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Literature review on current methodologies to assess C balance in CDM Afforestation/reforestation projects and a few relevant alternatives for assessing water and nutrient balance, as a complement to carbon sequestration assessments.

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INTRODUCTION

To abate continued anthropogenic driven climate change, the United Nations Framework Convention of Climate Change was established with the main objective of "stabiliz[ing] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The Kyoto Protocol to the Convention came into force in February 2005 that recognises a 'common but differentiated responsibility' between nations. Under the Kyoto Protocol, developed nation's greenhouse gas emissions are capped to an average level of 5% below 1990 levels within the first commitment period to the Protocol (2008-2012). Developing countries are not 'capped' within the first commitment period to the Protocol but can host Clean Development Mechanism projects.

The Kyoto Protocol includes three flexible mechanisms to assist developed countries in achieving their required targets. These mechanisms include International Emissions Trading, Joint Implementation and the Clean Development Mechanism (CDM). International Emissions Trading is the trading of emission allowances between two entities in Annex-1 countries to the Protocol.

In comparison, Joint Implementation and the CDM are 'project-based' mechanisms. With both mechanisms, an entity that requires emission credits, purchases them from a project that reduces atmospheric carbon dioxide through either an emission reduction or a sequestration project. Both mechanisms are essentially the same except that JI projects are implemented in developed countries and CDM projects are implemented in developing countries. The essence of the CDM is that developed countries will assist developing countries to develop in a sustainable 'climate – friendly' manner, either through the sharing of 'clean' technologies or the rehabilitation of degraded land. There are three main types of CDM projects, namely, carbon sequestration projects, fuel substitution and technology transfer:

1. Carbon sequestration projects. Often referred too as 'sink' projects, carbon sequestration is the accumulation and long-term storage of atmospheric carbon in vegetation and soil organic matter - long-term storage being 20 years or more. Atmospheric carbon is absorbed by vegetation through the process of photosynthesis. Most of this carbon is transpired shortly afterwards but a fraction is assimilated into plant matter through growth (wood is roughly 50 percent carbon). Within the first commitment period to the Kyoto Protocol the eligibility of Land Use, Land Use Change, and Forestry (LULUCF) projects activities is limited to afforestation and reforestation. Scientific and technical issues within this mechanism can be found in report 1/2003 of CarboEurope-GHG concerted action (Grace *et al.* 2003).

2. Fossil fuel substitution – either biomass or other non fossil fuels. This is an initiative where fossil fuels, generally coal, are substituted with biomass from a renewable plantation or other non fossil fuels such as methane derived from capping waste landfills. An example of such an initiative is the PLANTAR project in Brazil, where coal has been substituted with biomass from a Eucalyptus plantation for power generation.

3. Technology transfer. Such projects are through the introduction of a new technology that reduces greenhouse gas emissions. An example in this domain might be improved technology for converting wood to charcoal.

The present report concerns carbon sequestration projects. Two key issues have been identified in Sub-Saharan Africa for C mitigation project implementation: firstly sequestrating C through Afforestation and Reforestation (A/R) projects and secondly, reducing emissions from deforestation and forest degradation (REDD). One of the main hindrances to the implementation of carbon sequestration projects is the lack of formally registered monitoring, verification, validation and certification methodologies at present. Without the formal registration of such methodologies with the CDM Executive Board, sequestration projects cannot be registered and therefore no emission credits can be issued to the project implementer. This report is mainly dedicated to afforestation/reforestation project though numerous methodologies presented here can be applied without or little modifications to REDD projects.

In the context of the CDM, afforestation has been suggested as a way to simultaneously sequester carbon, increase wood and paper supplies, and diversify rural incomes. Hence, the focus of much of the research on this land-use change has been on sequestering and storing carbon in the biomass and soils of afforested areas. However, converting grasslands or shrublands to plantations will likely affect many other ecosystem processes, notably:

-water yield from rivers and streams (e.g. Duncan, 1995; Dye, 1996; Bashkin & Binkley, 1998; Paul *et al.*, 2002; Jobbagy & Jackson, 2003, 2004; Farley *et al.*, 2004, 2005; Jackson *et al.* 2005; Nosetto *et al.*, 2005; Sun *et al.*, 2006);

-acidification trend of the top soil (attributed to increased base cation uptake by tree roots and release of acidic compounds during litter decay); salinisation or desalinisation of soils (depending on the local context, Jobbagy et al, 2004; Robinson

et al., 2006), decrease in base saturation (decreasing under plantations), especially in the context of rotations, due to nutrient exports (Jackson *et al.*, 2005 for pine and eucalypt).
The magnitude of these changes is highly dependant of silvicultural practices, soil properties, climate and characteristics of the former vegetation. The major changes were observed after afforestation with fast growing plantations in degraded pastures but the same trends are observed after conversion of tropical lands in agricultural crops when fertilizations are inadequate (Hartemink, 2003).

Despite these known impacts, there are no published methodologies regarding measuring sustainability parameters such as the influence of biofuel plantation and sequestration projects on water provision and nutrient cycling. This is crucial as one of the core intentions of the Clean Development Mechanism, is that any CDM initiative must attribute to sustainable development (see CCB standards, http://www.climate-standards.org/). It is also a legal requirement of most Designated National Authorities to the Protocol that project implementers report in full on the sustainability attributes of their project.

Therefore, the aim of the present report is to review current methodologies to assess C balance in Afforestation/reforestation projects and a few relevant alternatives for assessing the H_2O and Nutrient balance, as a complement to CDM carbon sequestration assessments

The present literature review, although large, is not exhaustive. We focused on the main processes involved in C, water and nutrient budgets in forest ecosystems. The objective was to provide a simple report of the current methodologies the most used useful for students and engineers involved in Afforestation-Reforestation CDM projects in Africa.
Subsidiary requirements were the following:

-to be didactic: most important definitions, concepts, field methods and models have been summed up for the benefits of CARBOAFRICA students for instance. Alternatives (e.g. alternative field measurement or models) were classified, according mainly to their spatial or temporal scale
-to be general: a few examples are detailed by category, but a number of alternative tools are quoted.
-to be synthetic: tables are summing up the field methods and the models so that they can be easily cross-compared
-to be applicable to the case study: the examples were chosen specifically with intention to further apply them to our case-study

A- CARBON BUDGET

A1 - The carbon cycle in forest ecosystems

Figure 1 depicts the main fluxes involved in the carbon cycles in forest ecosystems. If there are no inputs from organic fertilizers, all the carbon inputs come from the gross primary production (GPP). A significant part of this carbon uptake is lost through autotrophic respiration (i.e. plant respiration, R_a) which can be arbitrarily divided into two main components: root respiration, R_{ar}, and respiration from aboveground plant compartments (leaves, branches, stems), R_{aa}. The fraction of GPP that is not lost through plant respiration is used to produce new biomass, thus contributing to the Net Primary Production (NPP):

$$NPP = GPP - Ra \quad \textbf{Eq. 1}$$

The ratio between NPP and GPP, the so-called Carbon Use Efficiency (CUE=NPP/GPP=1-Ra/GPP) often ranges between 0.40 and 0.50 for plantations and natural forest ecosystems (e.g. Landsberg, 2004). Allocation of NPP to the different plant compartments contributes to tree growth and litter production (L). Among the various plant compartments, we may distinguish between compartments with high turnover rate (leaves, bark, and fine roots), contributing to litter production, and compartments with low turnover rate (woody tissues of stems, branches, and coarse roots), contributing mostly to biomass accumulation. The stand growth (carbon accumulation in biomass ΔC_b) is the difference between NPP and L:

