BRAIN-be 2.0

BELGIAN RESEARCH ACTION THROUGH INTERDISCIPLINARY NETWORKS - Phase 2

Annual Network Report

To be filled in for the whole network in French, Dutch or English and sent to: BRAIN-be@belspo.be

Contract nr: B2 / 212 / P1 / REGE+

Project Acronym: REGE+

Reporting period: 15/05/21 - 15/04/22

The *Annual Network Report* (maximum 15 to 20 pages) is drawn up annually by the coordinator for the entire network and sent to the address BRAIN-be@belspo.be on the dates set in article 7.6 of annex I to the contract. It presents the state of progress and achievements of the research as well as the forecasts for the following year. This information refers explicitly to the tasks and the project schedule defined in articles 2 and 3 of annex I. It also informs of any modification of the data included in the initial reports and gives the list of publications and missions carried out during the past year.

This template can be completed in French, Dutch or English.

NETWORK

COORDINATOR (PARTNER 1)

1. Name and Institution : JONARD Mathieu, UCLouvain – Earth and Life Institute

OTHER PARTNERS

2. Name and Institution: LIGOT Gauthier, ULiège, Gembloux Agro-Bio Tech, TERRA, Forest is life
3. Name and Institution: VAN SCHAEYBROECK Bert, RMI
4. Name and Institution: GOOSSE Hugues, UCLouvain – Earth and Life Institute (Collaborator)
5. Name and Institution: VANNITSEM Stéphane, RMI (Collaborator)

AUTHORS OF THIS REPORT

1. Name and Institution: JONARD Mathieu, UCLouvain – Earth and Life Institute
2. Name and Institution: LIGOT Gauthier, ULiège, Gembloux Agro-Bio Tech, TERRA, Forest is life
3. Name and Institution: VAN SCHAEYBROECK Bert, RMI
4. Name and Institution: ANDRE Frédéric, UCLouvain – Earth and Life Institute
5. Name and Institution: CANDAELE Romain, ULiège, Gembloux Agro-Bio Tech, TERRA, Forest is life
6. Name and Institution: HOSSEINZADEHTALAEI Parisa, RMI

PROJECT WEBSITE, SOCIAL NETWORKS …

A website has been designed at the start of the project, and is available at https://www.regeplus.be/. See below for a detailed description of the website.

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY OF THIS REPORT

This report presents the progress of the REGE+ project after the first year of funding. The different tasks scheduled at this stage have been carried out. Most of the required HETROFOR model improvements have been implemented. These model adaptations are under evaluation using data collected on regeneration monitoring plots and within experiments designed to investigate the ungulate and climate change effects on seedling development. The next steps of the project will be (1) the definition of silvicultural and wildlife management scenarios to be considered for the simulation experiment, (2) the establishment of a bias correction procedure for the climate projections and its application to the climate series to be used in the simulation experiment, (3) the implementation of the simulation experiment aiming to test the selected silvicultural and wildlife management scenarios and climate projections for several case study sites, (4) the analysis of the outcomes of the simulations by comparing the scenarios with regard to tree regeneration effectiveness but also considering their respective financial profitability and ability to provide climate services and to ensure forest sustainability and resilience, and (5) the synthesis of the information generated by the simulation experiment to identify the most appropriate management options.

2. ACHIEVED WORK

WP1. Model improvements

Task 1.2 Ungulate impact on regeneration

Among others, the REGE+ project aims at testing the ungulate impacts on tree regeneration and long-term forest dynamics through a simulation approach taking the changing climate into account. Ungulates affect stand development by browsing tree seedlings and peeling the bark of coniferous tree species. At the beginning of the project, our forest growth model (HETEROFOR) contained a regeneration module but no routine to account for ungulate browsing and bark peeling.

Two options were considered for modelling ungulate browsing:

(i) a descriptive approach reducing seedling density and seedling height growth based on a fixed proportion provided by the model user. These ungulate effects are applied only on regeneration cohorts below a given height. When the seedlings have exceeded this height, they are no longer browsed.

(ii) a more process-based approach requiring as input the total biomass to be browsed (which reflects the ungulate pressure). This biomass is first distributed among tree species or ground vegetation (e.g. bramble) according to their biomass and palatability. Then, the browsing is applied by randomly selecting regeneration cohorts and by reducing their biomass by a given small quantity (bite). For each tree or ground vegetation species, the process is repeated and the biomass to be browsed is progressively decremented until reaching zero. When the biomass of a regeneration cohort (or ground vegetation layer) is reduced, all its characteristics are adapted accordingly (e.g., seedling height, cohort or vegetation cover or LAI). In the next months, the option will still be improved to calculate directly the total biomass to be browsed from the ungulate population density (see point 5.).

The modelling of bark peeling damages (including the progressive development of stem decay on the affected trees) has been integrated in HETEROFOR based on the approach implemented by G. Ligot in GYMNOS, a model of the CAPSIS simulator dedicated to even-aged coniferous stands. These model developments were achieved for Antoine Crochet's master thesis which aims at simulating the long-term ecological and economical consequences of ungulate overabundance on coniferous stands. This study is carried out in the communal forest of Stoumont based on well-documented case studies.
The bark peeling algorithm requires the annual bark peeling rate (%) as input parameter, which reflects the ungulate pressure level, especially red deer (*Cervus elaphus*) in this case, and has been found to not only depend on population density but also on other factors such as the environmental carrying capacity, the

landscape structure and the severity of winter conditions[1]. The bark peeling process is modelled year by year at the tree level. In a first step, bark peeling occurring in the current year is shared between trees already peeled previously and individuals still unaffected using a model proposed by T. Gheysen (unpublished) expressing the percentage of bark peeling on healthy trees as a function of annual bark peeling rate and the percentage of already peeled trees. A set of healthy trees to be peeled in the current year are then selected to reach the estimated percentage. These healthy trees to be peeled are chosen considering a probabilistic model describing the sensitivity of trees to bark peeling as a function of trunk circumference at breast height. Bark peeling damage is then applied on these selected trees by specifying the damage height, width and length by drawing these values from probability distributions fitted using bark peeling monitoring data[2]. Finally, for each bark-peeled tree, the development of stem decay is described using a model relating total decay length to tree social status, damage width and length, time since damage occurred and the average annual girth increment[3]. In the evaluation of financial profitability using the ECONOMICS2 library (see below), the market value of the stem part showing decay (purge) is considered to be zero, and the value of the healthy part is determined as that of a tree whose circumference at breast height is equal to the circumference of the trunk at 1.3 m above the purge. In this way, the value of the healthy part is somewhat overestimated as the increase in taper and relative importance of knots with height is not accounted for, which compensates for the fact that the purge could in reality be at least partly valued as trituration. This overcomes the difficulty in estimating the price discount to be applied for the healthy part.

Task 1.4 Assessment of forest production and diversity

At the beginning of this project HETEROFOR provided reliable estimates of tree growth but did not provide outputs, such as economic indicators, that were needed to compare management scenarios. As we aimed to develop a highly integrated decision-support tool, new functionalities had to be added in HETEROFOR to better assess forest diversity, timber production and financial profitability.

