

Chapter 5

Forest Eco-Physiological Models: Water Use and Carbon Sequestration

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5.1 Introduction

Modeling and monitoring the processes involved in terrestrial carbon sequestration are often thought to be independent events. In fact, rigorously validated modern modeling techniques are very useful tools in the monitoring of the carbon sequestration potential of an ecosystem through simulation, by highlighting key areas for study of what is a complex dynamical system. This is ever more important in the light of climate change, where it becomes essential to have an understanding of the future role of terrestrial ecosystems as potential sinks or sources in the global carbon cycle, as well as the feedback and trade-off mechanisms between climate change and ecosystem carbon balances.

The study of the effects of climate change on terrestrial ecosystems is one field of interest that requires the use of predictive tools such as functional simulation models. There are many possible applications of such models, from studying the responses of individual processes, the interactions of various processes, up to the responses of whole forest stands and ecosystems. This can be performed focusing on the response of forests to climate change (and in turn identifying feedbacks from forest ecosystem responses that may affect the rate of climate change), the effect of climate change on ecosystem service supplies which are necessary for societies wellbeing (such as water supply, soil fertility, bioeconomy), the effect of management on forest productivity, or in assessing the suitability of a certain site for plantation.

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Models can be taken as quantitative predictors of ecosystem responses by translating a particular “stress” of interest to a key ecosystem parameter, taking into account a margin of error, but perhaps more importantly, they give us a way to scale up our understanding of individual process reactions to drivers on the individual tree level to the ecosystem scale. The quantitative predictions have a large range of uncertainty, and are actually by no means predictions, but estimates. The only model that matches exactly reality is reality itself. All models are, by definition, simplifications of reality. However, the qualitative descriptions of ecosystem responses provided by models give a very valuable insight into the functioning and potential response of the ecosystem as a whole. “All models are wrong but some are useful”, as said by Box (1979).

In this chapter, we first outline the different approaches to forest eco-physiological modeling, with their associated pros and cons, and applications. We then give an example of the application of one such forest growth model, GOTILWA+, to different Scots pine (*Pinus sylvestris* L.) plots in Spain, as an example of a country-wide model application, and a further analysis of the suitability of the current forest management procedures under this changing conditions. Briefly, this exercise consists in the simulation of several national inventories’ based plots to a 2100 horizon, a calibration of the GOTILWA+ output, and a simulation of the performance of Scots pines forests across Spain during twenty-first century, besides an insight of how management can change carbon balances in Scots pine forests.

The methodology is then extended to the application of the model to the whole of Europe for the coming 100 years, with an exploration of the forest eco-physiological responses to climate change, in particular the effects on carbon and water balances.

5.1.1 Forest Services

Modelling can prove a useful tool in assessing the expected future state of forest ecosystem services (e.g. water availability, soil fertility, wood and non-woody products production, fire hazard reduction, etc.) that are vital for human wellbeing, as well as a net source of economic activity. This is of particular interest in the light of climate change. Global change is continually altering such services, and is expected to do so to an even greater extent in the future. Previous Europe wide studies have applied terrestrial ecosystem models such as those described in this chapter to assess the expected future status of services such as soil fertility, water availability and the risk of forest fires (Schröter et al. 2005). Both positive and negative trends were reported, with increases of forest area and productivity on one hand, but an increase in the risk of fire, and a decrease in soil fertility and water availability on the other. Currently, forest ecosystems act globally as carbon sinks sequestering from the atmosphere $2.4 \pm 0.4 \text{ PgC}\cdot\text{year}^{-1}$ and European forests contribute with a net

atmospheric carbon uptake of $0.44 \pm 0.1 \text{ PgC}\cdot\text{year}^{-1}$ (Pan et al. 2011). However, given the rising temperatures and the increasing of water stress projected by climate change (IPCC 2013), many EU forest ecosystems may shift their behaviour from net sinks to net sources of C. Differences in projections of the effects of climate change within the EU regions are acute, with a southern Mediterranean forest ecosystems under a severe threat by the worsening its growing conditions due to the aridification of their environment, contrasting with the increase in tree growth projected in the North-European temperate forests due both a slight increase in temperature and the fertilizing effect of an increasing atmospheric CO_2 concentration.

By applying the assumed changes in land use and climate, the models can be used to gauge the effect of such changes on ecosystem services. The GOTILWA+ model presented in this chapter has been involved in such studies and uses the same approach to assessing the future of forests and ecosystem service supply. Here, GOTILWA+ projections are coupled with an assessment of possible management strategies to assess the capability of forest management to offset or counteract any potentially negative or undesired effects.

5.1.2 Applications in Forest Management

Modelling can also be used to assess the potential of forest management strategies. Forest management practices aim to optimise the productivity of the forest and minimise the risk posed by environmental stresses. The suitability of a management strategy is highly dependent onsite characteristics and the general state of the forest stand. It is a difficult balance to achieve, where over-harvesting can lead to serious damage to a forest ecosystem, whilst under-harvesting can fail to make full use of the ecosystems potential, or indeed lead to a significant loss of aboveground biomass (e.g. in the case of fire, in abrupt and generalized mortality events under severe climatic disturbances, etc.). Models allow for the evaluation of many alternative strategies, and the effectiveness of each can thus be tested based on the requirements of the manager. This is relevant in maximising the potential for the forest to sequester carbon, in modifying forest green water to blue water balances, and in protecting ecosystems which are threatened by changing environmental conditions (with the aim to be to give the system more time to adapt naturally, and avoid threshold limits) (Kellomaki and Valmari 2005).

This ‘virtual management’ allows the forest manager to enter the forest and invoke management strategies, with the potential to remove selected trees based on different removal criteria, either at prescribed intervals based on a certain value such as average diameter at breast height, or at regular time steps. The value of this virtual management is that it immediately gives the forest planner the results of his strategy for the future. The effect of the strategy can be focused on maximising whatever variable the planner is interested in, or indeed finding the optimal maximum considering a variety of requirements. It is important to note that today’s

management strategy for a particular site might not be suitable in a changing world, and a modelling approach testing a range of plausible strategies can warn a planner of the need of a strategy change before damage is done to the ecosystem.

5.1.3 Process Based Models vs. Empirical Models

There are two main approaches available to modellers (Fontes et al. 2010): The empirical approach and the process based approach. The choice of approach taken is highly dependent on the problem being addressed. As always, both approaches have valid applications, each with their own strengths and weaknesses. In reality, the two options are not quite independent, with many models containing a synergy of both.

Empirical models attempt to simplify the system description, by relying purely on known system wide responses to external drivers. They are statistically based, are easy to feed (require less parameters) and generally have faster execution times.