$$\Delta C_B = NPP - L \quad \textbf{Eq. 2}$$

Litter production from aboveground plant compartments (leaves, bark, small branches), L_a, is easily measured using litter-traps. Conversely, litter production from fine root turnover, L_r, is not easily assessable.
Litter inputs to the soil are decomposed by soil microorganisms. The part that is not oxidized is transferred to the soil organic matter (SOM) pool. Emission of CO_2 through litter decomposition and subsequent SOM oxidation by soil microorganisms both contribute to the so-called 'heterotrophic respiration', R_h, but occur at different rates. If leaching of

dissolved organic carbon is neglected, the soil carbon balance (ΔC_s and ΔC_L are respectively the change in carbon content of the soil and the litter) can be estimated from carbon inputs from litter production, and soil carbon loss through heterotrophic respiration:

$$\Delta C_S + \Delta C_L = L - R_h \qquad \textbf{Eq. 3}$$

A proportion of the litter produced through NPP is thus lost through heterotrophic respiration. The difference between the rate of NPP and R_h controls the rate of net ecosystem production/ Net ecosystem production is defined by:

$$NEP = NPP - R_h = \Delta C_B + \Delta C_S + \Delta C_L \qquad \textbf{Eq. 4}$$

While important for estimating and modeling stand carbon balance, partitioning soil CO_2 efflux between its autotrophic (root) and heterotrophic (soil microbial) contributions is difficult. Among the methods used for estimating R_h (see the review by Hanson *et al.*, 2000), the 'root exclusion' method is probably the most widespread: R_h is estimated from measurements of soil respiration on plots were roots have been killed (e.g. trenched-plots or girdling).

The total respiratory carbon loss by the ecosystem, R_e (ecosystem respiration) results from plant respiration (R_a) and respiration of soil and litter decomposers (R_h). The net ecosystem exchange of CO_2 between the forest and the atmosphere (NEE) is the difference between CO_2 uptake through photosynthesis, and CO_2 emission through ecosystem respiration. This net flux is highly variable both diurnally (due to variations of light, temperature, and air relative humidity), and seasonally, but it can be monitored continuously with the eddy-covariance methodology, and cumulated over time for estimating monthly or annual Net Ecosystem Production:

$$NEP = GPP - R_e = GPP - R_a - R_h = \sum NEE \qquad \textbf{Eq. 5}$$

An inter comparison of these fluxes across boreal, temperate and tropical forests ecosystems can be found in Luyssaert *et al.* 2007.

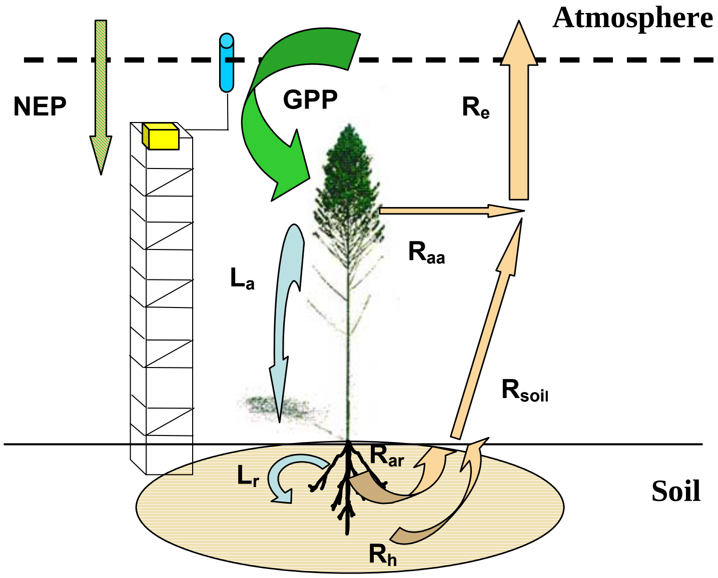


Figure 1: The carbon cycle in forest ecosystems. Brown arrows represent upward CO_2 fluxes (autotrophic respiration, Ra from above- and below-ground plant compartment, Raa and Rar, heterotrophic respiration, Rh, and ecosystem respiration, Re=Ra+Rh). Green arrows represent downward CO2 fluxes (gross primary production, GPP). Net ecosystem respiration, NEP, is usually a downward flux (sequestration), except in certain situations (after clear-cutting for example) when Re may exceed GPP. Blue arrows represents ecosystem internal fluxes of carbon due to litter fall (La) and belowground litter production by fine root turnover (Lr). Losses of carbon

by volatile organic compounds (VOC) emission, or by dissolved organic carbon (DOC) leaching have been neglected and are therefore not represented.

This short description of the carbon cycle in forest ecosystems suggests that carbon sequestration may be assessed from two main approaches, according to Eq. 4: (i) by measuring changes with plantation age of carbon stocks in the different compartments of the ecosystem (biomass, soil, litter), and (ii) by quantifying the forest carbon budget from measurements of the carbon input and output fluxes to and from the ecosystem. For this latter approach, two methods can be distinguished depending on the fluxes that are measured: (i) the eddy-covariance method that measures net CO_2 exchanges (NEE) between the plantation and the atmosphere; and (ii) methods that ascertain the ecosystem carbon budget from measurements of NPP and R_h.

Each of these methods has its own advantages and drawbacks and has the potential to complement the other. Methods based on carbon stock measurements require heavy sampling to deal with the spatial variability of carbon stocks in soil and biomass. They are nevertheless more cost-effective than methods based on the carbon budget methodology, so that they can be used to estimate carbon sequestration at sites that differ in previous land-use, soil properties (e.g. soil texture), or management practice and they can integrate age-effects along chronosequences. Thus, they can be used to identify factors influencing carbon sequestration. On the other hand, results are subject to inter-annual variability of climatic conditions and may therefore not be easily extrapolated. Furthermore, changes in some major ecosystem compartments such as soils are usually difficult to detect due to stand spatial variability and because they usually represent a small fraction of existing soil carbon stocks.

Methods based on the carbon budget methodology require heavy experiments, lasting for several years, so that they can't be applied on many sites or for many ages. However, they provide insight on the interacting environmental and biological factors and processes that determine carbon sequestration, and on the links between carbon, water and nutrients cycles. Information gained from these studies can therefore be used to develop models for extrapolating local measurements to broader spatial and temporal scales, to evaluate the plantation sustainability, and to examine the tradeoffs between carbon sequestration and plantation environmental impacts (e.g. plantation effect on hydrological and nutrient resources).
There is a great interest of combining both approaches on the same sites, in order to yield cross-validation of results (Grace *et al.*, 2001; Malhi *et al.*, 1999; Navarro *et al.* 2007) It should also be noticed that for both methods (carbon stock measurements and assessment from NPP and R_h), above- and below-ground biomass assessment is a key component. This point will be detailed, only once, in the C-stocks methods and the reader more interested in the C-budget methodology should refer to in chapter A22 for the biomass calculations.

A2 – Assessment of carbon sequestration using carbon stock measurements

This is the most widespread methodology for small and medium carbon sequestration projects. In this review, we will scan the main steps, highlighting differences (or similarities) between a selected numbers of reference papers (list given in Annex 1). The objectives are (i) to identify what should be done and when, (ii) to synthesize the recommended methodologies and the underlying assumptions and simplifications, (iii) to extract points that will be developed within the CarboAfrica project to improve methodologies and propose refined standards from a cost-benefit approach.