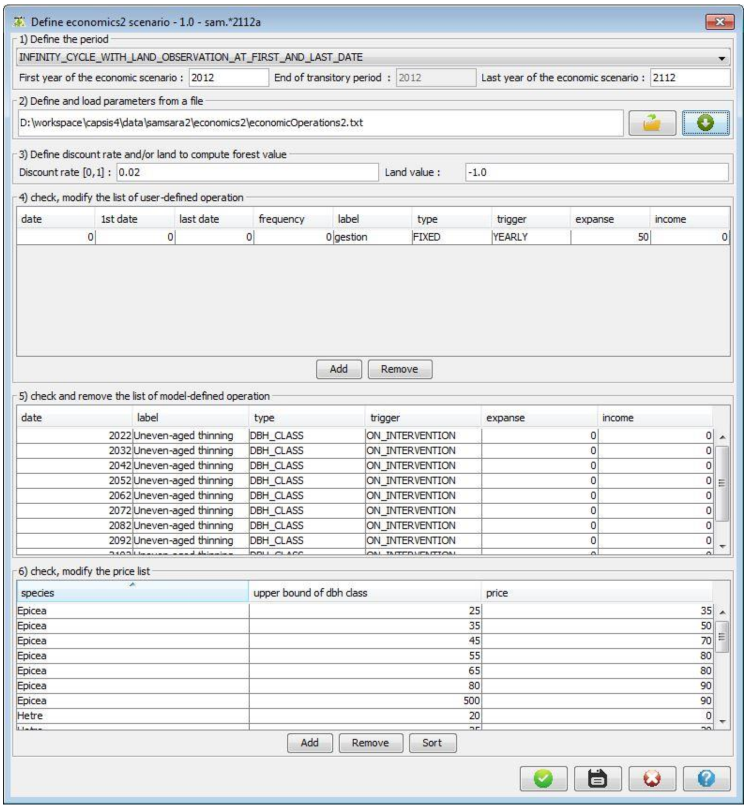

Figure 1. Graphical user interface that can be used to define the required economical parameters.

As planned, we connected the model HETEROFOR to the ECONOMICS2 library developed by G. Ligot, both tools being implemented in the CAPSIS simulation platform. Thanks to this work, it is now easy to assess the profitability of forest management scenarios that are simulated with HETERFOR. Once a simulation is completed, the user can set the required economical parameters (ex. Discounting rate, price lists) using a graphical user interface (Fig. 1). When the parameters are set, the user can compute various economic indicators such as the net present value, the variation of forest value through time, the annuity, the internal rate of return, etc.

The ECONOMICS2 library has moreover been improved to provide reliable economic indicators for uneven-aged and mixed forests. In particular, the computation of annuity indicators has been corrected and new features have been added such as plots to show the variation of stumpage prices through time et across diameter classes.
Moreover, a detailed user guide has been written (https://orbi.uliege.be/handle/2268/263994). This document not only provides step-by-step instructions on how to use ECONOMICS, but also presents the essential theoretical notions to be able to repeat and interpret the calculations.

The determination of several forest diversity indicators has been implemented in HETEROFOR. A first set of indicators are the widely used species richness, Shannon[4, 5] and Simpson[6] indices, which quantify the number of species in presence, community entropy (combining information on species richness and evenness) and species dominance, respectively. The species proportions used to compute the Shannon and Simpson indices are expressed in terms of basal area. Another set of diversity indicators accounts for the spatial arrangement of trees. Among them, the Clark and Evans index[7] describes the positioning of trees based on density and on distances among neighbours. It expresses the extent to which the spatial arrangement of trees deviates from that of a completely randomised positioning following a Poisson distribution, in which case it equals to 1. It takes values lower than 1 if clumping of trees occurs in the stand, while it presents values larger than 1 in regular positioned stands and shows the maximum value of 2.1491 in case of hexagonal arrangement of trees. A modified version of the original Clark and Evans index, minimising edge effects[8], has also been implemented in HETEROFOR. Besides, the Von Gadow mixture index[9] describes the spatial association among species within a stand. It can take values between 0 and 1, with low values indicating dominance of one or few species arranged in clusters and high values revealing intimate mixtures of species in the stand. Finally, two other implemented spatial diversity indicators are the horizontal and vertical differentiation indices of Von Gadow[8, 9] which characterise the heterogeneity of the stand structure in terms of trunk circumference at breast height and total height of the trees, respectively. In other respects, aside from tree attributes and spatial organisation, tree-related microhabitats (TreMs) are also used as surrogate biodiversity indicators. TreMs are “distinct, well-delineated structures occurring on living or standing dead trees, that constitute a particular and essential substrate or life site for species or species communities during at least a part of their life cycle to develop, feed, shelter or breed”[10]. They constitute an important tool for forest managers, notably to guide the selection of habitat trees for the conservation of biodiversity[11]. The formation of TreMs was implemented in the model based on the works of Courbaud *et al.*[12, 13] and by adapting to HETEROFOR the code initially developed by this author in Samsara2, a model of the CAPSIS simulator devoted to the modelling of the growth of mountain forests. The occurrence of TreMs may then be expressed as biodiversity level through a score integrating the size, the frequency, the degree or rarity and the replacement speed of TreMs appearing on trees during simulations[14]. The values of all these indicators can be exported for each year of the simulations allowing both to analyse their temporal evolution over the simulated period and to provide averages for the complete period or for sub-periods.

Task 1.6. Impact of extreme climate events (new task)
In the project proposal, we planned to add a soil carbon module to HETEROFOR in order to be able to estimate the total carbon sequestration by the ecosystem (including the soil component). However, during the first follow-up meeting, we decided to give priority to the modelling of extreme event impacts since their frequency is likely to increase in the future and to strongly impact the structure and functioning of forests (see point 6.). During the first year of the project, we implemented a new library in the CAPSIS simulator to describe wind damages based on a tree level approach. This library is largely inspired from ForestGALES TMC (turning moment coefficient) described in Hale *et al.*[15] and already available as a R package[16]. For each tree, our new library estimates the critical wind speed for overturning or breakage depending on tree

characteristics (species, size, crown and stem green mass), local environment and the phenology phase. This critical wind speed is then compared to the max gust speed at the top of the tree estimated from the hourly wind speed and by taking the vertical wind profile within a stand into account. The subsequent impacts of fallen trees on their neighbours are also considered. When the neighbouring trees are smaller than the fallen one, close to it and located in the falling direction, they are also broken or overturned. Similarly, the damages to the regeneration cohorts can be accounted for by estimating the area impacted by the falling crowns and by reducing accordingly the cohort cover.

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 complementary data needed to be added.

Task 2.1 Regeneration dynamics

In situ monitoring of advanced regeneration dynamics in broadleaved forests

In broadleaved forests, the growth of juvenile trees growing in the understory has already been well described by Ligot *et al.*[17] but this work was limited to juvenile trees of less than 3-4 meters in height. To be able to accurately model the growth of small and tall juvenile trees (poles hereafter), we collected new data about the growth, mortality, and density of poles.

Initially, we planned to monitor pole growth and mortality in a selection of 7 plots out of the 27 fenced plots studied by Ligot *et al.*[17]. Finally, we acquired data in 10 sites. In all sites, most poles were taller than 3 meters and smaller than 8 meters. 5 sites were established in beech-dominated pole clumps and 5 sites were established in oak-dominated pole clumps. In each site, 10-30 poles were selected and marked among the dominant poles without important defect (forks, wounds, …). The diameter at breast height (dbh) and the height were recorded for each of these poles. The selected trees were spaced at least 4 meters apart. Additionally, a circular plot of about 50 poles (plot radius of 3-3.5 meters) was established in the middle of each studied clump. The dbh and the height of all trees in these plots were also measured (Fig. 2).

Figure 2. Monitored oak-dominated clumps. The poles with a blue mark are located within the circular plots and the poles with a yellow mark and a plastic tag are the dominant selected poles.

In situ monitoring of regeneration dynamics in coniferous forests

In coniferous forests, the natural regeneration has been monitored since 2015 in the Belgian Ardennes within 108 plots installed at 9 sites. Though the monitoring of this network of plots is funded by another project, the collected data will be available to the REGE+ project. During the winter of 2021-2022, all the plots of this network were monitored as planned. With this data, it is therefore now possible to compute regeneration dynamics parameters in the understory of coniferous stands over a valuable 6-year period.