This is very useful, making it easy to build a simple and accurate description of a system with very few parameters. As their name suggests, they are based on empirical functions, which attempt to describe direct ecosystem responses. This simplicity and speed also helps in the analysis of model results, and is useful in giving insight into the general functioning of a system, highlighting the key processes and possible reactions. However the applicability of empirical models is restricted and their application as true exploratory tools is questionable. Limited by their simplicity and their basis of empirical responses, they lack the ability to explore new scenarios and conditions outside of those on which they were built and tested such as climate change.

Process based models, in contrast, are complex simulators that attempt to mimic the real world. The aim is to include mathematical descriptions of both the processes that govern a system, and their interactions, thus recreating the system in a virtual environment. Each process in the system is described separately, and dynamically interacts with other processes. Given an accurate description of each processes separately, it is argued that a better description of the ecosystem in general, through the interaction of these processes, can be achieved. Due to their detail, a large number of parameters are necessary. The parameters determine the response of each function describing an individual process, and are based on detailed field-work or lab experiments. This allows an accurate description of all factors affecting a process. However, such parameters are not always available. This can be a problem, and a lack of data often leads to assumptions and approximations, but the approach leads to a model with a wide applicability. The detail and dynamic characteristic of process based models allows them, theoretically, to function as effective exploratory tools and they should be fully applicable under new conditions and scenarios.

The scientific community is often somewhat sceptical about the effectiveness of complex process based simulation models, and the role they should play in

ecological studies. Many ecologists will laugh if you explain that you are trying to mimic the real world. And indeed they might! The environment is highly variable, and could be said to be the most complex system in existence: we are doomed to never succeed in designing a herring. However, complex process based models can have a much wider applicability than that of simpler empirical models that are simply designed to fit data. Although far more complicated than empirical models, and much more expensive to build, they give an insight into the internal functioning of the system itself, which could never be achieved with empirical models. For studies involving climate change, this is essential, as complex process are involved in ecosystem wide responses to global change. Unfortunately, our current understanding of many processes is still too limited to allow fully process based modelling, and most so called processed based models use a range of semi to fully empirical equations. This is perfectly valid, but one must keep in mind that most process based models, including the GOTILWA+ model, are actually hybrids of the two approaches.

5.2 Gotilwa+: A Process-Based Model

5.2.1 *The Model*

GOTILWA+ (Growth Of Trees Is Limited by WAter, <http://www.creaf.uab.cat/gotilwa/>) is a process-based forest growth simulation model (Gracia et al. 1999; Keenan et al. 2009a, b; Fontes et al. 2010; Nadal-Sala et al. 2014). GOTILWA+ model has been tested using data from Forest Inventories (e.g. National Forest Inventories), Eddy Flux towers outputs, as well as compared to other process-based models (see Kramer et al. 2002, Morales et al. 2005). GOTILWA+ has been successfully applied Europe-wide (see Schröter et al. 2005; Keenan et al. 2009a, b, 2010; Keenan et al. 2011; Serra-Diaz et al. 2013).

GOTILWA+ performs forest growth under different climates, stand structures, management options and soil traits. GOTILWA+ describes carbon and water fluxes through forests and has been applied on a wide range of environmental conditions, from boreal northern Europe to Mediterranean basin, and also in the Ecuadorian Andes in *Polylepis reticulata* tree species. Its programme code is built using Microsoft Visual Basic (6.0) platform.

The GOTILWA+ time step resolution is hourly, and calculations are integrated into daily, monthly and yearly values. Leaf area vertical distribution distinguishes two canopy layers (under sunny and shaded conditions) but there is no explicit description of the leaf area horizontal distribution.

Trees are grouped by DBH size classes, individuals within a DBH class are treated mostly as identical. Light extinction coefficient is estimated using Campbell's equation (Campbell 1986). Photosynthesis is calculated using Farquhar's equations (Farquhar and Von Caemmerer 1982). Stomatal conductance calculation uses the Leuning, Ball and Berry approach (Leuning 1995). Leaf temperature is determined

by the leaf energy balance equations described by Gates (1962, 1980). Potential evapotranspiration is estimated by the Penman–Monteith equation (Monteith 1965; Jarvis and McNaughton 1986).

Specific tree species parameters related to photosynthetic capacity, leaf morphology and leaf hydraulic conductivity are used (taken from measurements or literature) and environmental input variables are incident radiation, wind speed, atmospheric water vapour pressure, temperature max and min, precipitation and atmospheric CO₂ concentration.

5.2.1.1 Input and Output Variables

The input data includes: climate (max. And min. Temperatures, rainfall, VPD, wind speed, global radiation and atmospheric CO₂ concentration); stand characteristics (tree structure including the structure of the canopy; DBH class distribution); tree physiology (photosynthetic and stomatal conductance parameters, specific growth and maintenance respiration rates), site conditions including soil characteristics and hydrological parameters and also forest management criteria.

Many output variables can be extracted from the model. These can be separated into three main categories: canopy variables, tree and stand structural variables, and root and soil variables.

Canopy variables include: Gross Primary Production, Net Primary Production, Net Ecosystem Exchange, Leaf Area Index, Transpiration, Interception, Water Use Efficiency, Leaf Production, Leaf Respiration, Leaf Biomass, Growth Activity, The Length of the Growing Period and Volatile Organic Compound emissions.

Tree and Stand structural variables include: Tree Density, Sapling Density, Basal Area, Sapwood Area, Mean Quadratic Tree Diameter, Vigour Index, Tree Height, Wood Production, Wood Respiration, Mobile Carbohydrates, Tree Ring Width, Aboveground Biomass, the Weight of the Sapwood Column, Wood Volume, Dead Wood Volume and Yield (when considering management).

Root and Soil variables include: Soil Temperature, Water Stored in Soil, Fine and Gross Litter Fall, Soil Organic Carbon, Fine Root Biomass, Fine Root Production, Fine Root Respiration, Heterotrophic Respiration, Maintenance Respiration and Growth Respiration.

5.2.1.2 How Gotilwa+ Copes with Processes

Process based models start at the very basic physiological leaf level, combining and describing the different processes involved (Fig. 5.1). Figure 5.2 shows a schematic of the most fundamental compartment, the leaf. Here, photosynthesis is hourly calculated dynamically, based on internal and external conditions.