In this report, we focused on forest land and grassland which are 2 of the 6 top-level land use categories for green house gas inventories (IPCC Good Practice Guidance for LULUCF 2003, hereafter referred to GPG-LULUCF 2003). Carbon pools under consideration are corresponding to living above- and below-ground biomass, dead organic matter in dead wood and litter, soil organic carbon. Definition of these carbon pools can be found in GPG-LULUCF 2003 (table 3.1.2, page 3.15). The selection of which pools to measure and monitor in the different types of LULUCF Projects depends mainly *on the rate of change, the magnitude and the direction of the change, availability and accuracy of methods to quantify changes and cost to measure*. A decision matrix can be found in GPG-LULUCF 2003 (Table 4.3.1, page 4.96) or in Pearson and Brown 2005 (Table 1, Page 10). For this review, we will consider that all pools should be considered. For example, afforestation/reforestation projects often involve site preparation that may affect (or not) soil carbon (Paul *et al.* 2002, Guo and Gifford 2002, Nouvellon *et al.* 2007).

Whatever the methodology, assessing, monitoring and verifying carbon storage can be expensive depending on the level of scientific validity needed. For example, MacDicken 1997 distinguished three levels of efforts, the first and basic one being at low cost and providing estimates of carbon sequestration with accuracy approaching 30% and the third one, at higher costs and providing estimates that are within 10-15% of the mean. A similar classification is later presented in

GPG-LULUCF 2003, where Tier 1 approach uses the basic method and the standard values provided in the IPCC guidelines; Tier 2 applies stock change methodologies based on country/site-specific data; whereas Tier 3, the most accurate, combines inventory measurement, plant growth models fitted for each soil type and GIS maps of soils and climates for the whole area (see box 3.1.1 page 3.17). It is recommended to use methods that provide the highest level of accuracy but moving to a higher tier will generally increase costs. The main question, for any MDP carbon project, is to quantify costs and benefits of using one or another tier level. It should be noticed that, in case of Tier 3, complementarities between the two methodologies presented in this report (carbon stocks measurements versus carbon budget methodology) are obvious, at least for audits and validation.

This chapter follows a classical presentation and is divided into 3 main sections: (i) sampling design, (iii) measurements of carbon pools, and (iii) models for interpolation and simulations. When available, cost-benefit or cost-effective approaches will be indicated.

A21- Sampling Design

Once the project boundaries are defined, the sampling design determines how the sampling units are selected from the population and thus which statistical estimation procedures should be applied to infer the characteristics of the whole population from the sample. Several sampling techniques are applicable in forest ecosystems, and detailed information can be found in Pardé and Bouchon (1988), Avery and Burkhart (2002), West (2003), and Titus (2004). For both baseline and monitoring of carbon projects, it is generally recommended firstly, the use of auxiliary data and stratification, and secondly, a systematic sampling within each strata (GPG-LULUCF 2003, Pearson and Brown 2005, UNFCCC / AR-AM0008 and AR-AMS0001)

Stratification, which consists in partitioning the population into mutually exclusive sub-populations, allows a greater precision in biomass estimations because it is made so that the variation between the sampling units in a stratum is less than the variation over the whole area. Auxiliary data are in general: climate, soil type, land-use, species (or type of vegetation, or group of species with similar growth habits), topography (slope intensity, plateau, and bottomland), climate (arid, semi-arid, well distributed rainfall), and age (or stage of development). One should note that if nothing is known about the spatial distribution of these figures within the project boundaries, there is no alternative to a simple random sampling (SRS). Useful tools for stratification are satellites images and related products (ex Land-cover, CITER FAO), aerial photographs, maps and GIS (see Ponce-Hernandez 2004 for a general overview, and also AR-AM0008, annex 1 for the analysis of remote sensing data).

Once the zone is stratified, the systematic sampling within each stratum is recommended because it is convenient, easy to implement on the field (a grid of points is applied in each stratum from a randomly selected starting point) and less costly than the SRS. Pearson and Brown (2005) also indicate that stratification facilitates the control by an independent verifying organization. Two drawbacks can however be reported: (i) the error (or confidence interval) of the biomass estimates may be difficult to be calculated if the number of strata is high, but this aspect can be solved by an ANOVA (see Pardé and Bouchon, 1988), and (ii) if the grid lines coincide with a systematic variation of the biomass across the forest area, the result of the inventory may be strongly biased.

The spacing between points is determined by the number of sample units to be measured. Ideally, this number should be calculated after a pre-inventory study which will provide a first estimate of the variability of each carbon pool within each stratum. These calculations are applicable under the condition that the variable of interest is normally distributed or can be transformed into a normal distribution. Several tools may be applicable to test the normality of a given distribution (Kolmogorov-Smirnov for large datasets, W-test of Shapiro-Wilk for small to medium data sets n<50). However, the method proposed by D'Agostino *et al.* (1990) is interesting because it is applicable to medium to large data sets (n>20) and it tests in which way the distribution drifts from normality (skewness and kurtosis).

Some formulas to calculate the total number of plots required in carbon projects are given in MacDicken (1997), Titus (2004), Pearson and Brown (2005), etc… but the most complete one, for infinite (with replacement) and finite populations (without replacement), including the costs of inventories within each stratum, can be found in the following document: "Nb, size, location of sample plots: Methodological tool, Version 01, Calculation of the number of sample plots for measurements within A/R CDM project activities. UNFCCC, 6p":

-Method 1, without replacement (infinite population):

$$n = \left(\frac{t_{n-L,\alpha}}{E} \right)^2 \left[\sum_{i=1}^{L} N_i st_i \sqrt{C_i} \right] \left[\sum_{i=1}^{L} N_i st_i \Big/ \sqrt{C_i} \right] \qquad \textbf{Eq. 6}$$

- Method 2, with replacement (finite population):

$$n = \frac{\left[\sum_{i=1}^{L} N_i st_i \sqrt{C_i}\right]\left[\sum_{i=1}^{L} N_i st_i \Big/ \sqrt{C_i}\right]}{\left(N \frac{E}{z_{\alpha/2}}\right)^2 + \sum_{i=1}^{L} N_i st_i^2} \qquad \textbf{Eq. 7}$$

n = is the total number of plots required (for the whole project);
L = the number of project strata;
α = (1-α) is probability that the estimate of the mean is within the error bound E;
$z_{\alpha/2}$ = value of z statistic (inverse of normal probability cumulative distribution, for 95% confidence level, 1-a=0.05 and $z_{\alpha/2}$=1.9599);
$t_{n-L,\alpha}$ = Student's t-distribution value for a confidence level 1-α and n-L degrees of freedom;
E = absolute value of allowable error on *Q; E = Q.p*; with *Q* the approximate value of the estimated quantity *Q* on a per plot basis and *p* the desired level of precision (ex: 10%);
N = maximum possible number of sample plot in the project area;
N_i = maximum possible number of sample plot in stratum *i*;
st_i = standard deviation of the estimated quantity for each stratum *i*;
C_i = cost of establishment of a sample plot for each stratum *i*;

Then, there are two possibilities to allocate this total number to strata: proportional to the ratio Ni/N (for both methods) and optimal using the costs of plot establishments (method-dependant)
-Method 1:

$$n_i = n \frac{N_i \; st_i \big/ \sqrt{C_i}}{\sum_{i=1}^{L} N_i \; st_i \big/ \sqrt{C_i}} \qquad \textbf{Eq. 8}$$

