BRAIN-be 2.0
Belgian Research Action through Interdisciplinary Networks
PHASE 2 - 2018-2023

Forest regeneration under climate and environmental changes

REGE+

SUMMARY

Forests are key components of earth habitability since they contribute to climate change mitigation through carbon sequestration, are biodiversity hotspots and / provide many other ecosystem services (among others, wood production, recreation, soil and water protection). To maintain in the long run their multiple functions including the climate services, forests must be continually regenerated. European and specifically Belgian forests face however various threats. Warm and dry summers weaken trees and seedlings due to water shortage and trigger outbreaks of pests and pathogens. The recent outbreak of bark beetle in Belgium is one example of the consequences of several consecutive warm and dry years (2016-2018). Besides these, the management of wildlife population, and particularly of ungulate population (roe deer, red deer, wild boar) could critically affect forest dynamics as abundant ungulates browse regeneration and affect preferentially some tree species over others modifying forest composition in the long term. In this uncertain and changing context, forest managers must improve the resistance and resilience of forests. It has been suggested that this can be achieved by creating uneven-aged and mixed stands following the principles of the close-to-nature or continuous-cover forestry. Indeed, mixing tree species with contrasted functional traits offers a large variety of possible responses to the various stresses and therefore improves the forest recovering capacity after disturbance.

To make the forest more resilient and test innovative management strategies, foresters need guidelines. Unfortunately, one cannot test *in situ* all possible silvicultural options for each site conditions and climate scenario. Scenario analysis based on model simulations are therefore necessary to select the most promising management practices which can then be tested *in situ*. The models used to predict the effect of climate change on forest functioning are process-based and generally operate at stand scale or larger without considering the within-stand spatial heterogeneity. They are therefore not adapted to test silvicultural routes in structurally-complex and species-diverse stands. In this project, we will perform simulations using an individual-based and spatially-explicit model (called HETEROFOR) describing stand dynamics based on resource use (light, water and nutrients) and silvicultural operations (https://doi.org/10.5194/gmd-13-905-2020).

For a series of case studies (Belgian forest stands to be regenerated within the next 40 years), the project aims at testing various forest and wildlife management options on tree regeneration success or failure, on ecosystem service provision and on soil fertility (sustainability) while taking into account climate changes. To achieve this goal, simulation experiments will be carried out with HETEROFOR that will be adapted to take into account the effects of ungulate browsing on seedling development and mortality, the impact of climate change and to evaluate economic indicators and forest climate services. These experiments will incorporate stateof-the-art regional climate change scenarios that have been produced in the context of the Cordex.be project (http://www.euro-cordex.be/).

This prospective approach will support policies, for example, by promoting silvicultural operation and wildlife management aiming to increase forest diversity, resistance and resilience. The simulation analysis will allow policy makers and forest managers to realize the possible impact of various forest and wildlife management scenarios according to various climate change scenarios. In addition, the project will create a modelling tool that could be reused in other contexts to test the impact of forest management strategies while taking the changing environment into account.

RESEARCH OBJECTIVES AND STATE OF THE ART

Regenerating forests is crucial to maintain forest ecosystem goods and services (wood and nonwood products, carbon sequestration, recreation, air and water purification, soil protection and biodiversity conservation), which in turn are essential to maintain earth habitability. In Belgium, forest regeneration has always been a major concern for the foresters and even more so today given the ongoing ecological and climate changes.

For example, the Norway spruce stands planted after the second world war, which occupy nearly one-fourth of the productive forest area in Wallonia, have to be progressively regenerated in the next 40 years. The regeneration of these Norway spruce stands raises important questions as the adult stands have been massively attacked by bark beetles and the timber market for this tree species has collapsed (http://www.scolytes.be). As a solution, it is considered to replace spruce by Douglas fir. Yet, young Douglas fir are now severely attacked by different pests and pathogens (Contarinia pseudotsugae, Swiss needle cast, Sirococcus conigenus, ...). Even if the bark beetle attacks temporary, the exceptional climate conditions that favoured its appearance are expected to be more frequent in the future. More generally, many uncertainties weigh on the future of forests since most of the processes involved in the stand dynamics are climate sensitive. Among others, warmer and drier summers weaken trees and seedlings due to water shortage and trigger outbreaks of pests and pathogens.

Given these new conditions and uncertainties, new silvicultural strategies of forest regeneration must be sought. Traditionally regenerated by plantation after clearcutting, coniferous stands are now progressively transformed into uneven-aged stands according to the principles of the close-to-nature and continuous-cover forestry. This new silvicultural approach aims to improve the forest resistance and resilience by creating structurally-complex and species-diverse stands. Indeed, such forests are generally thought to better resist and to be capable of recovering after different disturbances. Hence, in the current ecological and climate context, this strategy is thought to be economically more interesting than the traditional one even though it remains unclear whether it maximizes profits.

Apart from regenerating the spruce stands, regenerating broadleaved stands is also essential. Oak is the dominant broadleaf in Belgium and is mostly present in stands originating from coppices or coppices with standards. With time, the oak stands are ageing and the lack of regeneration is becoming more and more obvious. Several reasons can be advanced to explain the lack of oak regeneration: very irregular fructification (masting), insufficient light conditions, competition with adventice vegetation, mildew attacks and ungulate browsing. In particular, ungulate pressure (roe deer, red deer and wild boar) is increasing in Europe and reaches levels that hamper regeneration, and that can critically affect forest dynamics. Since ungulates browse preferentially some species over others, the forest composition is modified in the long term. In summary, forest managers must regenerate their forests but they are undecided about the optimal choices of 1) the tree species given the pest and pathogen attacks and the climate change, 2) the regeneration mode (artificial *vs* natural), and 3) the silvicultural treatment (even vs unevenaged stands).