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. 971 pairs of plots were installed in 2016, 734 pairs of plots were measured until 2021 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 mostly settled in broadleaved forests managed in the continuous cover forestry system (493 pairs of plots), under conditions assessed as compatible with the regeneration growth. Some plots were also installed in coniferous and mixed stands (190 pairs of plots), and only 26 pairs of plots in clearcuts.

In plots of 6 m², the measures encompass the height of the 5 tallest saplings of one or two 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 and red deer standing population estimates from the DEMNA. These estimations are available at the hunting management district level.

During the first year of the REGE+ project, statistical analyses were carried out using this dataset. They particularly aimed at evidencing and quantifying the regeneration height reduction by ungulates. A scientific publication should soon be submitted with these analyses (see point 3.). In addition, explanatory variables have been computed to further evaluate the impact of ungulates in terms of biomass intake and model this impact with ungulate densities.

Nevertheless, this dataset needed to be completed as it could only be used to model ungulate impact on regeneration at the plot scale and not at the seedling scale. To calibrate our modelling approach, it appeared important to collect additional observations of recent browsing on individual seedlings. These measurements aimed to model the probability of a seedling to be browsed as a function of seedlings size, species, and environmental conditions and to estimate the amount of biomass consumed by ungulate for each browsed seedling.

The additional measurements were carried out in > 100 unfenced plots scattered across 3 forests with contrasted ungulate densities. In each of these plots, 4 seedlings were sampled per height class (]10-60],]60-120] and]120-180] cm) of each present species. The height and collar diameter were measured for all these sampled seedlings. For each seedling, the apical shoots and 5 lateral shoots were also measured. We measured their length, the diameter at the basis of the shoot, the height of the basis of the shoot and we noted whether these shoots had been browsed.

Additionally, the surrounding environmental conditions were assessed. We measured the basal area of the surrounding trees as well as the vegetation cover of bramble, the proportion of browsed bramble stems[18] and the density of ungulate faeces as a proxy of local ungulate density. This work was mainly performed by Mérilie Diacre during her Master thesis (Gembloux Agro-Bio Tech, ULiège).

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 is 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) were set up. Each experimental zone consists 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 is 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 is around 1.5 m and 2.5 m high at its lowest and highest sides, respectively, and was adjusted depending on the height of the seedlings underneath it. Besides, a plastic sheet was 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 (Fig. 3). The control unit (2 x 2 m area) was 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 were replicated three times for each considered species (sessile oak and European beech), resulting in a total of six experimental zones (blocks).

Figure 3. Partially covered roof installed above seedlings to induce artificial drought.

Measurements are 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 32 seedlings was 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, 100-150 cm and >150 cm height classes. These seedlings were labelled with a unique identifier and seedling height and collar diameter are measured on each of these selected individuals. Besides, complete counting of the alive and dead seedlings is carried out in each experimental unit. These observations were performed both at setup installation (March 2021) and in March 2022 and will be repeated every year all over the experiment duration in order 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 are continuously monitored in each experimental unit using, respectively, time domain reflectometry (TDR) and thermistor sensors.

Data collected during this first experimental year are currently under processing.

WP3. Establishment of climate projection scenarios
Task 3.1 Downscaled and bias-corrected multi-variable projections

Data provision

Datasets, as specified in Table 1, with raw downscaled climate time series over Belgium have been provided to UCLouvain at the Belgian plot sites (Deliverable 3.1.1). These datasets include reanalysis data from ERA5, a EURO-CORDEX climate projection with the Regional climate model RCA4 forced by the global model MPI-M-MPI-ESM-LR, and, high-resolution climate projection over Belgium with the ALARO-0 model. The climate variables include radiation, air temperature, soil temperature, rainfall, relative or specific humidity, rainfall and wind speed and direction.

Table 1. Raw model projection data provided.

Dataset	Time frequency	Spatial resolution	Data type	Time period
ERA5	1-hr	30-km	reanalysis	1979-2019
EURO-CORDEX	3-hr	0.11° or 0.44°	Model (RCA)	1950-2100 (RCP2.6, RCP4.5, RCP 8.5)
ALARO-0	1-hr and 3-hr	0.11° and 4-km	Model	1950-2100 (RCP2.6, RCP4.5, RCP 8.5)

Bias correction method for extreme rainfall

The effects of climate change will mostly be felt through the change in frequency and intensity of extreme events including droughts but also intense rainfall. A common tool to quantify extreme droughts in a climatological sense are the so-called severity–duration–frequency (SDF) curves. These provide one for instance with the drought severity of a drought of duration of 6 months that occurs only once in twenty years (so with a frequency of 1/20 years). The equivalent tools for extreme rainfall are called intensity–duration–frequency (IDF) curves, commonly used in hydrological investigations. Such curves are commonly used to quantify changes in extremes due to climate change.

Heavy precipitation is known to have major impacts on society, including crop damage, soil erosion, landslides and increased flood risk. In Belgium this again became dramatically clear in July 2021. In recent years, there is a growing body of evidence that anthropogenic climate change has intensified extreme precipitation on the global scale. Both regional and global climate models predict that this will continue as the climate warms. However, trend analysis or climate-change attribution of local rainfall extremes remains particularly difficult for many reasons including the intermittency of rainfall and the lack of long time series. Robust signals can be obtained using large climate-model ensembles or spatial averaging[19], but methods of analysis generally do not exploit relationships between rainfall extremes and duration. Models used to produce climate projections are known to exhibit systematic biases and therefore require bias correction that should be tailored for a specific purpose.

Recently Schmith *et al.*[20] identified bias adjustment methods for extreme precipitation and applied them to high return levels of hourly and 24-hourly rainfall from EURO-CORDEX ensemble projections at 0.11° resolution. In addition, they proposed an alternative approach based on quantile mapping of extreme value distributions. Taking this work as a starting point, we extend and improve in a number of aspects. While they considered hourly and 24-hourly extremes, we incorporate information for various predefined precipitation durations, using the so-called “scale invariance” (see Fig. 4 Left). Using a pseudo-reality approach, we compare the method with existing ones, based on hourly precipitation from 28 Regional Climate Model (RCM) projections of the EURO-CORDEX ensemble over Belgium. We show that this leads to improved adjustments. Additionally, we identify technical complications with analytical quantile-based methods, associated with bounded probability distributions.

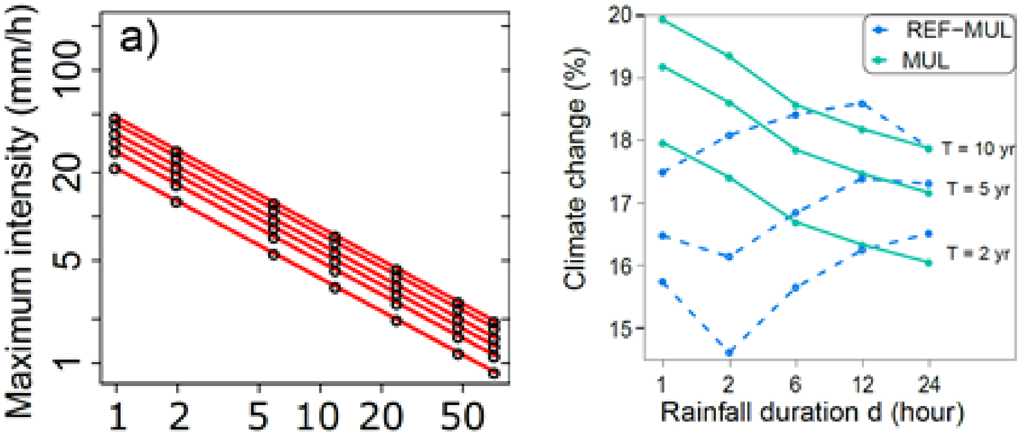

Figure 4. Left: An example showing the bias-corrected return levels against rainfall accumulation time in hours (x-axis) for different return levels (red lines for T = 2, 5, 10, 20, 50 and 100 year). Right: Relative climate changes of the IDF-values at the end of the century following the RCP8.5 scenario. The results are averaged over the 28 EURO-CORDEX members and 18 station locations.