-Method 2:

$$n_i = \frac{\sum_{i=1}^{L} N_i st_i \sqrt{C_i}}{\left(N \frac{E}{z_{\alpha/2}}\right)^2 + \sum_{i=1}^{L} N_i st_i^2} \frac{N_i st_i}{\sqrt{C_i}} \qquad \textbf{Eq. 9}$$

The plot size has a great influence on the sampling intensity and the time spent on the field. The area of a plot usually depends on the stand density and/or the tree size. It can range from 100m^2 for dense stands (more than 700 trees per ha) to 1000m^2 for open stands (less than 100 trees per ha) (see MacDicken 1997, Table 4, page 54). For example, in moist tropical forests, Pearson and Brown 2005 proposed a series of nested circles (or squared plots) ranging from 3m^2 to 1256m^2 (see Table 1). Similarly, Ponce-Hernandez 2004 used quadrats of regular shape dimensions (10m x 10m, 5m x 5m, and 1m x 1m) nested within each other, for the tree, shrub and herb layers. GPG-LULUCF 2003 also advocates for nested sample plots containing smaller sub-units depending on the variables to be measured. Ideally, the plot size should be assessed also in the pre-inventory study. Chave *et al.* (2003) made this calculation in a moist tropical forest in Panama and concluded that the minimal number of subplots required to know the mean aboveground biomass with 20% error (±10%) within the 95% confidence interval was 26 for 50x50m^2 plots and 481 for 10x10m^2 plots (see table 5, page 245 in Chave *et al.*, 2003). Because these figures were calculated for moist tropical forests, they can be considered as upper limits for afforestation/reforestation projects.
If the pre-inventory study was not designed to test several plot sizes, it is possible to use the following formula:

$$CV_2^2 = CV_1^2 \sqrt{\frac{AP_1}{AP_2}} \qquad \textbf{Eq. 10}$$

Where CV_2 is the coefficient of variation of the estimated quantity Q if the plot size was AP_2; CV_1 being the coefficient of variation of the estimated quantity Q obtained in the pre-inventory study with a plot size AP_1.

Tree diameter (cm) at breast height	*Radius for circular plots*	*Plot size for squared plots*
<5	*1 m*	*2m x 2m*
5-20	*4 m*	*7m x 7m*
20-50	*14 m*	*25m x 25m*
>50	*20 m*	*35m x 35m*

Table 1 : plot size for a nested sampling (reproduced from Pearson and Brown 2005)

A22- Measurements of the carbon pools in forest, methods and uncertainties

A221- Above-ground Biomass

Estimating carbon stocks in forest biomass can be based on forest inventories or on remote sensing. Inventory based method includes two main approaches: a direct one, using allometric equations and an indirect one using biomass expansion factors. The latter is mainly used in national forest inventories, whereas the direct one is recommended by GPG-LULUCCF 2003 for afforestation/reforestation carbon projects. In this document, we will therefore focus on the direct approach but indications concerning r biomass expansion factors will be also provided because they can provide alternate solutions.

A2211- Inventory based methods

General Principle

Biomass assessment is an old thematic (Boysen-Jensen and Müller, 1927, Burger, 1929, or see for example the XVth IUFRO Congress in 1971, working group on forest biomass studies and the emergence of the complete tree utilisation during the 1970-80's) which is renewed by the incoming of carbon and bio-energy issues linked to global change. The method consists in (i) performing an inventory of the trees in each sample plot (diameter at breast height and if possible tree height), (ii) applying appropriate allometric equations to the trees measured in (i), and (iii) up-scaling these figures to assess C stocks and their variation within each stratum. For the direct method, we use biomass equations, whereas in the indirect one, we use firstly volume or taper equations and secondly density and biomass expansion factors. Key points of these methods are the biomass (or volume) equations and the biomass expansion factors (BEF). Despite their apparent simplicity, they have to be fitted carefully, using the latest regression techniques (see Parresol, 1999 and 2001 for biomass equations; Wirth *et al.* 2004 for BEFs). An unsuitable application of biomass equations or BEF may lead to considerable bias in carbon stocks estimations. For example, the application of the tropical moist forest equation (Brown, 1997) to a tropical wet forest (Clark and Clark, 2000) over estimates aboveground biomass by 79% (in Clark et al, 2001). Therefore, in case of using general equations developed from biome-wide database, GPG-LULUCF 2003 indicates that it is good practice to verify the applied equation by destructive sampling.

Sampling strategy for building biomass equations

As for the plot sampling, the number of trees to be selected for building biomass equations is function of the wanted precision. Pardé and Bouchon (1988) gave some indications that are resumed in Table 2. MacDicken 1997 recommended 100-300 trees at a regional scale, 30 trees for a single species and 12 trees for a site-specific equation. Similarly, Pearson and Brown (2005) suggested 30 trees by species. Vallet (2006) used between 300 and 1300 trees per species to develop volume equations valid at the country scale. Lastly, in their monograph on biomass and tree volume equations for 39 tree species in Europe, Zianis *et al.* (2005) (figure 1, page 10) indicated that the amount of sampled trees varied between 3 to 1503 for biomass equations (the most usual amount was typically between 6 and 40 per study), and ranged between less than 10 to more than 5000 trees per study for volume equations. Interestingly, in about 30% of the studies the number of sampled trees was not reported. This illustrates the difficulty of gathering and interpreting information in some past published studies.

- **Mono-specific and even-aged stands : 30 trees**
- **A 15ha group of stand : 100 trees**
- **Forest of 1000ha : 400 trees**
- **region scale : 800 trees**
- **Ecological range of a given species : 2000 to 3000 trees**

Table 2 : Number of trees to be felled for building biomass equations (reproduced from Pardé and Bouchon, 1988)

If a pre-study was conducted to assess roughly the variability of tree biomass within each stratum, then the following methodologies can be applied to calculate the optimum number of trees to be felled.

Bootstrap on the pre-inventory study: this procedure was used by Laclau (1997) on eucalyptus clonal plantations. A total of 30 trees, covering the whole range of tree dimensions, were felled for biomass assessment. The biomass of the sampled plots, calculated with the equation fitted on the 30 trees, was used as reference one. Then, 1 to 4 trees per dimension classes were selected randomly. The procedure was repeated 20 times so as to obtain 20 equations built with 6, 12, 18 and 24 trees. These equations were applied to the trees inventoried in the sampled plots and biomass estimates were compared to the reference one. Two verifications were performed: (i) there was no bias on the average value, (ii) using 6 trees, the standard deviation of mean biomass estimates did not exceed 10% of the average value obtained with 30 trees, and this figure felled down to 5% using 12 trees. It was then decided to sample only 12 trees for further biomass studies on these eucalypt plantations. The main advantage of this procedure is that it can be applied to any types of models (linear, non-linear regressions weighted or not, etc…).