Confronted with this complex problem, foresters need guidelines to test suitable management strategies. Unfortunately, it is not possible to test *in situ* all silvicultural options for each site conditions and climate scenario. Scenario analysis based on model simulations are therefore essential to select the most promising management practices which can then be tested *in situ*. There is a large variety of forest dynamics models but only few of them are able to simultaneously include the effects of forest management and climate change. The models used to predict the effect of climate change on forest functioning are process-based and generally operate at stand scale without considering the within-stand spatial heterogeneity (e.g., ANAFORE or CASTANEA). They are therefore not adapted to test silvicultural routes in structurally-complex and species-diverse stands. Simulating the effect of various management strategies in heterogeneous forests requires spatially-explicit tree models in which the position and characteristics of every single tree are modelled. Few models combine a detailed spatial description with a process-based approach. Furthermore, none of those models had been calibrated for the Belgian conditions until this gap has recently been filled by the development of HETEROFOR, an individual-based and spatially-explicit model describing stand dynamics based on resource use (light, water and nutrients) and silvicultural operations. HETEROFOR has been implemented in the CAPSIS simulator devoted to tree growth and stand dynamics modelling and is especially convenient to simulate the evolution of structurally-complex stands. As HETEROFOR is developed within CAPSIS, it can directly be used by all the users and modellers of this platform.

The functioning of the HETEROFOR model can be described as follows. The reader not interested in these more technical aspects can skip this paragraph. After the initialisation step (which requires input files characterising the soil properties, the tree position and dimensions and hourly meteorological data), HETEROFOR first calls the phenology routine that calculates the key phenological dates (budburst start, complete leaf development, leaf yellowing start, leaf fall start, complete leaf yellowing and fall). Then, HETEROFOR estimates the solar radiation intercepted by each tree using the SAMSARALIGHT library based on a ray tracing approach. From the photosynthetically active radiation (PAR) absorbed per unit leaf area and the soil water potential updated hourly with a water balance routine, the gross primary production (GPP) of each tree is estimated hourly with the biochemical photosynthesis model of the CASTANEA library. The individual net primary production (NPP) is then obtained by subtracting the maintenance and growth respiration or by using a NPP to GPP ratio. NPP is first allocated to foliage and fine roots by ensuring a functional balance and then to structural components using allometric equations, which allows deriving tree dimensional growth. The water balance routine accounts for rainfall partitioning in throughfall, stemflow and interception, for tree transpiration and evaporation from foliage, bark and soil using the Penman-Monteith equation, for root water uptake and for soil water movements based on the Darcy law. This routine can be calculated at the stand or individual scale but calculation time considerably increases when the individual option is selected. Knowing the chemical composition of the tree compartments for a given tree nutrient status, HETEROFOR computes the individual tree nutrient demand based on the estimated annual growth rate. In parallel, the potential nutrient uptake (soil nutrient supply) is obtained by calculating the maximum rate of ion transport towards the roots (by diffusion and mass flow). The actual uptake is then determined by adjusting the tree nutrient status so that tree nutrient demand matches soil nutrient supply. The nutrient limitation of tree growth is achieved through the regulation of photosynthesis, maintenance respiration and through the effect of the tree nutrient status on fine root allocation. The soil chemistry is characterized for the various soil horizons defined by the user. In each soil horizon, the chemical composition of the soil solution is in equilibrium with the exchange complex and the secondary minerals. It receives the nutrients coming from atmospheric deposition, organic matter mineralization and primary mineral weathering, and is depleted by root uptake and immobilization in micro-organisms. The chemical equilibrium within the soil solution, with the exchange complex or the minerals is updated monthly with the PHREEQC geochemical model coupled to HETEROFOR through a dynamic link library.

As climate conditions influence most of the processes regulating seedling and tree growth, simulating stand dynamics over several decades requires to consider the possible evolution of the climate. For Belgium, the BELSPO-funded project CORDEX.be has established a unique set of high-resolution climate scenarios over Belgium that has been validated and used for impact assessment. Additionally, lower-resolution projections are available from the EURO-CORDEX project. Therefore, no additional climate simulations are required within this project. However, prior to its usage in the context of forestry modelling, the climate projections require bias correction (BC). BC aims at correcting systematic errors in the output of climate models. This stems from the fact that the climate models substantially simplify reality by including numerical approximation at finite spatiotemporal resolution and parametrization schemes for processes. However, the most common BC methods suffer from issues related to the underlying assumption of time-invariance as well as to the alteration of the spatio-temporal correlations and correlation among different variables as highlighted by the IPCC. Their main recommendation is to "Invite the development of methodologies to assess (and possibly correct for) the degradation of the physical links among multiple variables caused by BC." This issue will be addressed in the current project (Task 3.1) as the physical link between the different climate variables must be preserved to represent correctly the impact of climate changes on forests. Recently multiple BC approaches have been developed that perform so-called "multivariate" corrections as the applied BC method were found to strongly influence results of the impact model. A new such BC methodology will be developed, validated and applied on high-resolution climate data for Belgium.

The objective of this project is to develop a highly integrated tool allowing to test various forest regeneration strategies while taking local climate evolution and various levels of ungulate density into account. To reach this goal, HETEROFOR will first be adapted to account for the effects of ungulate browsing on seedling development and mortality. The model will also be improved so that it can evaluate forest climate services (carbon sequestration, evapotranspiration, reflected solar radiation) and supply economic indicators. For several climate projection scenarios, simulation experiments will be carried out in a series of case studies (10 representative Belgian forest stands to be regenerated within the next 40 years) to test various regeneration and wildlife management options on tree regeneration success or failure, stand resilience after disturbance, ecosystem service provision and management sustainability (soil chemical fertility). Based on discussions with stakeholders (private and public forest owners, forest managers, hunters), new and promising forest management strategies (e.g. regeneration of even-aged pure stands using continuous-cover forestry systems and mixing tree species with contrasted functional traits) will be tested and compared to more classical ones (e.g. even-aged forests with successive thinning phases followed by clear-cutting). This project aims indeed at providing guidelines to the foresters who want to adopt these new practices since the pros and cons of these relatively new strategies have not been thoroughly scientifically evaluated and quantified. Our results will also help to design forest policy at the regional and national levels by allowing policy makers and forest managers to realize the possible impact of various forest and wildlife management scenarios in the climate change context.