Fig. 4 (left) shows an example of the return-level dependence on the rainfall duration (x-axis). The red lines indicate the fits for different return periods and show that the intensities satisfy the linear scaling relation. Apart from the methodological development Fig. 4 (right) also shows the climate change as a function of the rainfall duration. The changes of the new MUL methods are larger for short-duration rainfall events, in contrast to the result of the conventional method REF-MUL that shows inconsistent behaviour.

A manuscript has been written and was submitted[21]. An extension of this methodology from the context of extreme rainfall (IDF curves) towards droughts (SDF curves) is planned and will help to better quantify the impact of climate change on droughts in Belgium.

WP4. Definition of silvicultural and wildlife scenarios

Task 4.1 Selection and characterization of case studies

A set of 11 sites, representative of the main forest types to be regenerated within the next 40 years in Belgium, was selected as case studies. Several of these sites are part of the Long-Term Ecosystem Research (LTER) and the International Cooperative Program on Forests (ICP-Forests, level II sites) networks for which data series over more than 20 years are available while others belong to the IRRES network installed to study the conversion of even-aged stands into uneven-aged ones. The selected sites are dominated by the major forest tree species in Belgium and encompass different species compositions and structures. These stands will be used as initial stages for the simulation experiment. Their main characteristics are presented in Table 2 and a more detailed description together with the corresponding input data files for the HETEROFOR model are available on the REGE+ website.

Table 2. Main characteristics of stands selected as case studies for the REGE+ project.

Site	Dominant species	Ecoregion	Structure	Density (trees/ha)	Basal area (m²/ha)	Mean girth (cm)	Dominant height (m)
Baileux							
Oak-dominated plot	*Quercus petraea*	Western Ardenne	Even-aged with regeneration	391	28.2	95	26.5
Mixed plot	*Quercus petraea* & *Fagus sylvatica*			302	29.4	111	28.5
Beech-dominated plot	*Fagus sylvatica*			280	29.5	115	27.0
Virton	*Fagus sylvatica* & various broadleaved	Belgian Lorraine	Uneven-aged	248	27.1	117	32.3
Wellin	*Quercus petraea* & *Fagus sylvatica*	Ardenne	Even-aged with regeneration	204	22.0	116	27.0
Eupen	*Fagus sylvatica*	Eastern Ardenne	Even-aged with regeneration	226	24.3	116	28.9
Louvain-la-Neuve	*Fagus sylvatica*	Loam region	Even-aged with regeneration	85	26.6	199	32.4
Buchholz	*Picea abies*	Eastern Ardenne	Even-aged in conversion to uneven-aged	355	35.0	111	34.6
Les Fossés	*Picea abies*	Southern Ardenne	Even-aged in conversion to uneven-aged	232	29.7	127	31.9
Gedinne	*Picea abies*	Ardenne	Even-aged with regeneration	220	31.8	135	32.0
Petit-Thier	*Pseudotsuga menziesii*	Eastern Ardenne	Even-aged in conversion to uneven-aged	176	43.4	176	39.2
Séviscourt	*Pseudotsuga menziesii*	Ardenne	Even-aged in conversion to uneven-aged	180	43.5	174	38.0
Louvain-la-Neuve	*Pinus sylvestris*	Loam region	Even-aged	314	34.0	117	21.1

WP7. Valorisation, dissemination, exploitation of results

Task 7.1 Website design and management

A website has been designed for the REGE+ project and is available at https://www.regeplus.be/ and serves as a platform for project overview, for result and model dissemination and for interactive exchanges with stakeholders and end-users. It consists of different sections. A first section gives a general presentation of the project, describing the research context, its objectives and the expected impacts. A second section presents the HETEROFOR model and its functionalities and provides access to an installer containing a recent version of the model and to the model user manual. It is regularly updated as improvements are made to the model. A third section describes in detail each case study selected for the project and contains links to the corresponding HETEROFOR input data files enabling to perform simulations. A fourth section is devoted to the presentation of the project results and is designed as a blog allowing for interactive exchanges with stakeholders and end-users. A fifth section describes the main datasets used to initialize, calibrate and evaluate the model as well as outputs from the simulations. Finally, other sections are dedicated (i) to the news and events (e.g., meetings, field trainings, training courses) related to the project, (ii) to project detailed description, reporting and scientific and popularization publications associated with the project, (iii) to the presentation of the project partners and follow-up committee and (iv) to contact request with the project partners. The website is hosted at UCLouvain.

3. INTERMEDIARY RESULTS

After 5 growing seasons (2016 to 2021), the 734 fenced-unfenced pairs of plots allowed foreseeing an important ungulate impact on the species composition of the recruited trees. Strong growth contrasts occurred across treatments and species (Fig. 5). The growth of some species was only moderately reduced, whereas others did not grow under ungulate pressure. The first will dominate the future stands, the latest remains very underrepresented under ungulate impact. The highest seedlings, and those with the fastest growth have the greatest survival probability. Even if no seedling outreached the height limit of browse sensitivity in most plots, the impacts on the growth ranks should be consistent with the recruitment success of the species.

Based on the growth potential and its realisation under ungulate impact, the 6 most frequent species can be classified in 3 groups as defined by Walters *et al.*[22]. Beech (*Fagus sylvatica* L.) and spruce (*Picea abies* (L.) H. Karst) belong to the *broad* group, these species are frequent, shade tolerant and lowly browsing sensitive. They have the ability to regenerate under the broadest range of light and ungulate pressure. Birch (*Betula pendula* Roth) and rowan (*Sorbus aucuparia* L.) belong to the *high-light* group. They have a higher growth potential when light is sufficient, but are highly browsing sensitive and shade intolerant. Oak (*Quercus* spp.) belongs to the *nowhere* group. His growth potential is the smallest and it is palatable for ungulates. Oak does not have regeneration niches in forest except when nutrient or humidity constraints the development of the other tree species. Finally, hornbeam (*Carpinus betulus* L.) shares common traits both with *high-light* (high growth potential and palatability) and *broad* groups (high growth under ungulate impact).