Direct assessment by way of regression estimators (Cochran, 1977 - Chapter 7, Thompson, 1992 – Chapter 8, de Vries, 1986, Shiver and Borders, 1996 – Chapter 6): this method can easily be applied on simple linear regression such as:

$$Y_i = a + b d_i^2 h_i \qquad \textbf{Eq. 11}$$

where Y_i is the individual tree biomass, d_i and h_i are respectively the diameter at breast height and the total tree height, *a* and *b* being the regression parameters to be estimated. We assumed that this equation can be fitted after the pre-study and that the relationship between biomass and tree dimension is correct (but the assumption is reasonable, see Parresol, 1999, 2001 or Saint-André *et al.*, 2005). For the whole stand, the total biomass is given by:

$$Y_{tot} = \sum_{i=1}^{N} a + b d_i^2 h_i = N\overline{Y} \qquad \textbf{Eq. 12}$$

where N, is the number of trees within the stand and $\overline{Y}$ is the average tree biomass. Because parameters *a* and *b* are obtained by linear regression, the unknown quantity $\overline{Y}$ is also given by:

$$\overline{Y} = \overline{Y}_e + b\left(\overline{d^2 h} - \overline{d_e^2 h_e}\right) \qquad \textbf{Eq. 13}$$

where $\overline{Y}_e$ is the average tree biomass for the sampled trees used for building the biomass equation (pre-study assessment), $\overline{d^2 h}$ and $\overline{d_e^2 h_e}$ are the average quantities of $d_i^2 h_i$ for the whole inventoried population and for the sampled trees used for building the equation. From Eq.13 and the known theory on the sampling by regression estimators, the confidence interval for $\overline{Y}$ is given by (Cochran, 1977, p199; Thompson, 1992, p83):

$$t_{n-2,\alpha/2}\,\hat{\sigma}\sqrt{\frac{1}{n} - \frac{1}{N} + \frac{\left(\overline{d^2 h} - \overline{d_e^2 h_e}\right)^2}{\sum_{i=1}^{n}\left(d_i^2 h_i - \overline{d_e^2 h_e}\right)^2}} \qquad \textbf{Eq. 14}$$

with $\hat{\sigma}$ the residual standard deviation of the regression (Eq.11). This formula can be used to calculate the optimum number of trees in case of measuring all the trees in the population of interest. However, for many forest inventories, we have a two stage sampling: the first one n<N where the tree dimensions are measured and the second one n<n where the tree dimensions and the tree biomass is measured for building the biomass equations. In that case, the confidence interval for $\overline{Y}$ is given by:

$$t_{n-2,\alpha/2}\sqrt{\frac{1-n/N}{n(n-2)}\left\{\sum_{i=1}^{n}\left(Y_i-\overline{Y}_e\right)^2-\frac{\left[\sum_{i=1}^{n}\left(Y_i-\overline{Y}_e\right)\left(d_i^2h_i-\overline{d_e^2h_e}\right)\right]^2}{\sum_{i=1}^{n}\left(d_i^2h_i-\overline{d_e^2h_e}\right)^2}\right\}} \qquad \textbf{Eq. 15}$$

Once the number of trees to be felled is known, it is strongly recommended to use basal area classes instead of diameter classes: (i) because the largest trees contribute more to the total stand biomass than the smallest ones (if biomasses are normally distributed) and, (ii) because the variance of volume, biomass or nutrient content increases with tree size, an over sampling of the largest trees allows to catch this variability (Cailliez, 1980). For multiple-stem trees, it is recommended to use the sum of stem basal area to get the average diameter of the trees and, in some particular cases (ex: dry areas), it is better to use the base of the trunk than breast height (Stewart *et al.*, 1992 in Brown, 1997). The repartition of the trees within each class depends on the objective of the model: if it is dedicated to a single use (for example, assessing the biomass of a particular stand without any will of using it elsewhere) then the number of tree per class can be proportional to the representation of the class in the total population ; but if it is intended to use it at a large scale, the robustness of the equation is a required quality and it is then better to apply a fixed number of trees per basal area classes (Cailliez, 1980; Pardé and Bouchon, 1988)

Another method based on biomass measurements for one tree representative of the stand (mean tree method) has been classically in the past. MacDicken (1997) and Pearson and Brown (2005) indicate that the mean tree method is likely to be applied, as a cost-effective alternative to more time-consuming allometric methods. This is indeed true, assuming that (i) the average-sized tree will also have an average biomass and, (ii) that the average-sized tree is representative of the whole stand (so that its biomass can be multiplied by the number of stems within the plot). The reader should carefully check the latter point by using the D'Agostino *et al.* 1990 test of normality. A wrong use of this method can lead to highly biased estimations of the standing biomass. Furthermore, the selection of the mean tree on the field is often problematic. A comparison of stand biomass assessed from the mean tree technique and allometric equations in even-aged forest plantations showed and underestimation of 10 to 16 % of stand biomass with the mean tree (Sicard *et al.*, 2006).

Work on the field

Detailed procedures as well as the list of required equipments and data collection forms can be found in MacDicken (1997), Brown (1997), Pearson and Brown (2005) or in any forestry manual. Main principles are the following: (i) use the appropriate device (especially the balance) for the right purpose, (ii) avoid as much as possible rainy days, (iii) for some compartments (such as leaves or fruits), the sampling season may be crucial, (iv) use as much as possible floor tarpaulins to catch all fragile compartments when the tree fells, (v) take advantage of the opportunity of tree felling to measure other features (for example wood density, diameters along the tree bole, separate the crown into three parts to differentiate upper, middle and lower crown characteristics, etc…), (vi) use aliquots for all compartments (for the trunk, cross-sections should be equally distributed along the tree bole), (vii) green weight of the aliquots should be measured at the same time of the whole compartment, or if not possible, they should be put in hermetic plastic bags to be weighted rapidly in a laboratory, (viii) aliquots should be dried at 65° mainly to avoid nitrogen volatilisation (if it is decided to measure also nutrient concentrations).

Building equations

Biomass equations or volume equations are now widely developed in forestry and agroforestry for both industrial and scientific purposes. These models have the same objectives: evaluate some non-easy to measure tree characteristics from easy collected data such as dbh (diameter at breast height), total height, or tree age. Most of equations are linear, exponential, allometric, or hyperbolic and correlations are often very good (R^2>0.8). For more details, one can refer to the

following reviews: Bouchon (1974), Hitchcock and McDonnel (1979), Pardé (1980), Cailliez (1980), Pardé & Bouchon (1988), and more recently Parresol (1999, 2001).
First biomass studies were probably published by Boysen-Jensen and Müller 1927, and by Burger from 1929 to 1953. Since these dates, numerous studies have been carried out in order: (i) to test different kinds of equations (e.g. Crow, 1971, Schreuder and Swank, 1971), (ii) to identify differences between silvicultural regimes or sites (e.g. Attiwill, 1966, Crow, 1978, Ranger, 1978), (iii) to estimate aboveground biomass of different compartments (e.g. Zavitkovski, 1971, Riedacker, 1971, Okello et al, 2001; Sebei *et al.*, 2001; Norgrove and Hauser, 2002; Blazier *et al.*, 2002), (iv) to assess belowground biomass (e.g. White *et al.*, 1971, Ranger and Gelhaye, 2001) and, (v) to estimate both belowground and aboveground biomasses (e.g. Hakkila 1971, Ni *et al.* 2001; Adegbidi *et al.* 2002; Bond-Lamberty *et al.* 2002; Mund *et al.* 2002). Within the context of carbon sequestration, new applications of these biomass equations are performed and innovative statistical methodologies are developed (Dynamic Multi-Variate Ordinal Probit Model, Chaubert *et al.* 2007). A correct evaluation of carbon storage within the ecosystem is of major importance, especially when these storages are low. It is then necessary to provide an accurate estimation of the stand biomass but also its interval of confidence in order to compare different methods of evaluation (e.g. destructive measurements versus atmosphere-ecosystems exchange) or to compare different stands or silvicultural regimes. This implies (i) to set up a representative sampling of the considered ecosystem, (ii) to take the data's heteroscedasticity (non homogeneous variance among the tree sizes) into account during the fitting process, and (iii) to simulate for the whole ecosystem both the mean and the interval of confidence of the biomass estimates. However, up to now, relatively few of the biomass studies take into account the three major difficulties that may occur when building such equations. Parresol (1999 and 2001) proposed a well documented and explicit review for both linear and non-linear relationships. The reader can refer to these two papers for a detailed description of the methodologies to be used.