The key environmental forcing factors taken into account are precipitation, air temperature, vapour pressure, global radiation, wind speed, and atmospheric carbon

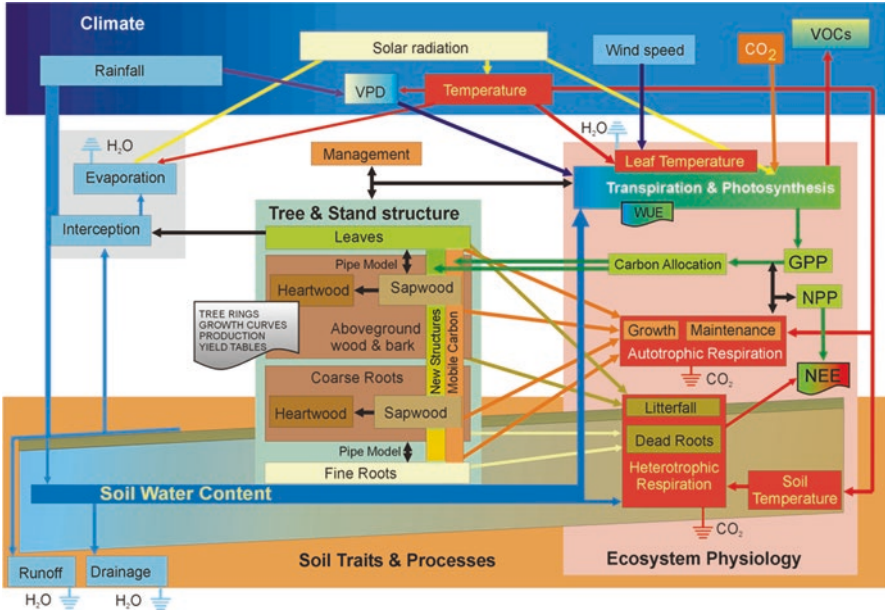


Fig. 5.1 A schematic graph of processes and interactions accounted for in the GOTILWA+ model

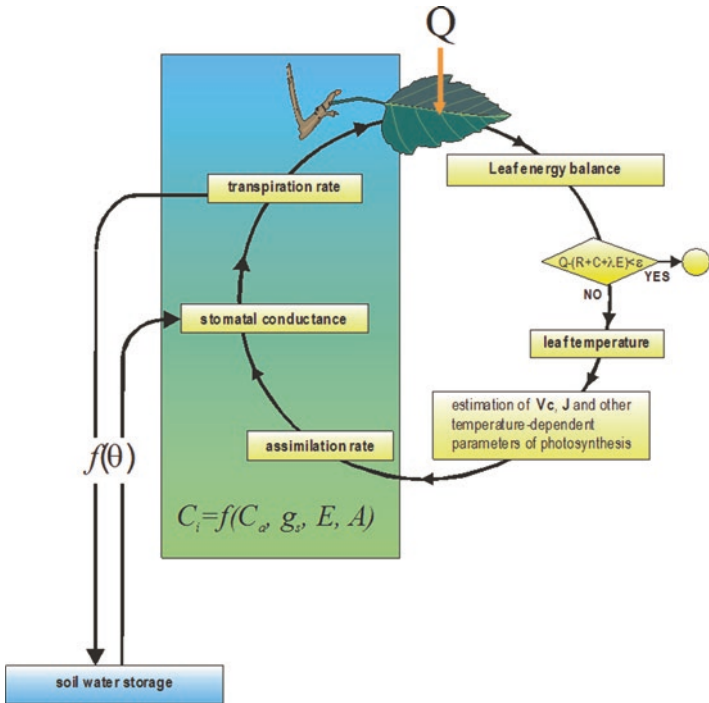


Fig. 5.2 A schematic diagram of the representation in GOTILWA+ of the photosynthetic assimilation rate

dioxide concentration. Using this data, the response of ecosystem processes is calculated to estimate the carbon and water fluxes in a forest ecosystem.

Assimilation rates depend on the direct and diffuse radiation intercepted, the species-specific photosynthetic capacities, leaf temperature, leaf angle distribution, available carbon, the extent of stomatal opening, and the availability of soil water.

Net Primary Production (NPP) is obtained from Gross Primary Production (GPP) minus maintenance respiration (M_R) following Eq. 5.1:

$$NPP = GPP - \left(\frac{M_R}{E_E} \right) \quad (5.1)$$

Where NPP and GPP are expressed in $\text{kg}\cdot\text{hour}^{-1}\cdot\text{ha}^{-1}$, M_R is maintenance respiration, expressed in $\text{kcal}\cdot\text{hour}^{-1}\cdot\text{ha}^{-1}$ and E_E is the energetic equivalence of organic matter, assumed as a constant value of $9.4\cdot 10^3 \text{ kcal}\cdot\text{kg}^{-1}$.

M_R is determined by the sum of the respiration of leaf biomass, fine root biomass and living wood biomass. Living wood biomass is a species-specific percentage of wood biomass. M_R rates depend on temperature according to a Q10 approach.

The respiration rate is $33.3 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ at 25°C for structural carbohydrates and $55.5 \text{ kcal}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}$ at 25°C for mobile carbohydrates, following Ovington (1961). Thus, M_R for a given tissue follows the Eq. 5.2:

$$M_R = B\cdot Q10_t \cdot RR_c \quad (5.2)$$

M_R is the tissue maintenance respiration for a given tissue, in $\text{kg}\cdot\text{ha}^{-1}\cdot\text{hour}^{-1}$, B is the respiring biomass of a given tissue, in $\text{kg}\cdot\text{ha}^{-1}$, $Q10_t$ is the value of Q10 at a given tissue temperature, RR_c is the respiration rate for a given carbon fraction – i.e. structural or mobile carbon fraction – in $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{hour}^{-1}$.

NPP is then allocated through the tree compartments following a set of hierarchical decision criteria (Fig. 5.3). First, NPP refills tree mobile carbohydrates (MCH) reserves up to the maximum replenishment values. Then NPP is used to equilibrate according to the pipe model leaf area, fine root biomass and sapwood area (Shinozaki et al. 1964). When new tissues are produced, carbohydrates are also spent on growth respiration (G_R). G_R is set as 32 % of the invested carbohydrates for growth – i.e. a constant efficiency of 0.68 g of new tissue per g of carbohydrate (Ovington 1961). Finally, if there is still NPP available, trees generate new sapwood area, new leave area and new fine root biomass according to the pipe model and accounting for GR costs as above.