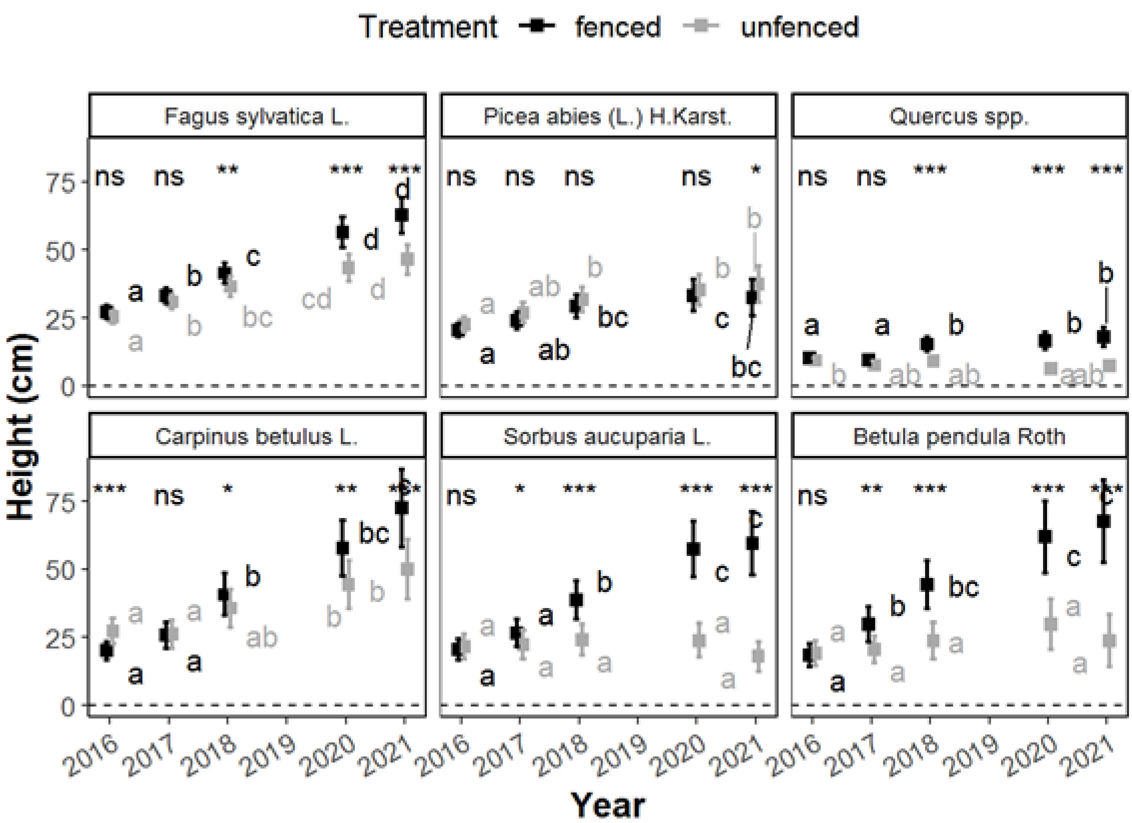

Figure 5. Evolution of seedling height through time in the fenced and unfenced plots. Within a species and a treatment (fenced or unfenced), mean height without common letters are significantly different following the max-t test. The indications above the means of a given species provide significance of the differences following student t. test or Mann-Whitney rank sum test when differences were not normally distributed. Means are displayed with their 95% confidence intervals. The impact of ungulates is particularly strong on oak, rowan and birch seedlings.

The results show that ungulates drastically reduced the recruitment potential for high light species since they did not grow in the unfenced plots. When these species were present in the fenced plots, they had however the fastest growth (Fig. 5). Ungulate impact is also important for oak but they are not the only factor causing a recruitment bottleneck. The growth of oak seedlings was generally lower than that of the admixed species in both fenced and unfenced plots. Finally, the *broad* group is favoured comparatively to the others under the sampled conditions since this is the only group with significant growth in the unfenced plots.

As the less frequent species mean growth was reduced to zero by ungulates, the resultant species assemblage is less diversified (Fig. 6A). Moreover, the *broad* species are not the species the most tolerant to drought and heat conditions. Ungulates thus also reduce the forest ability to face the rising intensity and frequency of climate extremes in the future. At the end of the study period, the ecological affinity indexes (EAI, Fig. 6) of the seedling assemblage show that the seedlings are composed of less heat and drought tolerant species (Fig. 6B, C) and more shade tolerant species (Fig. 6D).

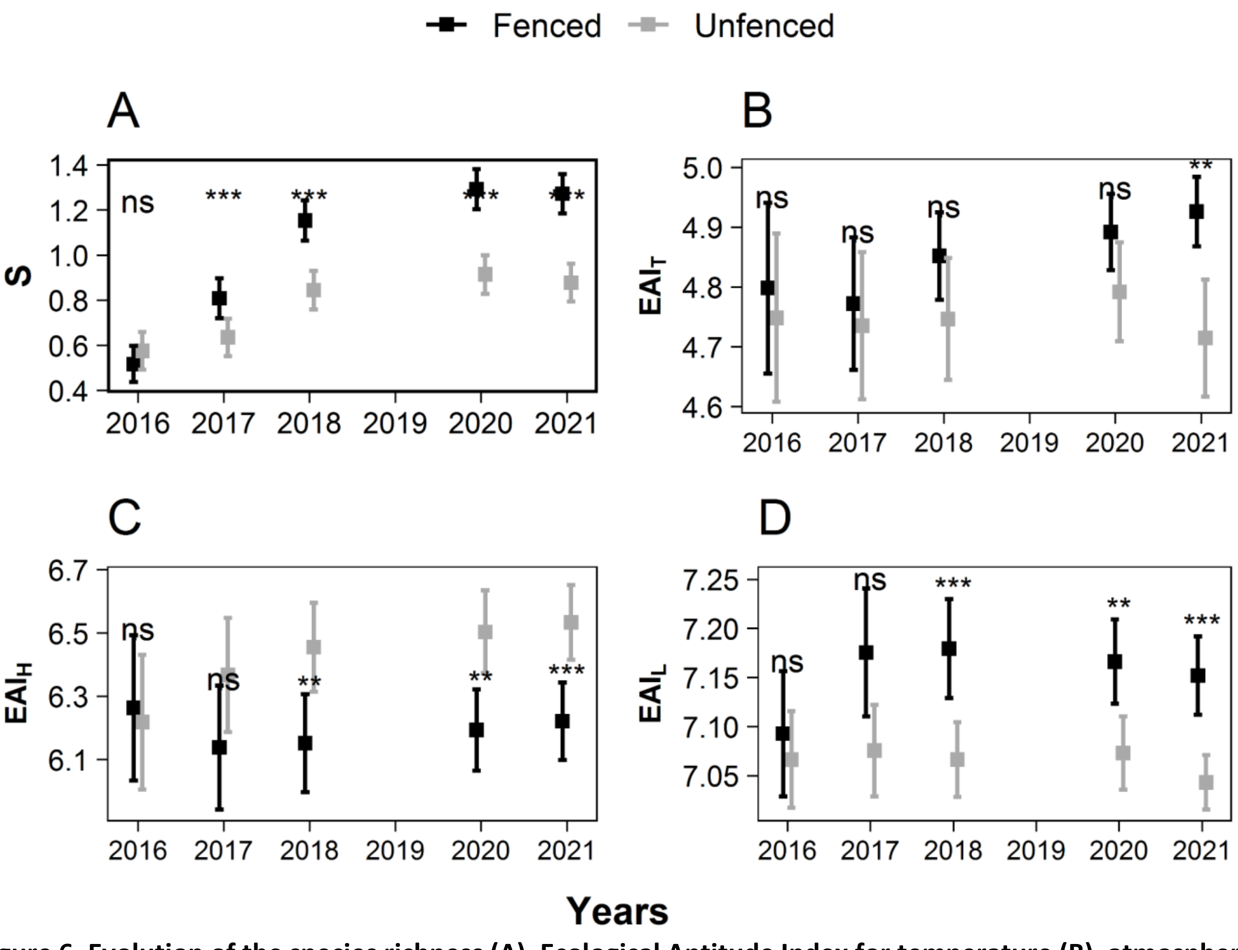

Figure 6. Evolution of the species richness (A), Ecological Aptitude Index for temperature (B), atmospheric humidity (C) and light (D) in the fenced and unfenced plots. The species richness is computed as the number of species with minimum one seedling taller than 50 cm. As seedlings can survive one year after the germination through the reserves of the seed before they disappear, excluding seedlings below 50 cm is more consistent with the future forest species composition. The EAI are height weighted means of the seedling species aptitude scores from the *baseflore* database[23]. The means are displayed with their 95% confidence intervals.