The first difficulty is linked to the data structure. Generally, the variance of biomass increases with tree age or dbh leading to heteroscedastic and, sometimes, non-normally distributed data. Application of ordinary least square regression under this variance heterogeneity generates (i) estimated parameters that do not have the minimum variance, (ii) biased estimators of the variances of the estimated parameters, and (iii) false estimation of the residual variance (Cunia, 1964, Parresol, 1993, Grégoire & Dyer, 1989). Fortunately, regression coefficients are unbiased and converged to the true parameters as the sample size increases (Kelly and Beltz, 1987) but this condition is rarely obtained fo biomass studies. It should be noted that variance heterogeneity was also reported by Box and Hill (1974) to generate parameter estimates with counterintuitive or anthetical signs. As a conclusion, even though parameters value and therefore mean biomass are little affected by heteroscedasticity, variances may be strongly badly estimated. This last point is a major drawback when the user wishes to give a valid interval of confidence of the tree or stand biomass estimates.

The second difficulty is related to the data sampling. Such kinds of models are basically non generic and should be applied with care to other trees or to other silvicultural regimes. The way of sampling may have a great influence on the coefficients estimators, their confidence interval and the residual variance (Cunia 1964, Madgwick 1971). If genericity is a desired property for the biomass equation, it is therefore necessary to take all the "between stand" and the "within stand" variability into account (e.g. sylviculture regimes, sites, clones etc..) for the equation building (Rennie, 1966; Wirth *et al.* 2004). Some general equations were developed from biome-wide database (ex. Cairns *et al.* 1997 for belowground biomass; Brown, 1997 for tropical species in dry, wet and moist climatic zones; Niklas and Enquist, 2002 or Enquist and Niklas, 2002 for angiosperm and conifer species; Zianis and Mencuccini, 2002 for beech trees, Zianis and Mencuccini, 2004 for different species spanning the world, Chave *et al.*, 2005 for tropical forests in America, Asia and Oceania (including mangrove); Muukkonen, 2007 for 5 tree species in Europe; The GCG-LULUCF 2003 provides a list of biomass equations that can be used for both tropical and temperate species (tables 4.A1, 4.A2, 4.A3 and 4.A4, pages 4.114-4.116); some monograph such as the one produced by Zianis *et al.* (2005) for temperate species are also useful, but we could not find similar information for Africa). The equations to be used should be, at the best, locally-derived and species-specific. If no local biomass equation is available for the afforestation/reforestation project, the main rule is to use the published one that corresponds ideally to the species, the climatic area, etc… In specific situations, different equations may be available and could be equally selected. Chave *et al.* 2003 proposed an interesting solution to select the most suitable equation in a tropical forest in Panama: they selected 4 equations from the literature and they examined how each equation predicted the results obtained by the other equations on theirs plots. They selected the equation that had the highest mean correlation with the other ones. GPG-LULUCF 2003 recommends verifying the equation by destructively harvesting of a few trees of different sizes. They fixed a 10% admitted error (page 4.101, Step 3 of the direct approach). We also recommend using the modelling efficiency introduced by Mayer and Butler 1993 and checking for bias (simultaneous test on the intercept, which should be null, and the slope of the regression, which should equal to unity, between the measured biomass and the simulated one). The ideal case would be a modelling efficiency close to 1 and no bias between the measured and the simulated biomass.

The third difficulty is linked to tree splitting into several compartments. When building models for each of them, the sum of the estimated biomass with the "compartments equations" might not lead to the estimated biomass from the "total equation" (see Kozak, 1970 for an illustration, Reed and Green, 1985, Návar *et al.*, 2002). Parresol (1999) indicates three different methods to ensure additivity in biomass equations: (i) the total biomass equation computed by the sum of individually best fitted equations for each compartment, (ii) the total biomass and all compartment equations are of the same form and have the same weighted function, the regression coefficient of the total biomass equations being simply the sum of compartment coefficients, (iii) the total biomass and all compartment equations are all different, the additivity is ensured by setting constraints on coefficients (SUR seemingly unrelated regressions, e.g. Parressol 1999, 2001, Návar *et al.*, 2002, Saint-André *et al.*, 2005). Theoretically, it is not necessary to split tree into several compartments for afforestation and reforestation projects. However, in the case of fast growing species (such as in tropics), the project duration may exceed one crop rotations. In that cases, forest management and more particularly harvest residue management, may have a strong impact on stand production, and carbon and nutrient cycles (see for example Corbeels *et al.*, 2005; Nambiar *et al.*, 2004). It is then necessary to quantify the amounts of nutrients contained in harvest residues to predict growth of the next rotation.

Simulations

The quantification of uncertainties in sample based surveys is of major importance, particularly in afforestation/reforestation projects where it is intended to compare two ecosystems. GPG-LULUCF 2003 gives a clear overview of the different types of errors (see part 5.3.6.1, page 5.26 and 5.27): (i) measurement errors, (ii) model errors, (iii) sampling errors (up scaling of plot level to larger areas), (iv) classification errors, (v) data registration and calculation errors. In this paragraph, we will focus on model errors and their consequences on the up scaling.

There are two main ways of quantifying model errors at the plot level: an analytical one, where we use the local derivative of the model with respect to each parameter (see Serfling 1980, Parresol, 1999, 2001 for a global overview of the methods, Fonseca and Parresol, 2001 for application to biomass estimations, or Maquere *et al.*, 2007 for application to carbon stocks in the soils), and a simulation one, where we use Monte-Carlo techniques (see for example Sicard *et al.*, 2006 for biomass estimations, or Marsden et al, 2007 for the root respiration). These two methods take heteroscedasticity and correlations between parameters into account and provide the confidence interval for individuals (if a new tree was sampled, what would be its biomass) and for the mean (in average, trees of such given size would have this biomass). Up scaling from the tree to the plot level is straightforward using Monte Carlo simulations and is well explained by Fonseca and Parresol, 2002 for the analytical method. This uncertainty quantifies the precision of the applied methodology and depends on (i) the sampling design used to select the trees for the biomass equation, (ii) the sample size, (iii) the estimation procedure and, (iv) the ability of the regression function to render the relationship between biomass and tree size.

Up scaling to the whole forest inventory (including all measured sampled plots) induce, in addition to the model error, a sampling error. In case of a random model error, GPG-LULUCF 2003 assumes that quantities connected to the population units (the plot) are unbiased without errors and the standard sampling theory for deriving the uncertainty estimates can be used with good approximation, without modifications (paragraph 5.3.6.3, page 5.28; see also Giardina and Ryan 2002, pages 495-496). However, if there are suspicions of systematic model error, then it is recommended to account for the two sources of errors (model and sampling). If biomass equations are of linear forms, it is possible to calculate analytically the contribution of both errors to the overall variance of biomass (see Parresol, 1999 and details in Cunia, 1987a,b,c,d,e,f for different sampling designs). If biomass equations are more complicated, then Tier1 (propagation errors, see for example Jalkanen *et al.* 2005, Tobin and Nieuwenhuis 2007) and Tier2 (Monte Carlo simulations, see for example Lehtonen *et al.* 2007) approaches as described in IPCC 2000 and GPG-LULUCF 2003 should be applied.