METHODOLOGY

The achievement of the project objectives will require some improvements of the HETEROFOR model (i) to account for the effects of soil water availability and ungulate browsing on seedling development and mortality; (ii) to describe soil organic carbon dynamics; (iii) to compute economic indicators; and (iv) to evaluate forest climate services (**WP1**). These model improvements will be evaluated based on existing datasets and on an experiment of environmental manipulation (**WP2**). Besides, three greenhouse gas emission scenarios from the IPCC assessment reports will be considered and the corresponding local climate projections will be obtained using (1) downscaled global climate model simulations and (2) corrections of these projections for the biases identified by comparison with observations during historical periods (**WP3**). A restricted number of old coniferous and broadleaved stands representative of the main forest types to be regenerated within the next 40 years in Belgium will be used as case studies. They will be chosen among existing well-documented experimental plots intensively monitored during at least two decades. Forest and wildlife management scenarios (regeneration modality and ungulate density) designed for each case study site will be defined based on stakeholder and end-user requirements (**WP4**). The simulation experiments will then be conducted using the improved model to test the climate, silvicultural and wildlife scenarios at each case study site. The outcomes of these simulations will be used to compare tree regeneration effectiveness amongst the investigated scenarios, as well as to give insights in their respective financial profitability and ability to provide climate services and to ensure forest sustainability and resilience. The information generated by the simulation experiments will be synthesized to identify the most appropriate management options (**WP5**). The management of the data involved in the project is described in **WP6**. **WP7** is dedicated to the implementation of optimal valorisation, dissemination and exploitation of the project outputs as well as to the interactions with stakeholders (collecting of the stakeholder and end-user requirements, collaboration with forest managers for *in situ* trials, interpretation of the results, guidelines to foresters and recommendations for policy-makers). Finally, the strategy adopted to ensure efficient coordination and project management is presented in **WP8**.

WP1. Model improvements

Task 1.1 Soil water availability effect on regeneration

The processes of seedling development and mortality were recently integrated in the HETEROFOR model through coupling with the REGENERATION library of CAPSIS. In this library, seedlings or saplings and herbaceous species are grouped into cohorts and layers, respectively. The amount of available light allocated to the different cohorts is used to predict cohort growth dynamics and survival considering competition both among cohorts and with the adult trees. For each cohort, the height growth of the average seeding is predicted based on an empirical relationship depending on the relative transmitted light. In this task, we plan to adapt this relationship in order to also consider the seedling height growth sensitivity to soil water availability based on the results of the rainfall limitation experiment (see Task 2.1). Currently, seedling survival is obtained by dividing the cohort net primary production by that of the average seedling. In other words, the regeneration module estimates the number of seedlings that can survive given the carbon available for the whole cohort. For this project, the possibility to account for other mortality causes (hydraulic failure as well as pest attacks or diseases) will also be implemented.

Task 1.2 Ungulate impact on regeneration

The influence of browsing by ungulates on seedling and understory vegetation development is not included at this stage in the REGENERATION library. This functionality will be implemented in the framework of this project in order to allow considering the impact of ungulate on regeneration in the simulation experiments of WP5. The implementation will be carried out in close collaboration with P. Balandier (INRAe) and N. Dones (INRAe) who developed the library and who are among the researchers interested in further modelling ungulate impacts on forest ecosystems. Based on preliminary results, species-specific generalized linear models will be fitted to predict the growth reduction due to browsing as a function of its height and an index combining ungulate density and biotope richness. These models will be fitted mainly using existing data from fenced/unfenced plots (see WP2).

Task 1.3 Implementation of a soil carbon module

Forest soils are known to store large amounts of organic carbon, which constitute thereby a key component of the global carbon cycle. In other respects, soil organic carbon (SOC) is sensitive to climatic, ecological and management changes. Therefore, proper modelling of SOC dynamics considering the influence of these factors is necessary when testing and comparing various management options on carbon sequestration in the context of climate changes. This requires the implementation of a module dedicated to SOC dynamics modelling in HETEROFOR. Numerous models have been developed for describing soil carbon dynamics in forest ecosystems (e.g., CENTURY, ROMUL, YASSO). They usually present a quite complex structure considering several soil organic matter and litter pools connected with carbon flows and differing in their susceptibility to decomposition. These models involve a large number of parameters and state variables (organic matter pools), which makes their initialization and calibration challenging.

The soil organic carbon module implemented in HETEROFOR will rely on the same principles as the preceding models but considering simplified concepts. Litter fall and root turnover will purvey carbon stocks in the forest floor and the mineral layers, respectively. In each organic and mineral horizon, two organic carbon pools will be distinguished: a labile pool subject to mineralization and a stable, humified, pool. Transfers will be possible from the labile to the stable pools, but not reversely. In each layer and at each hourly time step, a part of the labile pool will be converted to CO_2 based on a mineralization coefficient expressed as a function of soil layer temperature and water content, organic matter quality (e.g., C/N ratio, nutrient content) and soil richness (e.g., base saturation rate, pH_{H_2O}) and texture. Organic carbon flows among layers will occur through transfers in both solid and dissolved forms. The concentration of dissolved organic carbon (DOC) in the soil solution will be determined as a function of temperature and of litter and soil organic matter quality. The module will be calibrated and evaluated based on existing laboratory and *in situ* data from soil respiration monitoring, incubation and leaching experiments as well as using results of repeated soil surveys in ICP-Forests sites (see WP2).

Task 1.4 Assessment of forest production and diversity

HETEROFOR currently provides reliable estimates of tree growth but does not provide outputs, such as economic indicators, that are needed to compare management scenarios. As we aim to develop a highly integrated decision-support tool, new functionalities will be added in HETEROFOR to better assess forest diversity, timber production and financial profitability.

Indicators of forest diversity and related ecosystem services will then be implemented in HETEROFOR such as the abundance of large trees, deadwood and micro-habitat. These indicators will be developed in collaboration with B. Courbaud (INRAe) who has already developed such indicators in CAPSIS (SAMSARA model).