In conclusion, the results evidence a strong impact of ungulates on the height growth of palatable species, that are also the most light demanding. As these species are more adapted to droughts and heat extremes than the browsing resistant species, managers will have to regulate ungulate population to improve their regeneration success and the forest adaptation to global changes.

4. PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS

One year after its start, the project is progressing as planned. No major difficulty was encountered. Most of the developments required to adapt the HETEROFOR model to the needs of the project have been implemented. These model improvements are assessed using data collected during regeneration monitoring campaigns. Seedling growth measurements were done in long-term regeneration monitoring plots and within experiments set up to evaluate ungulate (fenced – unfenced plots) or climate change (drought) impacts on seedling development. These data have already enabled to highlight the short-term effect of ungulates on the development of regeneration and its specific composition. Through modelling, we will be able to study the long-term impact on stand growth dynamics and ecosystem services. The sites to be considered for the simulation experiment have already been selected. Before launching the simulations, the silvicultural scenarios to apply still have to be defined in consultation with forest stakeholders and the climate projections have to be corrected.

In other respects, a web site has been launched. It presents the project and is used as a platform for disseminating the project outcomes as well as for interactive exchanges with stakeholders and end-users.

5. FUTURE PROSPECTS AND PLANNING

WP1. Model improvements

<u>Task 1.2 Ungulate impact on regeneration</u>

The ungulate browsing routine requires the total biomass to be browsed as input. In the coming months, we will implement a new option allowing us to calculate this browsed biomass based on

- the red deer, roe deer and boar population densities,
- their body mass,
- their energy requirement,
- their diet composition,
- and the energy content of seedlings, seeds and external food supply.

This improvement will be done in the framework of Matt Willecomme's master thesis whose objective is to simulate the regeneration and long-term stand dynamics under various scenarios of ungulate pressure, climate change and silvicultural treatment. He selected and characterised two broadleaved stands at different development stages (case study approach) in the communal forest of Stoumont where ungulates are very abundant.

<u>Task 1.4 Assessment of forest production and diversity</u>

The connection between HETEROFOR and the ECONOMICS2 library is now functional and the library can be used to assess the profitability of simulation scenario under the classic Faustmann hypotheses (e.g., present value of perpetual series of costs and revenues, internal rate of return). As initially planned, 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.[24] 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.

This task is planned to be addressed at the end of the REGE+. Before starting this task, it is necessary to improve the HETEROFOR model (ex. implementing models of the impact of ungulate on regeneration) and hire a new person for this task.

Task 1.5 Assessment of climate services

Forests interact with the atmosphere through exchanges of energy, carbon dioxide and water and influence thereby the climate, either amplifying or mitigating 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. On the other hand, studies have shown a gain in tree growth associated with the CO2 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.

These forest climate services will be assessed in HETEROFOR. Carbon sequestration in biomass and evapotranspiration are already among the outputs of the model. Regarding albedo, it will be implemented as proposed by Planque[25] based on radiative transfer modelling through the canopy (Fig. 7). Using a simplified approach, forest albedo (αforest) may be formulated as:

$$\alpha_{forest} = (1 - T)\alpha_v + T^2\alpha_s$$

in which T is the canopy transmittance and α_v and α_s are the soil and vegetation albedos, respectively. Values for α_v and α_s may be found or modelled from literature while T would be provided by the canopy radiative transfer already implemented in HETEROFOR through the SAMSARALIGHT library of CAPSIS.

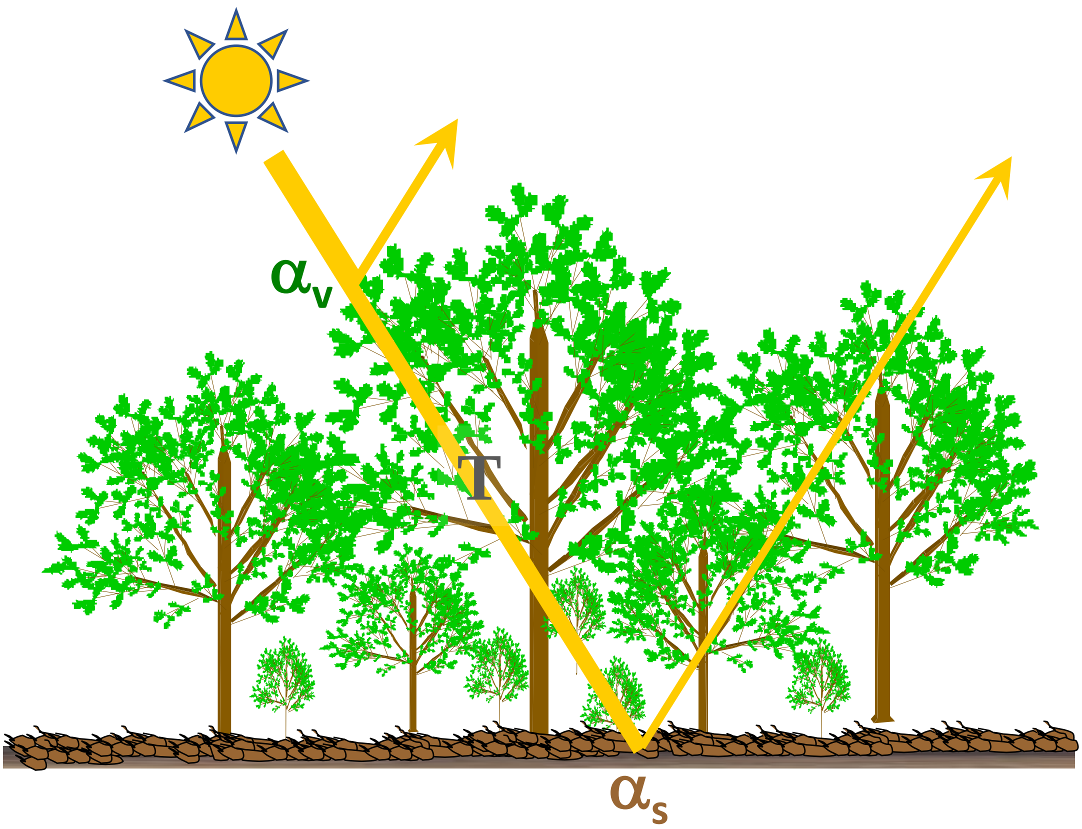

Figure 7. Schematic representation of the approach considered for forest albedo determination with HETEROFOR.

WP2. Data acquisition and use

Task 2.1 Regeneration dynamics

The monitoring of broadleaved and coniferous regeneration will be carried out every two years. As the last field measurements occurred between October 2021 and March 2022, the next field measurement will be carried out in the winter of 2023-2024 and 2025-2026.

In the meantime, the data will be cleansed and shared to the collaborators thanks to the REGE+ website. The data about broadleaved regenerations is stored in a MS Access database whereas the data about coniferous regeneration is today stored in a Firebird database that will be soon converted into a PostgreSQL database.

Additional measurement will likely be performed. In particular, the trees around the studied pole clumps should be measured once again. These trees were last mapped and measured in 2013 by Ligot et al. (2013) (Fig. 8). Since then, the trees have grown and, more importantly, some of them have been harvested. Therefore, the competitive environment around the pole clumps has changed. As we aim to use this dataset to calibrate models of pole growth and mortality as functions of the competitive environment (e.g. as function of the amount of intercepted light, Fig. 8), it is important to update the old measurements. Every tree with a girth larger than 40 cm and within less than 20 meters from the studied pole clump (or from the fence) will be mapped and measured. The studied tagged poles as well as plot centers will also be mapped.