Biomass expansion factors

This refers to the indirect approach described in GPG-LULUCF 2003 to estimate forest biomass. It applies to forest inventories when the commercial volume is obtained either directly (derived from stem diameter measured at different heights on standing trees with instruments such as Bitterlich relascope or laser dendrometer) or indirectly by volume or stem taper equations. One should notice that such equations require the same sound procedure as biomass equations (genericity and heteroscedasticity). Once the commercial volume is known, it is converted to biomass using a density factor (tonnes of dry matter per m3 of green volume) and a biomass expansion factor (BEFs, to shift from commercial to whole tree biomass). Values of tree density for several tropical tree species can be found in Brown 1997-Appendix 1; and/or in GPG-LULUCF 2003 Table 3A.1.9-1 for temperate and boreal species, Table 3A.1.9-2 for tropical species.

Default values of BEFs can be found in GPG-LULUCF 2003 Table 3A.1.10 (page 3.178). But both quantities may vary considerably with the species, stand age, or/and site (Brown 2002, Lehtonen *et al.* 2004, Vande Walle *et al.* 2005, Tobin and Nieuwenhuis 2007). When a destructive sampling has to be done for building local BEFs, it is recommended to use the direct approach (biomass equations) instead of the indirect one. But because this information (BEFs as well as may be required for other country project, the sampling.

A222- Below-ground Biomass

Compared with the relative abundance of information on aboveground standing crops, belowground information is rather limited. Nevertheless, root systems are an important fraction of plant biomass and play a significant role in forest net primary production (Fogel, 1985; Canellas and San Miguel, 2000). The proportions of above- and below-ground biomasses are highly variable according to the vegetal formations (Grier et al, 1981; van Noordwijk *et al.*, 1996). Although scientists recognize the important role of these biomass fractions, the studies are still scarce. This is at least partially due to the fact that roots, but even more so, entire root ecosystems, are difficult to observe, that has made it difficult to develop a reliable methodology of study. Comparison, generalization and modeling of root systems, are very difficult to study due to the scarcity of data, and lack of precision in the methodology used. Thus there is no global theory which explains the dynamic and structural relations of root systems in natural ecosystems.

Tree roots contain a high proportion of forest biomass but the estimations of root biomass vary greatly due to the different excavation methods used (Hoffman et al, 2001). Root biomass is often reported per unit of forest area only (Santantonio *et al.*, 1977; Grier *et al.*, 1981), making these data unusable for modelling based on individual trees.

There are no well-established methods for measuring root biomass (Fabiao *et al.*, 1995; Misra *et al.*, 1998; Oleksyn *et al.*, 1999; Millikin and Bledsoe, 1999; Tufekcioglu *et al.*, 1999), despite some suggestions to the contrary (Vogt *et al.*, 1998). Consequently, root biomass data are still sparse, limiting our capacity to fully characterize forested ecosystems and accurately assess forest C stocks. The recent publication of a standardized protocol (Snowdon *et al.*, 2002) may partly address this situation.

Most existing techniques to measure fine root biomass and production are labor intensive and controversial (Vogt *et al.*, 1998), and this has resulted in a scarcity of accurate estimates on roots relative to the aboveground components. Various methods, both direct and indirect, have been used to measure fine root biomass and production, but no one technique has been accepted universally as the best (Vogt *et al.*, 1998). Belowground spatial heterogeneity is large (Haynes and Gower, 1995; Vogt *et al.*, 1998), and the allocation of photosynthate to fine roots in trees is highly variable (Vogt *et al.*, 1996). Belowground carbon allocation, including fine root growth and senescence, is subject to many biotic and abiotic factors that vary spatially and over time. These factors include stand or tree age, tree species, soil temperature, moisture, and nutrient availability, as well as impacts by insects, fungi, and other soil organisms (Gill and Jackson 2000; Haynes and Gower 1995; Hendrick and Pregitzer 1993; Nadelhoffer *et al.* 1985).

When the objective is to assess carbon budgets and carbon allocation within a forest ecosystem, coarse root biomass and production data should also be collected. Methods for measuring coarse root biomass are well developed and not controversial. Large, structural roots can be estimated using allometric equations developed from above-ground measurements (see Santantonio, 1990) as their growth is similar to above ground branches. On Eucalyptus plantation these allometric relationships were particularly well fitted (Saint-André *et al.*, 2005). However, only a small part of annual root production occurs in this root size fraction (see Grier *et al.*, 1981).

Many different approaches have been used to study fine root biomass in the field, with some techniques used more frequently than others. However no one technique has been accepted universally as the best. The main methods used can be classified as (i) extraction methods (generically known as root washing); (ii) mapping techniques; (iii) in situ imaging techniques; and (iv) other (often sophisticated) imaging techniques (Pierret *et al.*, 2005). Extraction methods are based on collecting soil samples of known volume (core or monolith) from which roots are physically separated by carefully washing the soil away, and finally measuring the length of the separated roots using stereological or image analysis techniques (do Rosario *et al.*, 2000) or weighting them after drying for biomass measurement. The sequential root coring method was the most commonly used method to assess the time course of root biomass data in the past and is still commonly used to estimate fine root turnover. But within the last decade the use of minirhizotrons has become a favourite method of many researchers (Vogt *et al.* 1998). The principle of mapping methods is to record the occurrence of root contacts on a destructively exposed soil surface (van Noordwijk *et al.*, 2000). Root contacts, whether enumerated on a pit face or a core surface with the naked eye, or on soil thin/polished sections using a microscope, are subsequently converted to length measurements according to a calibration procedure (Newman, 1966; Chopart and Siband, 1999). With in situ imaging methods, roots are observed at transparent interfaces with soil, such as the walls of transparent plastic tubes (minirhizotrons) (Smit *et al.*, 2000) or transparent glass panel (Thongo *et al.*, 2007) inserted into the soil for several months. This method allows dynamic monitoring of root growth, mortality and decay and measurement of root length either directly, or based on calibration procedures. Biomass estimation by this method remains difficult and need also a calibration procedure via specific root length calculation (estimated as the mean length divided by dry weight). Moreover, the bias resulting from specific growth conditions close to the walls of the rhizotrons (soil water content in particular) is difficult to estimate. Finally, other imaging techniques involve probing (using electromagnetic radiation such as light, X-rays or γ-rays, particle beams or variable magnetic fields) of either field specimens or whole root systems confined within the delimited volume of specifically designed containers (the size of which is a function of the probing technique). The result is the reconstruction of either 2D (e.g. X-radiography) or 3D (X-ray CAT scanning, NMRI) images from which a range of root measurements can be derived by means of image analysis (Moran *et al.*, 2000; Pierret *et al.*, 2003).

It is well documented that all these techniques yield highly variable results (e.g. CV > 100% for minirhizotron and washing techniques), and that results obtained using two different techniques are difficult to compare. For example, Kucke *et al.* (1995) compared the core-break, trench-profile, core and monolith methods. They found good agreement between core and monolith methods, but obtained variable results with the core-break and trench-profile methods, the results from the two latter being poorly correlated with results from the two former. Unlike Heeraman & Juma (1993), they found more consistently lower CVs with monoliths (4500 cm3) than with cores (754 cm3). These authors interpreted the differences between mapping and destructive techniques as the result of (i) preferential orientations of roots, and (ii) differences in root visibility depending on contrast with soil matrix. Tierney & Fahey (2002) noted differences between minirhizotrons and a radiocarbon method, but were able to analyse their results making sense of both data sets.