HETEROFOR will additionally be connected to the ECONOMICS2 library developed by G. Ligot in CAPSIS. The connection with this library will provide indicators of forest profitability under the classic Faustmann hypotheses (e.g., present value of perpetual series of costs and revenues, internal rate of return). Next, during this project, the library will be improved to implement state-of-the-art indicators considering the risks associated with future environmental changes in relation with tree species diversity. We will follow the framework proposed by Friedrich et al. that combines elements from the classic Faustmann approach with elements from the Markowitz' Modern Portfolio theory. Mixed stand will be considered as a portfolio of different assets and the approach seeks to minimize the risk for a given value of forest return. Besides, this approach will consider stochastic variation in forest return thanks to Monte Carlo simulations. This new approach has proven to successfully deliver interesting results when combining it with a forest dynamics simulator and has been particularly recommended to evaluate the financial risks caused by ungulates.

Task 1.5 Assessment of climate services

Interacting with the atmosphere through exchanges of energy, carbon dioxide and water, forests influence climate and may either mitigate or amplify climate change resulting from human activities. In addition to carbon sequestration in tree biomass, evapotranspiration from forest canopies promotes cooling of the atmosphere, while the low surface albedo of forests tends to contribute to its warming.

These climate services of forests are expected to be affected by changing climate conditions. Notably, the rise of temperature and modifications in the precipitation pattern may induce severe water stress leading to loss of tree growth, reducing thereby carbon sequestration, and limiting evapotranspiration due to drier soil conditions. Furthermore, higher temperatures may favour the mineralization of soil organic matter resulting in an increase in CO_2 emissions. On the other hand, studies have shown a gain in tree growth associated with the CO_2 fertilization effect. Therefore, predicting the effects of climate change on forests and, consequently, on their climate service provision is not straightforward. Likewise, forest management will also influence forest climate services either positively or negatively with regard to mitigation of climate change effects. Indeed, changes in forest canopy structure and species composition due to management actions affect exchanges with the atmosphere and, thereby, forest climate services.

Assessment of forest climate services will be implemented in HETEROFOR so as to consider them in the evaluation and the comparison of the investigated scenarios (see WP5). For each scenario, carbon sequestration over the simulation period will be determined by making a carbon budget on tree biomass and soil carbon stock. The albedo will be estimated based on radiative transfer modelling through the canopy, using the SAMSARALIGHT radiative transfer library of CAPSIS which is already coupled to HETEROFOR.

WP2. Data acquisition and use

The calibration and validation of newly implemented features in the HETEROFOR model (see WP1) require specific observations and measurements. Most of the data already exist and are available, and will be completed by some additional acquisitions as detailed below.

Task 2.1 Regeneration dynamics

***In situ* monitoring of regeneration dynamics**

The research consortium of this project has accumulated different data of regeneration dynamics in broadleaved and coniferous forests. Such data are essential to calibrate/validate the regeneration models that will be implemented in HETEROFOR.

In broadleaved forests, the natural regeneration of oak and beech has been monitored at 27 fenced sites in the Belgian Ardennes within 242 square plots of 4 m². In each of these plots, the species-specific sapling density and the height of the three tallest oak and beech saplings was measured in years 2007 and 2012. Hemispherical photographs were also taken in most subplots to assess understory light between 2009 and 2012. New measurements of sapling size and density will be performed within a subset of 7 plots during the project in order to complete the existing datasets with data acquired on more advanced natural regeneration. These data will be particularly helpful to evaluate the performances of the REGENERATION library as most of the available data concern young regeneration stage (height < 4 m).

In coniferous forests, the natural regeneration has been monitored since 2015 in the Belgian Ardennes within 108 plots installed at 9 sites. Similarly to the plots in broadleaved forests, trees were georeferenced and are regularly monitored and the measures carried out in the regeneration aimed to assess sapling growth and understory light conditions. The measures in these sites will continue during this project.

The effect of competing vegetation on regeneration will be considered based on literature. If necessary, corresponding data can also be available through collaborations with P. Balandier (INRAe).

***In situ* monitoring of ungulate damage on regeneration**

Species-specific browsing damages by ungulates will be modelled based on the vast network of pairs of fenced and unfenced plots (n > 850 pairs) that has been installed and monitored by the "Département de la Nature et des Forêts" (DNF, SPW) and supervised by the "Département de l'Etude du Milieu Naturel et Agricole (DEMNA, SPW) and Gembloux Agro-bio Tech (ULiège). Pairs of fenced/unfenced plots have been settled in forest gaps. In plots of 9 m², the measures encompass the height of the 5 tallest saplings of the main target species, the height of the 10 tallest saplings of other species, the height of the 4 tallest individuals of Vaccinium myrtillus or Rubus ideaus, sapling density, the number of saplings of each species, and ground vegetation cover. For each plot, the abundance of ungulates can be estimated thanks to culling statistics.

Additionally, the project will benefit from data of a regeneration inventory carried out by Gembloux Agro-bio Tech (ULiège). Non-permanent sampling units were laid out in a broadleaved forest of 3,200 ha (n = 726) in Nassogne. Each sampling unit was composed of a circular plot to measure stand attributes and 4 subplots to measure regeneration attributes and browsing damages recorded by species and height classes. The intensity of browsing damage was evaluated on a scale with 3 levels. In this forest, six zones were defined depending on red deer densities ranging from 20 to 89 red deers/1,000ha.

As aforementioned in WP1, these data will be used to calibrate and validate the new developments implemented in the REGENERATION library to account for the ungulate impact on regeneration dynamics.

Rainfall limitation experiment

In order to investigate and quantify the effects of climate changes and, in particular, of drought on seedling development, an *in situ* rainfall limitation experiment will be conducted in regeneration patches of the Lauzelle wood (Louvain-la-Neuve, Belgium). This forest presents patches with well-established oak and beech regeneration in which experimental zones (blocks) will be set up. Each experimental zone will consist into (i) a 'treatment unit' subject to artificial drought and (ii) a 'control unit' receiving natural throughfall (i.e., no artificial interception). In the treatment unit, drought will be induced through the installation of a partially covered roof (4 x 4 m horizontal area) consisting of 25 cm wide transparent plastic strips spaced 12.5 cm apart (i.e., 2/3 covered area). The roof will be around 1 m and 2 m high at its lowest and highest sides, respectively. It will be adjusted depending of the height of the seedlings underneath it. Besides, a plastic sheet will be inserted vertically in the ground to a depth of 40 cm at the periphery of the roof to avoid lateral transfers of water between the soil subject to natural throughfall and the soil under the roof. The control unit (2 x 2 m area) will be delimited in the proximity of the roof: not too close to avoid an influence of the roof on the throughfall reaching the control unit area neither too far to stay in the same environmental conditions, especially with regards to light, soil and water supply. Such experimental zones will be replicated three times for each considered species (sessile oak and European beech), resulting in a total of six experimental zones (blocks).