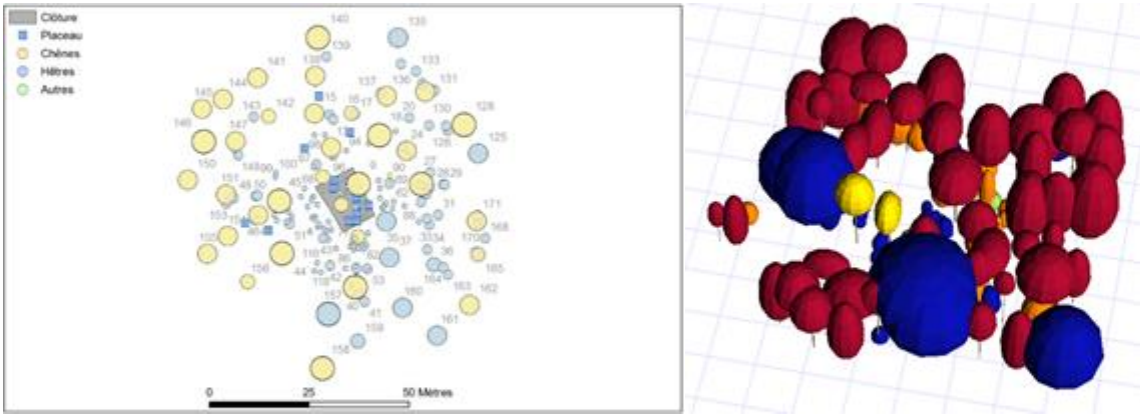

Figure 8. The trees around studied regeneration were mapped and measured. These measurements are used to build 3D mock-ups of the stand in order, for example, to compute the amount of light that is available for each tree, poles and seedlings.

Regarding the rainfall limitation experiment, seedling counting and measurements (see point 2.) will be repeated every year and soil water content and temperature monitoring will be continued throughout the project duration. Furthermore, seedling biomass measurements will be carried out on individuals from both the 'treatment' and the 'control' modalities. These measurements will allow to improve the modelling of seedling growth and development in HETEROFOR through a better quantification of the effects of water shortage on these processes.

WP3. Establishment of climate projection scenarios

Task 3.1 Downscaled and bias-corrected multi-variable projections

Climate data provision

During a WP3 meeting in December 2021, it was decided to calculate climate change signals for all the global-regional climate model combinations available using first a classical bias-correction method for the locations below and deliver the results as text files readable by HETEROFOR. In the next phase, a more sophisticated bias-correction method (multivariate) will be used for the same variables and locations. Since providing a good estimate of projection uncertainty is seen as essential, it was decided during a recent meeting (March 30 2022) that as much projection data as possible will be used. Even though some sub-daily meteorological data from the EURO-CORDEX models is available, most models do only provide only daily data. Additionally, global circulation models from CMIP6 also only provide daily data. On the other hand, HETROFOR describes climate dependent processes at an hourly timestep and requires hourly meteorological data. As a result, for cases for which only daily data are available, a temporal downscaling method will be worked out to go from the daily to the hourly timescale. A literature study to perform a tailored approach per variable will be done.

Projection analysis
A table will be produced summarising the mean climate changes for the different climate variables, the various RCP scenarios and for each global-regional climate model combinations. This table will also include the mean bias for the different climate variables.

Task 3.2 Bias correction methodologies
Different multivariate bias-correction methods will be tested and explored for the different sites over Belgium. The impact of the bias correction on the droughts will be analysed. The bias correction techniques will be applied to the sub-daily EURO-CORDEX ensemble available and provided to the project partners. A representative selection of the ensemble members will be proposed based on drought-based metrics to reduce the dataset and the required simulations with HETEROFOR.

WP4. Definition of silvicultural and wildlife scenarios
Task 4.2 Definition of silvicultural scenarios
The silvicultural scenarios to be applied to the selected case studies in the simulation experiments (WP5) will be established from exchanges with forest and forest-related sector stakeholders. 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
The impact of ungulate on regeneration development depends on the intensity of the damages, the amount of consumed biomass and its repartition across species. This partly depends on ungulate abundance but also on environmental factors. Work is going on to model the relationships between these variables (Task 2.1). Depending on the results of this work, different wildlife management strategies will be defined. They will be defined in terms of intensity of the damages (e.g., browsing rate), the amount of biomass consumed by ungulates and/or the density of the different species of ungulates

WP7. Valorisation, dissemination, exploitation of results
Task 7.2 Dissemination through publications and meetings
Deliverables planned for the coming year:

Deliverable 7.2.1: Article in peer-reviewed journal about the modelling of ungulate damage on regeneration (Month 20)

Deliverable 7.2.2: Article in peer-reviewed journal describing the module for organic carbon dynamics and its validation (Month 20)

Deliverable 7.2.3: Article in peer-reviewed journal describing the new bias correction method applied to the climate projections (Month 18)

Deliverable 7.2.6: Article in peer-reviewed journal describing the new regeneration module and its validation (Month 26)

Deliverable 7.2.9: Popularisation article presenting the climate change in Belgium by 2100 and potential implications for forestry (Month 15)

Deliverable 7.2.10: Popularisation article presenting the project results regarding the ungulate and drought impact on natural regeneration in the Belgian forests (Month 22)

Task 7.3 Organisation of meetings with the stakeholders and end-users
Meetings with forest stakeholders will be organised so as to exchange with them on the first results of the project and to benefit from their expertise for the definition of the silvicultural scenarios and the wildlife management strategies to be considered for the simulation experiment of WP5.

6. FOLLOW-UP COMMITTEE

A meeting of the follow-up committee was organized on October 19 2021. Beyond the presence of each project partner, 10 representatives from regional and national forest and environment services (i.e., Département Nature et Forêt (DNF), Cabinet du Ministre Willy Borsus, Office économique wallon du bois (OEWB), Département de l'Étude du milieu naturel et agricole (DEMNA), Commune de Stoumont, Office National des Forêts (ONF)), research organisations in the fields of environment and climate (i.e., Institut Royal Météorologique (IRM/KMI), Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAe)) and non-profit organisations in forestry and nature conservation (i.e., Société Royale Forestière de Belgique (SRFB), Forêt.Nature) attended the meeting.
The project partners presented the project and the different work packages in turn. These presentations generated very rich discussions underlining the interest of the project for the various members of the committee and allowing to better specify the work to be carried out. The main points decided/suggested during this meeting are:

- to lower the priority for the implementation of a soil organic carbon module (Task 1.3 in the project proposal). Indeed, the modelling of soil organic carbon dynamics is complex, with a large number of compartments to be considered, and the availability of the data required for their initialization is quite limited which requires to make strong assumptions. Furthermore, while relevant as model output, soil organic carbon has no implication on other processes described in the model. In addition, this aspect was considered as somewhat out of scope during the project evaluation;
- to dedicate the time originally reserved for soil carbon modelling to the consideration of the effect of extreme events (i.e., storms, droughts, late frosts) in the simulations as these events are likely to play a critical role in the response of forest ecosystems to climate change. Though the increase in their frequency is a major concern for foresters, their consideration remains limited in existing modelling approaches. It is also suggested to investigate the possibility of accounting for attacks by pathogens/pests;
- add a study case representative of pine stands on sandy soil. Such a stand, located in the bois de Lauzelle, is currently characterised in the framework of a master thesis and the corresponding data will be available for the REGE+ project;
- to identify the most sensitive climate variables for the simulations through sensitivity analyses. It is also recommended to carry out simulations with a maximum of climate projections to encompass the uncertainty associated with climate scenarios;
- to draw up the management scenarios to be tested in close consultation with managers, including in particular the DNF;
- to characterise the climate scenarios by considering the warming instead of the radiative forcing, the latter being less meaningful for the manager.