When there is no photosynthetic activity or assimilated carbon is not sufficient to compensate respiration rates, NPP values turn to negative. If so, the lack of photosynthesis is offset by MCH reserves. When mobile carbon pool is fully available, it can be depleted without consequences for tree population. When MCH reserves fall close to the mortality threshold, trees lose specific respiring tissues such as leaf and fine roots biomass. If carbon starvation continues and MCH falls below a certain species-specific threshold, a tree mortality event occurs. Mortality also occurs if the

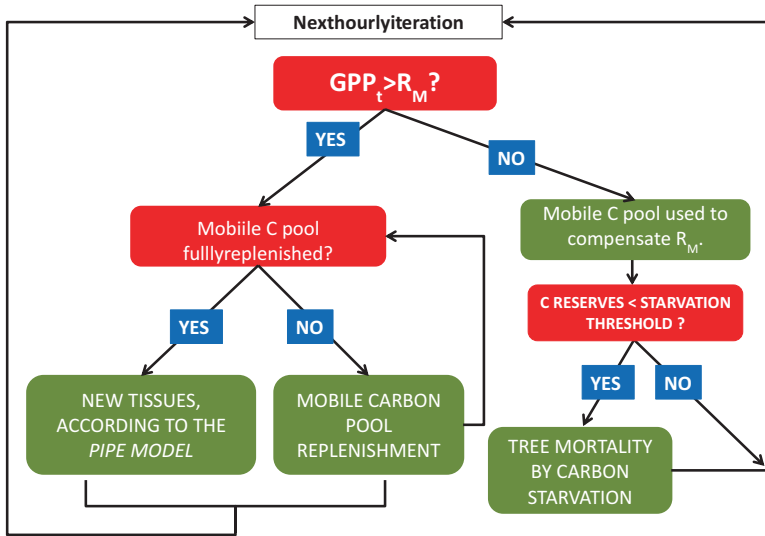


Fig. 5.3 Flow diagram of carbon allocation hierarchical criteria followed by GOTILWA+. Red boxes represent hierarchical questions. Green boxes represent main processes

diametric class is completely defoliated, and MCH is not available anymore, during the vegetative period in the case of deciduous tree species or at each moment of the year for the evergreen ones.

GOTILWA+ does not consider a homogeneous distribution of mobile carbon reserves within a DBH class. Concerning mortality, GOTILWA+, instead of working with the DBH class average tree, assumes differences within trees in the same DBH class. As the pool of MCH is not homogeneously distributed, there are trees in a better condition than others. The number of dead trees is established as follows: The number of trees that can be sustained by the current MCH value is calculated. Then, the difference between the current number of trees and the number of trees that can be sustained is the mortality within the DHB class. In addition to the MCH, the rest of the tree structure compartments are restructured accordingly.

Fine litter fall (e.g. leaves), gross litter fall (e.g. bark, branches, dead stems) and the mortality of fine roots add to the soil organic carbon content. The soil in GOTILWA+ is divided into two layers, an organic layer and a mineral layer, with a fixed rate of transfer between them. Soil organic carbon is decomposed depending on to which layer it belongs, with both decomposition rates depending on a Q10 approach taking into account soil water content and soil temperature. Soil temperature is calculated from air temperature using a moving average of 30 days. The amount of soil water available for organic layers is calculated taking into account the cumulated rainfall of the previous 30 days. Soil water availability for mineral layers depends on the soils water filled porosity that in turn is a function of the organic matter present in soil.

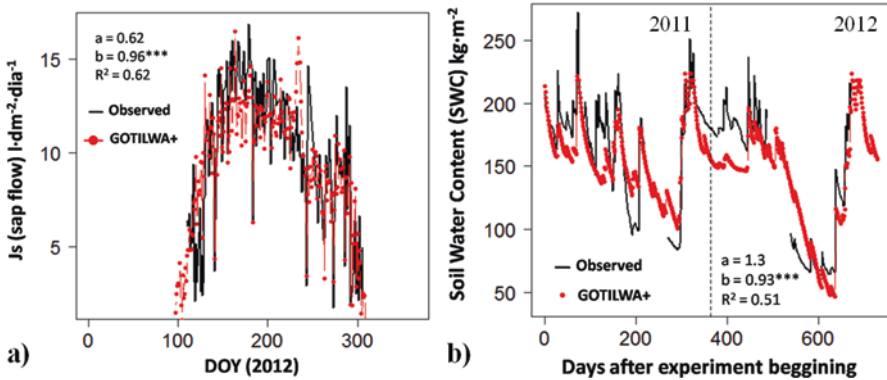


Fig. 5.4 Modelled gotilwa+ versus measured “in situ” values for (a) daily sap flow density (J_s , in $l \cdot dm^{-2} \cdot day^{-1}$) in the el regàs *Fraxinus excelsior* spanish forest study plot, and (b) daily soil water content (SWC, in $kg \cdot m^{-2}$) for the same plot

Soil water content is described as one layer, taking inputs though precipitation less leaf interception, which is evaporated, (stem interception, or stem flow, is not evaporated, but directed to the soil), and outputs though drainage, runoff, and transpiration.

5.2.1.3 Model Validation

GOTILWA+ model validation has been carried out at various sites across Europe and the United States (Kramer et al. 2002, Morales et al. 2005, Schröter et al. 2005; Keenan et al. 2009a, b, 2010, 2011; Serra-Diaz et al. 2013), using canopy level measurements gathered by the FLUXNET network. Figure 5.4a shows the results at one site, a *Fraxinus excelsior* riparian forest in the northern of Spain, providing simulated GOTILWA+ daily sap flow density values against 1 year of field data (2012) measured values. Besides, comparison between modelled and measured soil water content for the same plot during 2 years (2011, 2012), is noted in Fig. 5.4b.

The model successfully matches the sap flow density, with a R^2 of 0.62 and a slope of 0.96. It also captures both the trend of high sap flow values observed in spring and the decrease in sap flow density during summer drought. Besides, the soil water content (SWC) pattern follows the same trends in both 2011 and 2012, with a summer depletion of SWC, followed with an autumn refilling matching the end of the growing season and the beginning of the autumn rains.

5.2.1.4 Unknowns in Forest Modelling

A correct description of each process is crucial. This requires intense and extensive field work, data collection and experimentation. Thus, by using field work to better our understanding of the processes involved and the factors that affect them, we can build more accurate models. There is yet a lot to be understood, and many interactions between species, soil and atmospheric processes are still poorly understood. Such factors include the role of belowground biomass (the “hidden half” of the forest), the effect of nutrient availability, factors affecting soil organic matter decomposition, and species-specific responses to climate change factors such as elevated CO₂, drought and the role of acclimation.

This lack of information is exacerbated by the problem of scale. Many questions remain as to how processes scale up from the chloroplast or mitochondrial level, to the leaf, the stand, and the ecosystem as a whole. The problem of physiological scale is coupled by a problem of temporal scale. An ecosystem incorporates many processes, each with their own temporal scale. Fast processes (such as the leaf energy balance, photosynthesis, stomatal conductance, transpiration, autotrophic and heterotrophic respiration, water and light canopy interception, cambium cell division) interact with slow processes (tree ring formation, sapwood to heartwood changes, tree mortality, cavitation, wood production, management, soil organic matter decomposition, climate change). These questions are all approached with as much accuracy as possible in the model, but many factors could be improved. Such problems go hand in hand with any modelling attempt but each year we are improving our knowledge, and our ability to use it.