Measurements will be carried out on seedlings over the complete area of the 'control' units (2 x 2 m) and over the central 2 x 2 m area of the 'treatment' units, considering thereby a 1 m wide peripheral buffer zone in this latter case. A set of 30 seedlings will be selected in each of the 12 experimental units, covering the encountered height range and evenly distributed over the 0-25 cm, 25-50 cm, 50-100 cm and 100-150 cm classes. Seedling height and collar diameter will be measured on each of these selected individuals. These seedlings will be labelled with a unique identifiant. Besides, complete counting of the alive seedlings will be carried out in each experimental unit. These observations will be repeated every year all over the experiment duration and will allow to study the effect of water limitation on seedling growth and survival.

In addition, soil water content within the upper 30 cm soil layers and temperature at soil surface will be continuously monitored in each experimental unit using, respectively, time domain reflectometry (TDR) and thermistor sensors.

Task 2.2 Estimation of soil carbon sequestration

Two existing datasets will be used to calibrate and validate the soil organic carbon module implemented in the HETEROFOR model as described in WP1.

The first dataset contains *in situ* CO_2 efflux and litter decomposition measurements carried out in an oak and beech forest. In addition, incubation experiments were performed in controlled conditions to evaluate soil respiration and DOC production of the forest floor and Ah horizons. This dataset will allow parametrizing the relationships of the soil organic carbon module relating mineralization rates and DOC concentrations to temperature, water content and organic matter quality.

The second dataset corresponds to repeated soil surveys with a time lag of 15 years in the plots of the forest monitoring network in France (RENECOFOR) and Belgium, covering a wide range of ecological conditions and 10 species. Applying the HETEROFOR soil organic carbon module on some of these plots will allow evaluating its ability to reproduce the SOC stock changes in the different soil horizons over the inter-survey period.

WP3. Establishment of climate projection scenarios

Task 3.1 Downscaled and bias-corrected multi-variable projections

Bias correction has become a common practice to improve numerical weather forecasting. However, bias correction (BC) methods for ensembles typically deteriorate the relation across space, time, and different variables, thereby leading to physically unrealistic atmospheric situations. Complicated additional steps based on copula methods are therefore required to correct these deficits. A simple member-by-member (MBM) post-processing method was developed that required no additional correlation-preservation steps. In this work package, this MBM post-processing method will be adjusted to serve as a method for BC in the context of climate projections.

In order to encompass uncertainty, three greenhouse gas emission scenarios used in the IPCC assessment reports will be considered (i.e., RCP2.6, RCP4 and RCP8.5) and bias-corrected over Belgium. In order to serve as input for WP5, a subset of ensemble members will be identified as representative scenarios according to different criteria. The criteria will be developed together with the WP5 partners. Such subset is necessary given the large computational cost of the impact models such as HETEROFOR. The correction scheme will be compared with the reference quantile mapping (QM) method.

For coupling to forest models, as will be done in WP5, hourly-adjusted and bias corrected time series will be provided for eight surface variables (two components of wind, radiation and temperature, rainfall and specific humidity).

Task 3.2 Trend correction

As aforementioned, the climate projections from climate models are considered as sensitivity experiments in the sense that the climate changes or trends are considered as their main output. However, one may ask whether the climate change trends in the past decades can be successfully reproduced. The ensemble simulations are perfectly reliable when the reality (observations) can be considered as a (random) sample from the ensemble. It has been shown that global models cannot reliably reproduce some aspects of the climate change trends of the past decades. The MBM and QM methods in Task 3.1 will be adjusted and applied in the context of climate projections with the aim of increasing the reliability of climate trends from the existing datasets from the CORDEX and CORDEX.be ensembles. The new scenarios will also be tested in the context of the forest model.

WP4. Definition of silvicultural and wildlife scenarios

Task 4.1 Selection and characterization of case studies

Case studies representative of the main forest types to be regenerated within the next 40 years in Belgium will be used as initial stages for the simulation experiments carried out in WP5. These sites will be selected among existing highly documented and intensively monitored Belgian plots of the Long-Term Ecosystem Research (LTER) and the International Cooperative Program on Forests (ICP-Forests, level II sites) networks. The selection will focus on plots dominated by the major forest tree species in Belgium, namely, native oaks (*Quercus sp.*), European beech (Fagus sylvatica L.), Norway spruce (Picea abies (L.) Karst.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), larches (*Larix* sp.), pines (*Pinus* sp.). So as to encompass the variability of stand types, notably with regard to structure (i.e., even-aged vs uneven-aged stands) and species composition (i.e., pure vs mixed stands), several stand types could be considered for a given species, resulting however in no more than ten case studies.

Task 4.2 Definition of silvicultural routes

The silvicultural scenarios considered in the simulation experiments of WP5 will be established from exchanges with forest and forest-related sector stakeholders during follow-up committee meetings. Innovative management strategies presenting potentially beneficial features with regard to tree regeneration success and/or to forest adaptability and sustainability in the context of climate changes will be considered. In addition, traditional silvicultural practices will be compared to close-to-nature forestry considering various levels of target stand density. The silvicultural routes will be defined in terms of silvicultural operations (i.e., thinning intensity, frequency and type, rotation length, tree species selection, harvest intensity) and of regeneration modalities (i.e., natural vs. artificial, extended vs. small patches, mono-specific vs. multi-specific, with or without protections against wildlife).

Task 4.3 Definition of wildlife management strategies

Damages on regeneration by ungulates depend on the density of animals. It also depends on animal behaviour and biotope richness. Nevertheless, as animals move over much larger territories than the stand scale used for the modelling, their behaviour will not be described dynamically. Instead, we will use relationships between damage occurrence/intensity and ungulate density.