7. VALORISATION ACTIVITIES

7.1 PUBLICATIONS

An article has been written, presenting the compared vegetation development in the 734 fenced-unfenced plots network across a major part of Ardenne and Famenne region. The foreseen consequences of the ungulates impact on the species composition are discussed with considerations to the forest succession dynamic, tree diversity and resilience of the forest to face the ongoing climate changes. The management options to diversify the forests under ungulate pressure are also discussed. Co-authors are currently reviewing the manuscript. It will be submitted to the journal : Current Forestry Reports. (*Deliverable 7.2.1*)

7.2 PARTICIPATION/ORGANISATION OF SEMINARS (NATIONAL/INTERNATIONAL)

Oral presentations, posters… and/or organisation of workshops, conferences, etc.

A general overview of the REGE+ project and of its objectives has been presented at a popularisation conference on the ungulate pressure of ungulates on forest ecosystems organized by the "Plan Communal de Développement de la Nature" of Stoumont (September 17 2021)

7.3 SUPPORT TO DECISION MAKING (IF APPLICABLE)

One of the main objectives of the REGE+ project is to improve the HETEROFOR model and to apply it to a set of contrasted case studies so as to demonstrate its potentialities as a decision-making tool for the design of silvicultural and wildlife management scenarios and for testing their effects on forest dynamics, considering also climate changes. The model is freely available and would be of interest for a broad audience including notably scientists, forest managers and policy-makers.

7.4 OTHER

8. ENCOUNTERED PROBLEMS AND SOLUTIONS

Encountered problems/obstacles, implemented and/or considered solutions, if any.

9. MODIFICATIONS COMPARED TO THE PREVIOUS REPORT

9.1 PERSONNEL

In case modifications have occurred since the previous report regarding personnel in charge and at the disposal of the project, please list these in the following table conform the instructions given in the *Initial Report*. Send a copy of the employment contracts of the personnel in charge to brain-be@belspo.be.

Partner	Name	Nationality	Gender	Date of birth	Academic degree or certificate	Year of completion	Professional status	Time implication in the project financed by BELSPO (in FTE)	Type of labour contract	Annual gross salary	Time implication in the project financed by other source(s) (in FTE)	Name(s) of the other funding source(s)	Remarks
RMI	HOSSEINZADEHTALAEI Parisa	Iranian	F	1/2/1986	X (Civil Engineer)	2020	S	1 FTE	Cd	48 350 EUR (SW21)	0	NA	Parisa was hired on the REGE+ project on November 8 2021, until October 31 2022

9.2 COMPOSITION OF THE FOLLOW-UP COMMITTEE

The follow-up committee is composed of the following members:

- De Waele Valérie (Researcher, DEMNA)
- Licoppe Alain (Premier Attaché, DEMNA)
- Colson Vincent (Head of the small private property support unit, OEWB)
- Cléda Martin ("Hunting and Fishing" advisor, Office of Minister Willy Borsus)
- Barvaux Catherine (Chief of cantonment, DNF)
- de Wouters Philippe (Director of the Royal Forestry Society of Belgium, SRFB)
- Timal Grégory (Forestry researcher and trainer & Forestry expert, CDAF)
- Sanchez Christine ('Pro Silva' forestry trainer, Forêt.Nature)
- Monville Marie (Forest alderwoman, Stoumont)
- Balandier Philippe (Research director, INRAe)
- Deleuze Christine (Modelling research and development manager, ONF)
- Hamdi Rafiq (Researcher, RMI)
- Terlinden Michel (Forestry expert)

10. REMARKS AND SUGGESTIONS

Concerning for example: the coordination, the use or valorisation of the results, personnel change …

11. REFERENCES

1. Ligot G., *et al.*, 2013. Modeling recent bark stripping by red deer (Cervus elaphus) in South Belgium coniferous stands. Annals of Forest Science, 70: 309-318.
2. Gheysen T., *et al.*, 2011. A regional inventory and monitoring setup to evaluate bark peeling damage by red deer (Cervus elaphus) in coniferous plantations in Southern Belgium. Environmental monitoring and assessment, 181: 335-345.
3. Löffler H., 1975. The spreading of wound rot in Norway spruce. Forstwissenschaftliches Centralblatt, 94: 175-183.
4. Shannon C.E., Weaver W. The Mathematical Theory of Communication. University of Illinois Press, 1949.
5. Margalef R., 1958. Information theory in ecology. General Systems, 3: 36-71.
6. Simpson E.H., 1949. Measurement of Diversity. Nature, 163: 688-688.
7. Clark P.J., Evans F.C., 1954. Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations. Ecology, 35: 445-453.
8. Füldner K., 1995. Zur Strukturbeschreibung in Mischbestanden. FORSTARCHIV, 66: 235-240.
9. Von Gadow K., 1993. Zur bestandesbeschreibung in der Forsteinrichtung. Forst und Holz, 21: 602-606.
10. Larrieu L., *et al.*, 2018. Tree related microhabitats in temperate and Mediterranean European forests: A hierarchical typology for inventory standardization. Ecological Indicators, 84: 194-207.
11. Asbeck T., *et al.*, 2021. The Use of Tree-Related Microhabitats as Forest Biodiversity Indicators and to Guide Integrated Forest Management. Current Forestry Reports, 7: 59-68.

12. Courbaud B., *et al.*, 2017. Modelling the probability of microhabitat formation on trees using cross-sectional data. Methods in Ecology and Evolution, 8: 1347-1359.
13. Courbaud B., *et al.*, 2022. Factors influencing the rate of formation of tree-related microhabitats and implications for biodiversity conservation and forest management. Journal of Applied Ecology, 59: 492-503.
14. Larrieu L., Amberger C. Ecological tree scoring system based on TreMs for marteloscopes. Unpublished, 2021:5 p.
15. Hale S.E., *et al.*, 2015. Comparison and validation of three versions of a forest wind risk model. Environmental Modelling & Software, 68: 27-41.
16. Gardiner B., *et al.* fgr: R Version of the ForestGALES wind risk model, 2020.
17. Ligot G., *et al.*, 2013. Height competition between Quercus petraea and Fagus sylvatica natural regeneration in mixed and uneven-aged stands. Forest Ecology and Management, 304: 391-398.
18. Boulanger V. Pression d'herbivorie et dynamique des communautés végétales : influence à court et moyen termes des populations de cervidés sur la diversité des communautés végétales en forêt: Doctorat spécialité Biologie végétale et forestière de l'École doctorale RP2E, Université de Nancy, 2010:315 p.
19. Kreienkamp F., *et al.* Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021: World Weather Attribution, 2021:54 p.
20. Schmith T., *et al.*, 2021. Identifying robust bias adjustment methods for European extreme precipitation in a multi-model pseudo-reality setting. Hydrol. Earth Syst. Sci., 25: 273-290.
21. Van de Vyver H., *et al.*, submitted. Bias adjustment methods for future subdaily precipitation extremes consistent across durations.
22. Walters M.B., *et al.*, 2020. Deer browsing and shrub competition set sapling recruitment height and interact with light to shape recruitment niches for temperate forest tree species. Forest Ecology and Management, 467: 118134.
23. Julve P., 1998. Baseflor. Index botanique, écologique et chorologique de la flore de France.
24. Friedrich S., *et al.*, 2019. Economic impact of growth effects in mixed stands of Norway spruce and European beech – A simulation based study. Forest Policy and Economics, 104: 65-80.
25. Planque C. Observation satellitaire et modélisation de l'albédo des forêts sur le territoire français métropolitain : dynamiques temporelles et impacts radiatifs. Climatologie. Toulouse, France: Université Paul Sabatier, 2019:271 pp.