5.3 Model Applications

5.3.1 Carbon Balances and Water Cycles in Spanish Forests

5.3.1.1 GOTILWA+ Calibration Against National Forest Inventories Data

As an example model application, we assess results from model simulations at 64 Spanish sites. Those sites have been randomly sampled from the Spanish National Inventory Data (IFN). The sampling criteria used was: (a) The exercise is focused in Scots pine *Pinus sylvestris* pure stands, (b) we consider pure stands those in which 80 % of total basal area is sustained by Scots pine, as well as the number of trees in the plot was greater than 200 trees·ha⁻¹ during the IFN2 (year 1995), (c) initial sample was formed by 100 random plots. From these plots, managed sites or that experienced forest fires during the IFN2 (year 1995) – IFN3 (year 2005) interval have been removed.

Due to lack of information about soil conditions, three simulations under three different soil characteristics (soil depth of 0.25, 0.5, and 1 m) were run under observed (Ninyerola et al. 2007a, b) climate conditions in each plot. Simulated basal area

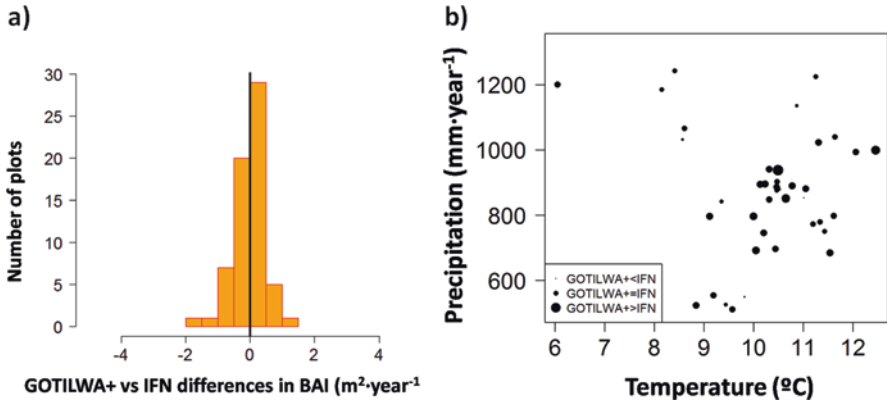


Fig. 5.5 (a) Differences in basal area increment bai ($m^2 \cdot year^{-1}$) for the 64 *P. sylvestris* plots between GOTILWA+ best fit simulation and ifn2-ifn3 inventories. Positive values indicates overestimation in GOTILWA+ simulations, and negative values indicates underestimation of GOTILWA+ simulations. (b) Plot distribution for the 1971–2010 reference period mean yearly precipitation and mean yearly temperature axis. The size of the *dot* indicates the degree of deviation from the ifn predictions. Thus, *smaller dots* represent underestimation in GOTILWA+ simulations, and *bigger plots* represent overestimation in GOTILWA+ simulations

increment for each plot was compared to the IFN2-IFN3 basal area measured increment, and the soil depth that minimizes the difference between the observed and modelled basal area increments was selected for each plot. According to the Fig. 5.5a, Root Mean Square Error (RMSE) between observed and simulated basal area increment was 0.473, with 51 % of plots within the $\pm 0.25 m^2 \cdot ha^{-1} \cdot year^{-1}$ range, and 77 % of the plots within the $\pm 0.5 m^2 \cdot ha^{-1} \cdot year^{-1}$ range. Besides, there is no precipitation related trend in differences between observed and modelled basal area increments 5b. However, GOTILWA+ systematically slightly overestimates basal area increments in warmer plots.

5.3.1.2 Future Climate Uncertainty: Coupling Gcm's and Socio-Economic Forcing

Projecting forest growth into the future is highly dependent on the climate data used to run the model. The best tools available for predicting future climate evolution are Global Climate Models or General Circulation Models (GCMs). GCMs aim to describe climate behaviour by integrating a variety of fluid-dynamical, chemical, or even biological equations that are either derived directly from physical laws (e.g. Newton's Law) or constructed by more empirical means. A large number of GCMs exist for predicting future climate evolution. Each applies the laws of physics and mathematical descriptions of atmospheric interactions to varying degrees to give a prediction for the evolution of future climate.

A range of socio-economic scenarios has been developed to explore future paths of carbon emissions related to the burning of fossil fuels. These can be used to force GCMs. This approach is currently used by the IPCC (Inter-governmental Panel on Climate Change) is used as a driver for the GCMs, giving various possible future greenhouse gas emissions, depending on the economic model applied and the resulting changes in population, land use change and energy consumption. Four climate forcing scenarios are derived from the IPCC (2013): RCP8.5, RCP 6.0, RCP4.5, and RCP2.6, ranging from pessimistic to optimistic regarding future anthropogenic impact on the climate system. As this exercise was run before the new IPCC (2013) climate forcing scenarios, we used A2 and B2 socioeconomic forcing scenarios from IPCC 2007. They both match pretty well with RCP 6.0 and RCP 4.5 CO₂ emissions respectively.

A large difference exists between the predictions of each of the GCMs, and each of the scenarios. They differ in: (a) their climate sensitivity and (b) the spatial pattern of change, making multi model assessments essential for a good understanding of potential changes. Although the climate models and scenarios vary in their predictions, they agree in qualitative terms and there is a general consensus that, although it would refine the results, increased accuracy would not change the conclusion with regards to many ecosystem variables. In this exercise, an ECHAM4 GCM was considered, obtaining two possible combinations of scenario projections: ECHAM4-B2 and ECHAM4-A2.

5.3.1.3 Stand Performance at the Selected Sites

Here, to ease the interpretation of the results, we present results from the ECHAM4 model predictions with the A2 and B2 emission scenario as our description of future climate (this gives mid-range levels of future climate change). Regarding to carbon balances, Fig. 5.6 shows the mean Gross Primary Production (GPP) and mean Net Ecosystem Exchange (NEE) predicted by the model for all 64 plots used under the two socio-economic scenarios. In both cases, an increase in GPP can be observed, resulting from higher temperatures and CO₂ fertilisation. This increase in GPP is greater in A2 scenario than in B2 scenario. However, NEE increases along the twenty-first century for both climates change scenario projections. Thus, resulting in a reduced carbon sink capacity of Scots pine forests in Spain.

With regard to forest water balances, Fig. 5.6 shows that the projected fraction of the precipitation transpired by the forest would increase during the twenty-first century and drainage and runoff would decrease downstream. This decrease of water availability would imply relevant consequences for downstream ecosystems, as well as for human societies' water resources. That would be exacerbated under the higher CO₂ emissions scenario (ECHAM4-A2) than under the lower one (ECHAM4-B2).