WP5. Simulation experiments and output analyses

Task 5.1 Simulation experiments

The silvicultural and wildlife management scenarios defined in Tasks 4.2 and 4.3 will be tested through simulations with the improved HETEROFOR version (WP1 and WP2). In these simulations, the management options will be applied to the selected case study sites (Task 4.1) considering the different climate projection scenarios established in WP3. For each 'case study x management option x climate projection' combination, the simulations will be reiterated with different sets of parameter values drawn randomly from parameter distributions to quantify uncertainties associated with model predictions. Furthermore, for each climate projection scenario, simulations will be run for several generated climate time series to assess the part of variations in model predictions ascribed to the natural variability of climate.

Task 5.2 Output analysis and synthesis

The outputs of these numerical experiments will be synthetized as indicators characterizing simulation results in terms of regeneration development and diversity, ecosystem resilience (recovery after disturbance), provision of climate services (carbon sequestration, evapotranspiration, reflected solar radiation), financial profitability (e.g., internal rate of return, value-at-risk) and sustainability (maintaining of the soil bioavailable nutrient pools). These indicators will be combined and analysed through a multi-criteria analysis in order to identify the most appropriate management strategies. The results of this analysis will be discussed with stakeholders and a synthesis of the pros and cons of each management option will be achieved.

WP6. Data Management

The data involved in the project may be classified into three categories: (i) data for the calibration and the validation of the new functionalities implemented in the model during the project, (ii) input modelling data required by the model to perform the simulation experiments and (iii) outputs of the simulation experiments. So as to ease data manipulation and processing as well as their sharing both among the project partners and with other potential users, these data will be systematically incorporated into databases. The strategy specifically planned for each of the three types of data is presented in the tasks below.

Task 6.1 Management of the calibration and validation data

As detailed above in WP2, the calibration and validation of the newly implemented features will rely on several available datasets acquired by the project partners and their collaborators. Currently located into different databases or spreadsheets, these datasets will be centralized in a single database that will be extensively described and installed in a shared repository accessible to all project partners, enabling common access and update. This database will be completed by the additional monitoring data of *in situ* regeneration dynamics for more advanced development stages that will be collected during the project. Besides, the database will also host the data from the rainfall limitation experiment designed for this project in order to more specifically investigate the effect of drought on seedling development (see Task 2.1). At the end of the project, when all collected data will have been integrated into this database, it will be made freely available through an open-access repository together with the other project datasets (see below).

Task 6.2 Management of the input modelling data

Input modelling data include climate projection scenarios, forest inventory data and the main soil horizon physico-chemical characteristics for the case study sites. Climate projection scenarios will be generated in WP3 based on the existing climate projections of the EURO-CORDEX and CORDEX.be projects. Regarding the soil and inventory data, selection of the case study sites will be operated according to species composition and stand type as specified in Task 4.1 among the plots for which the required variables are available. These data will be extracted from the LTER and ICP-Forests databases and will be gathered together with the climate projections series into an 'modelling input' database. Queries will be implemented in this database for automatic generation of the input files required by the model to initialize the simulation experiments. The database and the generated input files will be made freely available through an open-access repository.

Task 6.3 Management of the simulation experiment outputs

The data generated by the simulation experiments will be stored into a 'simulation experiment output' database. It will notably serve to prepare these data for the multi-criteria decision making analysis aiming at identifying the most relevant strategies (see WP5). It will also constitute the catalogue of all the ecosystem responses predicted by the model to each case study and according to each combination of climate and management scenarios that will be of high interest for a large target audience, from forest scientists to forest managers and policymakers. As for the other databases, this database will be made available on an open-access repository together with an installer of the improved HETEROFOR model accompanied by a user manual, allowing any interested user to launch the simulation of its choice.

Task 6.4 Data Management Plan update

The data management scheme proposed above and in the attached Data Management Plan form will be regularly updated according to the needs of project partners and of the stakeholders.

WP7. Valorisation, dissemination, exploitation of results

The aim of this work package is to promote the transfer of the results and knowledge emerging from the project towards a wide audience panel, encompassing scientists, forest stakeholders and policy makers, so as to maximize the valorisation and the exploitation of the project outcomes. It not only relies on the delivery of the outputs of the project under the form of publications, datasets, simulator and practical recommendations and guidelines, but also involves interactions with forest stakeholders, managers and decision-makers. Indeed, the active involvement of the stakeholders and of the end-users throughout the project by providing ideas and guidance for reaching the research objectives will ensure that the project is in line with their needs, increasing its chances to have real implications. Collaborations with forest managers are foreseen to continue beyond the end of the project through the follow-up of *in situ* trials implemented according to the recommendations and guidelines arising from the project in order to perpetuate the exchanges between scientists and practitioners but also in a process of continuous evaluation and improvement of the model.
As specified through the tasks presented below, different formats and medias will be used to valorise and disseminate the project outcomes so as to cover the whole targeted audience.

Task 7.1 Web site design and management

A website will be designed and launched at the project start. It will constitute a dynamic communication interface serving as an interactive information and feedback tool for future users. It will present an overview of the project and will be continuously provided with up-to-date information regarding the project progress, its outcomes and its related events.

Task 7.2 Dissemination through publications and meetings

The main scientific outcomes of the project will be published in high impact and open-access peerreviewed international scientific journals and will be presented in international conferences. The key project results will be published in popularization journals intended to forest owners and managers and will also be summarized under the form of non-specialized leaflets to reach a wider public audience. Finally, the project outputs will also be synthetized as targeted messages for policy makers.

Task 7.3 Organization of meetings with the stakeholders and end-users

Exchanges with stakeholders and end-users will occur throughout the project duration, from the initial steps in order to gather insights for the definition of relevant forest and wildlife management scenarios until the translation of the project results into pragmatic recommendations and tools promoting their adoption and use in practice. These exchanges with the stakeholders will notably occur during the follow-up committee meetings but will also be organized on other occasions with people external to the committee. To ensure the active participation of stakeholders in our study, the project will be presented during events (conferences, trainings, workshops) organized for the forest sector by organizations such as the Belgian Royal Forest Society (SRFB), the Forest.Nature organization, the Flemish and Walloon forest services (ANB, DNF), the Walloon Economic Office for Wood (OEWB) among others. In addition, we will stimulate the involvement of forest owners and managers by contacting them personally and via LinkedIn, by inviting them to workshops and by maintaining the contact through a forum on forest management on our website.

