium desires to **communicate with the society** and, as already mentioned, we plan to communicate with various media (fête de la science, café des sciences, journées en jeune public, …) and invite city planners and end-users to the final workshop.

Lastly, this project will help **SME AUBEPINE**, in developing inventory tools and in daily using Artificial Intelligence during trees audit assignment. The produced knowledge will significantly **improve both performance (quantity) and relevance of expertises (quality)**. In addition to a better understanding of tree responses stresses, the tools developed will obviously **help city managers** for an **intelligent monitoring of their vegetation**, and also **engineering consulting** firms as AUBEPINE to improve both the time spend on tree diagnostic and the recommendation they produce in response to the evolving challenges and threats on the tree heritage.

IV. References related to the project

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