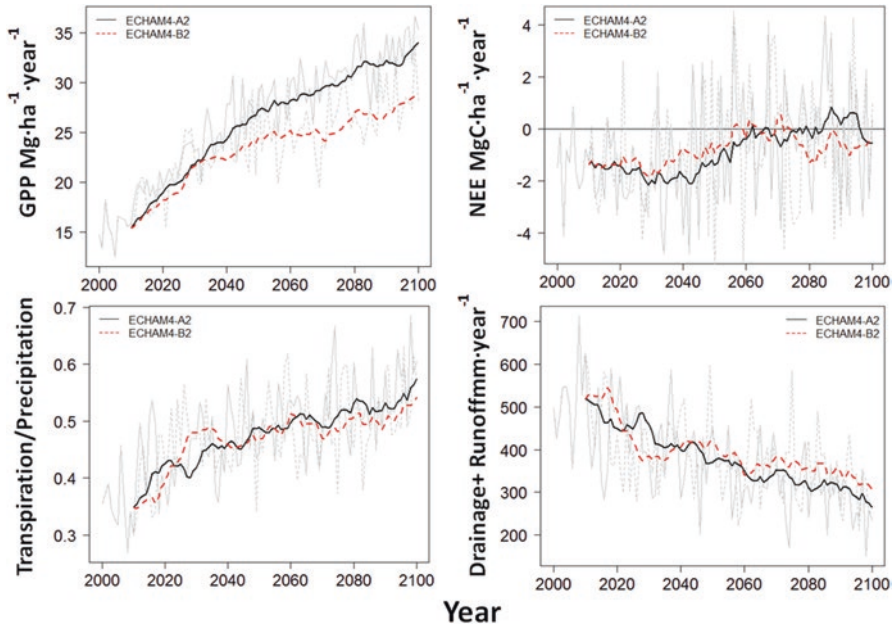


Fig. 5.6 Gotilwa+ projections for the twenty-first century forest ecosystem carbon and water balances. Mean gross primary production (gpp, $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$), net ecosystem exchange (nee, $\text{mgc}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$), fraction of the precipitation transpired by tree population (unit less), and drainage + runoff exiting downstream the plot ($\text{mm}\cdot\text{year}^{-1}$) for all sites are indicated between 2000 and 2100, both for the a2 and the b2 socio-economic scenarios. *Grey lines* represent the yearly mean values for the 64 plots, and *black* and *red lines* represent the 10 years average trend for the a2 and b2 socio-economic scenarios

5.3.2 The Effect of Management

Management can play a very important role in ecosystem function. In the model, various different management regimes and strategies can be defined, and their effect on the forest ecosystem can be gauged. Such strategies are often focussed on optimizing carbon sequestration, wood production, yield, or aboveground biomass. Particular interest in the Mediterranean region is focused on using management to mitigate the effects of drought on forest stands. Here, an example is given of a management strategy applied to a typical Scots pine Mediterranean plot. The management strategy in this simulation is to enter the forest when the basal area reaches $42 \text{ m}^2\cdot\text{ha}^{-1}$ and remove the larger trees until a basal area is reached of $38 \text{ m}^2\cdot\text{ha}^{-1}$. This has the effect of increasing wood production, while giving a high yield from the system, thus increasing the capacity of the stand to act as a net sink for atmospheric CO_2 . This strategy can be contrasted against alternatives, and an optimum strategy found, depending on the prerequisites of the user.

Figure 5.7 Shows how management can increase the productivity of the forest, with the total wood volume (yield + standing volume) at the end of 100 years being greater in the managed forest than in the unmanaged forest. This occurs due to the

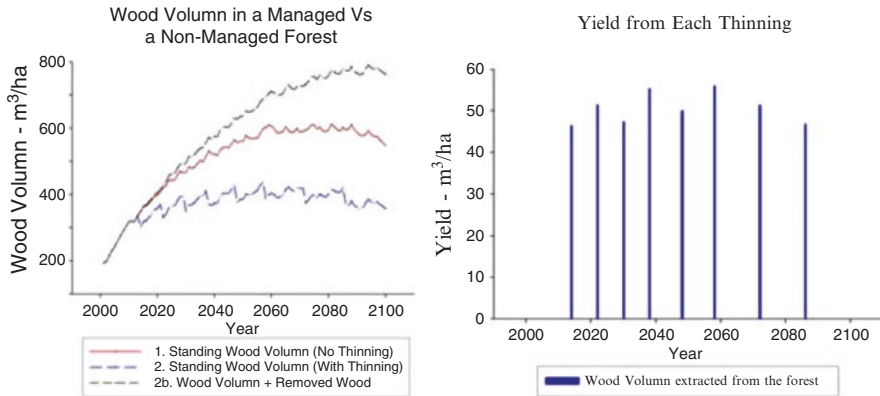


Fig. 5.7 *Left:* GOTILWA+ projection of wood volume remaining in an unmanaged forest and in the same forest with management. *Right:* The wood volume extracted from the managed forest at each intervention in the simulation

response of the forest to decreased competition for resources. It has been argued to increase the lifetime of a forests sequestration capacity. It can also increase the capacity of the forest to act as a sink of atmospheric CO_2 . On the other hand this also depends on what use the extracted wood is put to. The mean life-time of wood products is estimated to be about 30 years, though this is highly dependent on the product, thus any additional sink that results from the extraction of wood from the system can be presumed to be short lived.

5.3.3 *The Future of European Forests – Europe Wide Simulations*

GOTILWA+ has been validated extensively in Europe (Kramer et al. 2002, Morales et al. 2005, Schröter et al. 2005; Keenan et al. 2009a, b, 2010, 2011; Serra-Diaz et al. 2013). This has helped to refine the model, and now the same modelling approach can be applied throughout Europe. This can be a very useful tool for those monitoring future carbon sequestration trends in European forests. To supply the input data required by the model, an extensive database has been built within the framework of the European ALARM project (Assessing Large-scale Risks for biodiversity with tested Methods, www.alarmproject.net/alarm), connecting diverse information sources at a European level and adapting them to fit the same spatial resolution.

The database contains data related to forest functional types, forest cover, forest structure (tree density and size distribution), forest function (photosynthesis, respiration rates), soil hydrology, organic matter decomposition rates and management strategies. This data base provides the model with all the necessary information to run in each pixel and it also provides the climatic series at this level of detail for different climate change scenarios generated by several general circulation models (GCMs).

Given the computational expense of running GOTILWA+ with the predictions of each GCM and each climate scenario, and providing that ECHAM4 GCM was not available all over the UE, we chose the HadCM3 IPCC (2007) scenario to simulate future forest stands over Europe.