Task 7.4 Organization of training courses and field trainings

Training courses will be provided to students and scientists to present them how forest dynamics can be modelled and how models such as HETEROFOR can help understanding forest ecosystem functioning. Besides, field trainings will be organized in collaboration with forest stakeholders (private and public forest owners and managers) in order to illustrate the potential of HETEROFOR as a management support tool.

Task 7.5 Organization of a final meeting

A meeting will be organized close to the term of the project to present its achievements. This meeting will target a large audience, encompassing scientists, forest stakeholders, forest owners and decision makers. This meeting will be a privileged place for exchanges and analysis by these actors of the innovative aspect of the final outcomes of the project.

WP8. Coordination, project management and reporting

The aim of this work package is to ensure efficient coordination and management of the project at the scientific, administrative and operational levels so that it reaches its objectives and provides quality results and deliverables in accordance with the work plan schedule.

Task 8.1 Project coordination

The successful achievement of the project objectives strongly relies on the close cooperation of the different actors of the project, including the scientific partners and the stakeholders, in order to provide outcomes integrating their complementary expertise and addressing also questions in line with the needs of forest practitioners, managers and decision makers. An important part of the present task will therefore be devoted to organizing and stimulating interactions among these actors and to coordinating the partner scientific activities. The project partners will meet regularly throughout the project. During the first year of the project, meetings will be organized every two months so as to coordinate the work of the different teams and clearly identify the links to be made between their respective contributions so that all of them work in phase towards an easy integration of their outputs. Later, meetings between researchers will still occur frequently, especially when specific questions or problems arise but also to follow the work of each other. Besides, meetings involving all researchers and principal investigators of all groups will be organized at least twice a year to thoroughly discuss the progress of the project. Aside these scientific partner workshops, meetings will also be organized with stakeholders (see Task 7.3). In other respects, national and international interactions with other teams working on related fields or projects will also be encouraged.

The aim of this coordination task is also to monitor the scientific quality of the results and to ensure their proper dissemination, valorisation and exploitation.

Finally, this task is also intended to steer the project to the achievement of its objectives by implementing appropriate mitigation measures or alternative plans in response to risks, either identified beforehand or arising during the project.

Task 8.2 Administrative management and reporting

This task is devoted to the organization of the project meetings, to the preparation of the project reports, to the financial management of the project and to the implementation of effective communication and collaboration amongst partners.

IMPACT

Scientific knowledge, future capacities and skills: major

During the project, we will create a tool integrating the whole modelling chain from the generation of bias-corrected climate projections to the multicriteria analyses of model outputs (regeneration success, wood production, biodiversity indicators, financial profitability, sustainability, resilience and climate services). This methodology and the associated tool will be available to all scientists wanting to reuse or adapt it to other questions and contexts. In particular, the improved version of the HETEROFOR model and of the coupled CAPSIS Open-Source libraries will benefit the forest modelling community. The project will also contribute to the development of tools for correcting the biases of climate projections produced by RMI, that can then be further used for other applications.

The originality of this project lies in the development of a highly integrated tool allowing to test various forest regeneration strategies with an improved process-based model of forest dynamics considering local climate projections and various levels of ungulate density. Compared to other projects based on simulation studies (e.g. ECORISK, SUSTAINFOR), the specificity of our approach is to focus on the regeneration phase, to account for the ungulate pressure and to rely on bias-corrected local climate projections. Most of the process-based forest models describe forest growth but the regeneration and mortality processes are rarely considered while these processes are strongly affected by climate. Another specificity is the use of a forest model that combines a detailed spatial representation (spatially explicit and individual-based model) with a process-based approach, which provides a high flexibility to simulate climate change and management impacts.

Economy: moderate

In this project, we will simulate the evolution of old stands entering into a regeneration phase according to contrasted silvicultural strategies. Among others, we will compare the close-to-nature and continuous-cover forestry approach with the traditional forestry (plantation or natural regeneration, successive thinning phases, clear-cutting). The comparison will be done on the wood production, biodiversity indicators, climate service provision, sustainability (soil chemical fertility), resilience after disturbance and also on the financial profitability through the ECONOMICS2 library. Whether close-to-nature forestry is more profitable than traditional forestry is still under debate. In Wallonia, the forestry sector is concerned about the long-term wood supply (in quantity and quality) in relation to a wide application of the close-to-nature approach. Such debates took place in the Walloon parliament in 2016 and 2020. The debates in 2016 gave rise to the resolution 546 which stresses the need for studies evaluating the economical impacts of applying the close-tonature approach on the Walloon territory. Comparing the two approaches is however quite challenging since it must be done on long time periods (at least one rotation) and in similar economical and ecological conditions. In this respect, simulations studies can be very useful.

In addition, climate change and natural disturbances could strongly affect forest productivity and therefore wood supply to the industry.

Civil society: moderate
Improved forest management will have broad consequences for civil society through improved habitability with respect to, for instance, health and adaptation to climate change. Given the conditions of stress and pollution in which city dwellers live daily, they increasingly need natural and beautiful landscapes such as forests to relax, which was clearly noticeable during the COVID19 lock down. Many people use the forests as recreational spaces for walking, running, cycling, observing the fauna and flora, hunting,... To maintain these recreational and aesthetic functions of the forests, they must be regenerated. However, the public has a quite static and conservative view of the forests. They want to conserve them as they are without human interventions. However, forests naturally evolve and need to be managed to improve their adaptability to climate change and resilience after disturbance. Based on our simulation study, we will be able to raise awareness of the need to manage forests. By contributing to regenerate forests and to educate the public, our project could have a strong impact on civil society. Because this impact is partly indirect, we qualified it as moderate.

Policy and public services: major
The simulation analysis carried out in this project will allow policy makers and forest managers to realize the possible impact of various forest management strategies according to various climate change scenarios.