Here, in Fig. 5.8, we see a shift in the majority of European forest ecosystems from being net sinks of carbon to net sources of carbon. This reflects what we observed earlier for the Spanish plots in Fig. 5.6. It represents a potential feedback on the climate system, where terrestrial ecosystems themselves do not help to solve the problem of climate change and may even serve to augment it. Currently, most are acting as sinks, effectively removing and storing carbon from the atmosphere.

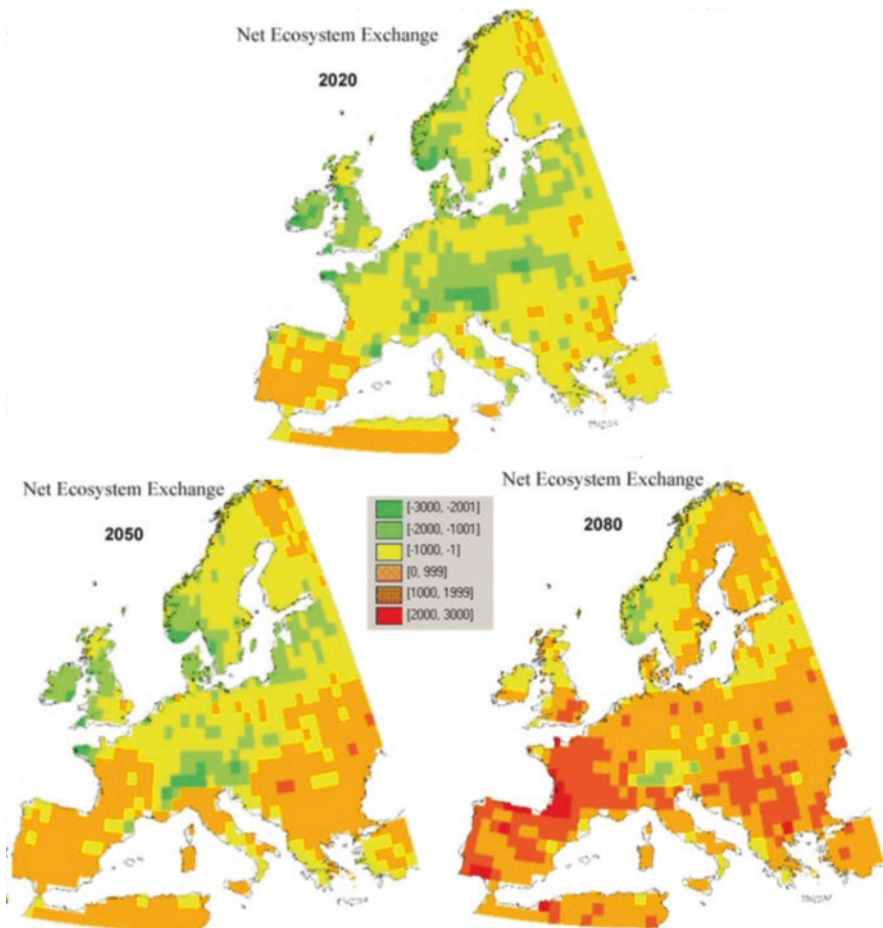


Fig. 5.8 GOTILWA+ projections of net ecosystem exchange (kg/ha/year) for *P. sylvestris* forests in europe-wide simulations (values represent the annual average for each time slice 2020: 2010 to 2030, 2050: 2040 to 2060, and 2080: 2070 to 2090)

The perspective of them becoming sources is not a pleasant thought, with vast amounts of carbon currently stored in soils and ready for release, if there is an increase in temperature.

Figure 5.9 allows us to further explore this response. As can be seen, productivity, in general (in areas not under stressed conditions) is expected to increase, thus constituting an increase in the ability of the ecosystem to remove carbon from the atmosphere. The conversion of the ecosystem to a net source of carbon results from the reaction of respiration rates and the large available pool of carbon in the soil. The description of soil respiration is as good as our current understanding of these processes allows (Fang et al. 2005, Janssens et al. 2005), though undoubtedly further work is required to reduce our uncertainty. As exact future climate scenario is still unknown and the soil respiration processes are not fully understood, quantitative conclusion may be questionable, but the qualitative conclusion should not vary greatly with a better understanding of the processes involved.

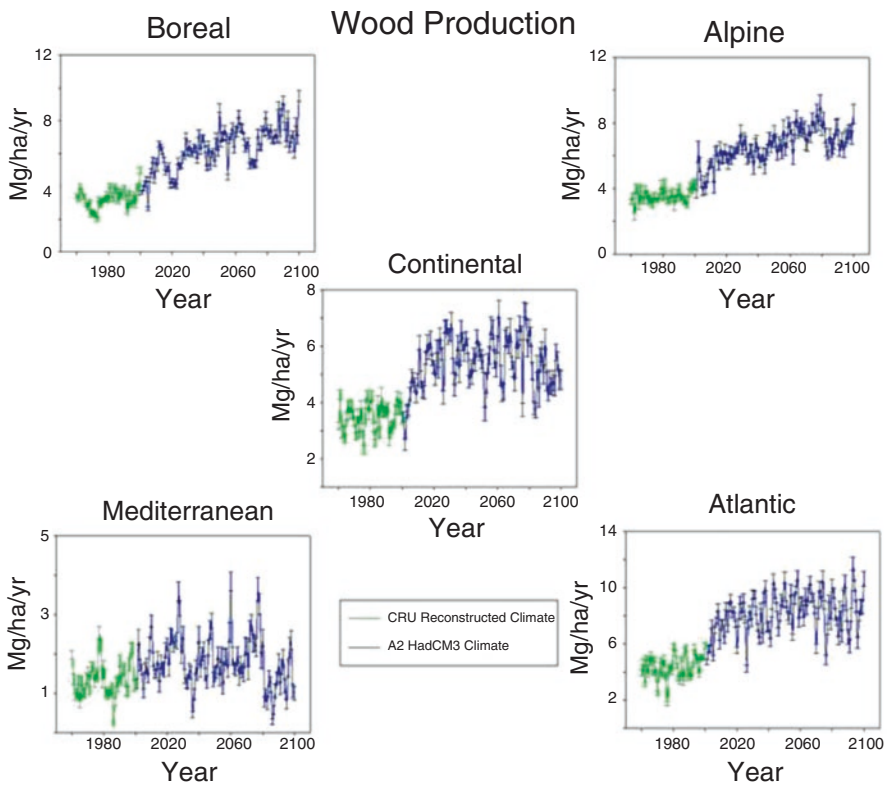


Fig. 5.9 GOTILWA+ projections of wood production (mg/ha/year) for five main European climate regions from 1960 to 2100 under had CM3 socio-economic scenario

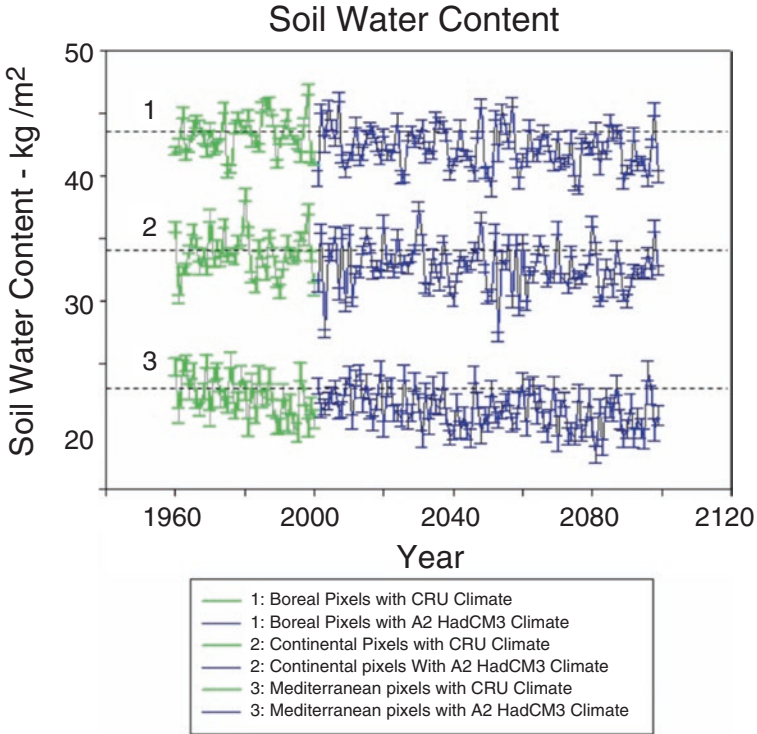


Fig. 5.10 GOTILWA+ projections of the quantity of water in the soil for three climate types, boreal, continental, and mediterranean climates, with reconstructed climate from 1960 to 2000, and the hadley center had CM3 model with scenario a2 until 2100

In Fig. 5.10, a general tendency for a decrease in soil water content can be observed. This is due more to higher Evapotranspiration rates, from a combination of increased productivity and higher temperatures, than to changes in the distribution of precipitation. The effects are expected to be more extreme in the Mediterranean region, where soil water content is already extremely low. This can have repercussions outside of the ecosystems in question, effecting other ecosystems and society at large.

5.4 The Future of Eco-Physiological Models

As our knowledge of processes and ecosystem responses develops, in parallel with computing science, so too does our ability to build eco-physiological models with higher accuracy and a broader applicability. Future efforts will be focused both on the development of our scientific knowledge of the processes involved, and in using the models themselves to better our understanding of how these processes link

together to form an ecosystem. This will be carried out through extensive field work and experimentation, from field trials to stand simulations, up to the coupling of vegetation ecosystem models with global climate models.

5.4.1 Climate Models and Eco-Physiological Models

It has long been accepted that regional climate affects the local distribution of vegetation and soils, with natural undisturbed vegetation effectively mirroring the long term local climate (Koppen 1936). In recent years, a broader understanding of the interaction between vegetation and climate has been developed. Not only does climate affect the distribution and functioning of vegetation, but vegetation also has an effect on climate, and the two are inextricably linked. This feedback mechanism is now recognised as being crucial to the evolution of the Earth's climate (Bonan 2002), and equally crucial in predicting the anticipated change in the earth's climate in the future (Cox 2000). Potentially one of the most interesting future prospects for eco-physiological models is their coupling with regional climate models, in an attempt to incorporate the dynamic relationship between vegetation and climate.

5.4.2 Development

Our current understanding of terrestrial processes is limited in many areas, with various key features only relatively weakly represented. The advancement of our understanding of these critical processes should better enable us to accurately model real world situations. This will be achieved by integrating the latest understanding in climatic, hydrologic and edaphic controls on forest ecosystem process, obtained from the analysis of intensive field and laboratory data, into novel model parameterisations.

The list is long, but key areas currently being developed include: the representation of soil organic matter decomposition, which is very variable and not always best described by a simple temperature-water relationship; the coupled Nitrogen cycle, which is being greatly altered throughout the world due to anthropogenic global change, and is at present very poorly understood; eco-physiological responses to elevated concentrations of atmospheric CO₂, and the problem of acclimation; accurate descriptions of the functioning of belowground biomass, the hidden half of terrestrial ecosystems. Belowground biomass can account for half of the total biomass of a terrestrial ecosystem in the Mediterranean, but it is difficult to study; species interactions (competition/mutualism) provide one of the key problems in describing succession and dynamic vegetation problems; the role of Volatile Organic Compounds, which play a part in protection and the processing of assimilated carbon in many species, and fire events, very frequent in the Mediterranean environments, and often poorly integrated in forest dynamic models.

Besides, finding truthfully parameters to feed the model to run is a key issue when process-based models are run. Considering that GOTILWA+ uses more than 100 simulation parameters, there is a huge need for robust and reliable parameterization techniques. Innovative iterative parameterization techniques, such as Bayesian or neural network approaches, would help us to improve model functioning and applicability, as well as to determine accurately the strengths and weakness of each model.

5.5 Conclusion

Process based forest eco-physiological models are very useful tools and have a wide application through many streams of research. Their functions range from assessment tools for forest managers and policy makers, to predictive tools for studies on ecosystem functioning, to essential components of large scale global models of climate evolution. The concept of this chapter has been to give a general overview of the structure and applications of such models, using the process based model GOTILWA+ as an example. We have discussed both empirical models, and process based models, and their relative pros and cons, and used GOTILWA+ as an example of how their application can give useful insights into current and future ecosystem functioning, both on a local, regional, and indeed global scale.

Although our knowledge is far from complete, and qualitative results are associated with a large amount of uncertainty, it is a rapidly developing area of research, and state of the art techniques are constantly being applied to improve our understanding, and the ability to produce accurate results. Current efforts are focusing on using highly accurate field data (such as that produced by the EUROFLUX network, using eddy covariance techniques (www-eosdis.ornl.gov/FLUXNET), and local intensive experimental stand measurements, such as the El Regàs MED-FORESTREAM plot) to further validate the models over a wide range of site conditions and ecosystem structures. This newly available high quality data also allows us to highlight important processes that are not sufficiently described. Besides, new parameterization and calibration techniques, such as Bayesian parameterization, are gaining importance in modelling. Those techniques are going to help us to improve the accuracy of the model projections.

Little by little, as our understanding grows, so too does the capability of such models to accurately replicate real life processes. Here we have given an overview of the current state of the art of biogeochemical terrestrial modelling.

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