At the national level, the project will contribute to the achievement of some specific objectives of the plan for biological diversity and of the energy climate plan for 2021-2030 (e.g., production of renewable energy).

At the regional level, the expected results will allow policy makers to identify the forest and wildlife management strategies that best promote forest resilience in a changing environment and ensure long-term sustainability of wood production and climate service provision. Indeed, traditional silvicultural systems have clearly shown their limit in today's conditions (bark beetles, new pathogens, drought...). The most promising strategies in terms of forest regeneration and climate service provision will be tested *in situ* in close collaboration with the owners and managers of the private and public forests and then integrated in the forest management plans.

For the local foresters, the project will provide guidelines to test innovative forestry practices and create species-diverse and uneven-aged stands.

Environment, Health and quality of life: strong
Since the project aims at comparing various silvicultural options on the climate service provision, its results could be used to improve the role of forests in climate change mitigation strategies. The climate is indeed an essential component of our environment and of the earth's habitability. Forests also play a major role in soil and water protection as well as in air purification. The positive impact of forests on mental and physical health is also undeniable and has been mentioned above in the point on civil society.

Collection management and conservation: moderate
Unique datasets of climate change projections over Belgium at high resolution have been produced in the past few years and have been widely distributed and used. For impact assessment purposes, however, such datasets are not directly usable but require an additional bias correction. The addition of such calibration time series to the existing collection of climate projections is therefore an essential component for the provision of climate services.

VALORISATION

The scientific outcome of the project will be published in high impact open-access international scientific journals (8 peer-reviewed papers at least) and presented at international conferences (3 oral communications planned). The improved HETEROFOR model will be freely distributed using an installer containing the CAPSIS software with only HETEROFOR and the associated libraries (and the source code). All the input files used for the project (including the bias-corrected climate projections) will be embedded in this installer, which will allow the user to reproduce all the simulations he wants. A user manual will be provided as well. At the end of the project, we will organize training courses on the improved version of HETEROFOR for master and PhD students as well as for interested scientists (description of the model functioning, illustration by case studies, introduction to the practical use of HETEROFOR).

For the forest owners and managers, the main results of the project will be published through articles in popularization journals. The choice of the journals will be done not only based on the topic but also with the aim to broaden the project audience. Potentially suitable popularization journals are Forêt.Nature in French, Sylva Belgica in French and Dutch, Forêt entreprise, Rendez-vous techniques de l'ONF or Revue Forestière Française in French. Besides, the HETEROFOR model will be used during training courses in addition to exercises performed in demonstration stands in order to allow the foresters to realize what could be the impact of their choices and help them to adapt their practices. To assist us in the training, we will call on external non-funded partners specialized in the popularization of forest knowledge. These partners will change depending on the audience. For public forest managers we will work with Forêt.Nature (https://www.foretwallonne.be/qui-sommes-nous), and we will rely on the Société Royale Forestière de Belgique (SRFB, https://www.srfb.be/) for private forest owners and managers from Wallonia and Flanders. UCLouvain and Gembloux Agro-Bio Tech have a long history of collaborations with both popularization organisms, especially with Forêt.Nature in the framework of the 5-year forest research plan funded by the Walloon public service (Plan quinquennal de recherches forestières).

Meetings with stakeholders will be organized throughout the project duration to continuously maintain multi-actor exchanges about the research outcomes, thereby favouring smooth transfer of knowledge. A first meeting will occur at the beginning of the project. Its purpose will be to present the project and its objectives, to identify with the stakeholders key pragmatic questions and co-design the way they should be addressed through the project as well as to gather from them first insights for the definition of the climate and management scenarios to be used for the simulation experiments. Other meetings with the stakeholders will be organized at least once a year to regularly present and discuss with them the generated outcomes, and to benefit from their advice in translating the project results into management guidelines and tools favouring their integration by practitioners and their use in the field. At the end of the project, based on the results of the simulation experiments, these participative workshops will lead to the selection of the most promising management strategies to be applied *in situ* in collaboration with forest owners and managers. Besides their role as showcases for the implementation of innovative management strategies, these field trials could be monitored and compared to model predictions for validation.

For the policy planning, a summary of the study with targeted messages will be prepared to show policy makers how the project results can contribute to the achievement of some objectives of strategic plans such as the plan for biological diversity or the energy climate plan for 2021-2030.

A final meeting will be organized near the end of the project to present its achievements and to exchange with scientists, stakeholders, forest owners and policymakers on the ground-breaking nature of the project outcomes. This final meeting will be organized in collaboration with an external partner specialized in communication and scientific popularization in forestry (e.g., Forêt.Nature, SRFB). Beside its ability to ensure optimal knowledge transfer from scientists to practitioners, such a partner will also help to significantly increase the visibility of both the meeting and the project outcomes given its wide network of contacts in the forest-related sector.

To reach a wider public audience, non-specialized leaflets will be published, illustrating and explaining in simple words the need to manage and regenerate forests according to well-designed strategies to ensure their sustainability, particularly in the context of climate changes, raising thereby public interest in the research conducted in the framework of the project. These leaflets will notably be distributed during events aimed at the general public and relating to the forest and the environment (e.g., forestry fairs, environment days). Besides, a short video will also be produced for the same purpose so as to further increase visibility through digital medias.

At the project start, a website will be launched, serving as a platform for project overview, for result and model dissemination and for interactive discussion with stakeholders and end-users. A section of the website will give a general presentation of the project, of its objectives and expected outcomes and of its progress. A second section will present the HETEROFOR model and will describe, based on illustrative examples, its functionalities and capabilities both for scientific, forest management and decision-making purposes. It will be regularly updated as improvements are made to the model. A third section will provide access to project resources and outputs such as model installer, project open-access databases, scientific and popularization publications, management guidelines, recommendations to policymakers, non-specialized leaflets and promotional video. A fourth section will be devoted to the news and events related to the project, it will notably promote the training courses and field trainings organized in the framework of the project. Finally, a blog section will allow interactive exchanges between anyone interested in the project and the project partners. The website will be maintained by UCLouvain for a minimum of five years after the project has ended.