Discussions occur as to which method should be used but without gathering data from the same site using different methods, these discussions can be futile (Vogt *et al.* 1998). No consistent relationships were apparent when comparing several sites where at least one of the indirect and direct methods were used on the same site. Until the different root methods can be compared to some independently derived root biomass value obtained from total carbon budgets for systems, one root method cannot be stated to be the best and the method of choice will be determined from researcher's personal preference, experiences, equipment, and/or finances.

A uniform agreement of how root biomass and production should be sampled and calculated, however, does not exist in the literature. Most of the controversy for estimating fine root dynamics is associated with the estimates of production and turnover, and how different abiotic resources may change these parameters (Aber *et al.*, 1985; Gower *et al.*, 1992; Grier *et al.*, 1981; Publicover and Vogt, 1993; Singh *et al.*, 1984; Vogt *et al.*, 1986a). However, recent techniques based on C labelling should greatly improve our understanding of fine root dynamics in forest ecosystems (Hobbie *et al.*, 2002; Joslin *et al.*, 2006).

The high labour-intensive requirements of most techniques to measure root biomass means that any attempt to build consensus on different approaches has been difficult because few studies have been designed to measure and compare different methods at the same time (Vogt *et al.*, 1998) and in the same place.

A223- Shrubs, Herbaceous Vegetation, Dead Wood and Litter on the soil

Theoretically, the sampling design described in A21 should also be applied for any of these quantities to ensure an unbiased and accurate estimate of these C stocks. However, the stratification is often made only for the trees because they account for the major part of the standing biomass. Nested quadrats or circles are then applied within the tree plots to assess shrubs and herbaceous vegetation biomass. A pre-study should be done prior the inventory to assess the optimal sub-plot size (see the procedure indicated in A21). Brown (2005) indicates squared plots of 30cm x 30cm for the herbaceous vegetation and 1 to 2m^2 for the woody vegetation. Within each quadrat, all the vegetation is cut usually without any species distinction. In tropical forests, lianas may be difficult to measure but the reader can refer to DeWalt and Chave (2004), Gerwing *et al.* (2006), Schnitzer *et al.* (2006). For palm trees, where a large part of the carbon is allocated to fruits and for which tree height is a better predictor than $d_{1.3}$, the reader can refer to Brown (1997) or Navarro *et al.* (2007).

A224- Soil Carbon

Soil organic carbon amount is first estimated from soil sampling and then from upscaling of plot data.

A2241- Measuring soil carbon

Soil samples are usually taken at different depths within a soil profile. Litter layer and living vegetation can be separately sampled, depending on the aims of each study, but it must be explicitly specified.

For CDM projects, it is advised to measure SOC until 30 cm (or the whole profile if the soil is shallower than 30 cm). The top 30 cm store indeed most of the soil active carbon. Deeper stocks are not negligible, but could be estimated as more recalcitrant, in a land-use or climate change perspective (Rumpel *et al.*, 2002) It is recommended to collect two to four samples each time and pool them so as to obtain a composite sample, including the spatial variability.

The texture of the soil determines the soil collection methodology. Core sampling with metallic cylinder is well appropriate in fine textured soils. In stony soils, it is recommended to practise an excavation so as to estimate the proportion of volume occupied by stones.

It could be then necessary to assess the density of the soil so as to express the carbon stocks on a mass basis or on a surface basis (Eq. 16)

$$SOC_{kgC.m^{-2}} = [OC]_{kgC.ton\ soil^{-1}} \times density_{tons.m^{-3}} \times depth_m \qquad \textbf{Eq. 16}$$

When using the above equation so as to monitor carbon stock changes, it is absolutely required to take into account the changes in density over the time (Zhou *et al.*, 2006).

There are different methods to quantify organic carbon in soil (MacDicken, 1997): dry combustion or wet oxidation. It is important to assess whether the soil contains inorganic carbon as carbonates that could create an artefact using the dry combustion method. If there is carbonate, it is necessary to remove it by acidification before SOC analysis (Harris *et al.*, 2001). Near infrared reflectance spectroscopy (NIRS) is a complementary and useful tool for the determination of soil properties, especially C (Al-Abbas *et al.*, 1972; Morra *et al.*, 1991; Barthès *et al.*, 2006, Viscarra Rossel *et al.*, 2006). Indeed, NIRS is a non-destructive, rapid, reproducible and low-cost method. Reflectance in the near infrared region (800-2500 nm) depends on vibrations in bonds between H and C, N, O, P or S atoms, and includes information about the composition of the sample analyzed. NIRS analysis involves calibration. The regression model is developed using samples that have been characterized conventionally and spectrally, and is then applied to predict the property for other samples according to their reflectance spectrum only.

The number of samples required to provide a robust SOC value is rapidly time-consuming, and, considering the cost of each analysis, SOC stock inventory could be relatively expensive. Moreover, despite the size of the sampled data, all the inventories (Howard *et al.*, 1995 ; Arrouays *et al.*, 2001; Lettens *et al.*, 2004) faced the problem of assigning OC content to polygons representing large area of land with no measured values.

As a result, upscaling schemes are under development at the national or regional scale (Jones et al, 2005; CarboInvent project).

A2242- Estimating organic carbon in the soils at a regional scale

Within the framework of the CarboInvent project (http:/www.joanneum.at/CarboInvent) the main goal was to asses the capacity of existing national and regional soil inventory schemes to provide baseline soil C assessments and to detect soil C changes. In order to fulfil these objectives, plot level errors and errors related to the upscaling of plot data had been developed and the rules of accounting for errors are described in the Good Practice Guidance of the IPCC.

The up scaling extrapolations are based on various pedotransfer equations (e.g. van Ranst *et al.*, 1995). The quality of up scaling can be greatly improved using geomorphographic landscape analyses of digital elevation models combined with various site informations, such as land cover, climate and soils.

The methods used in the CarboInvent project made it possible to assess the performance of the main factors responsible for the accumulation of soil carbon, which differed in each region. The evaluations were conducted separately for the forest floor and the mineral soil at varying total depths depending on data availability in the inventories. Different approaches to stratification have greatly improved the predictive value of the regional models.

Application of this methodology needs at least inventory data often obtained for a 16 * 16 km grid which is not available for Africa. Therefore upscaling of soil C stocks is often based on single observations covering few soil types in a region.

Nevertheless the ongoing research project should make an effort to gather and to provide the data representative for African grasslands and forests.

A23- Measurements of the carbon pools in Grasslands, methods and uncertainties

A231- Above-ground Biomass

A2311- Harvest based methods

Unlike for trees, grassland is subject of grazing. Moreover, leaves and thatch use to dry without falling on soil. They are considered as standing necromass and not litter as they are not decomposed by soil decomposers. So, two components have to be added to the NPP equation:

$$NEP = \Delta C_B + \Delta C_N + L + H \qquad \textbf{Eq. 17}$$

Where
ΔC_B is the difference of standing biomass
ΔC_N is the difference of standing necromass
L is the quantity of litter
H is the quantity of grass grazed.

For grassland, the measure of above-ground biomass and standing necromass is generally based of total harvest of a given surface, separation of green biomass and standing necromass, and eventually separation of species. The grass is then dried and weighted. The harvest is generally for a number of squares of 1 square-meter, randomly chosen in the grassland. The number of squares depends on the structure of the grassland. For sahelian zone, 30 repetitions are necessary to have a good precision (Levang and Grouzis, 1980). For more homogeneous formation, 15 repetitions are generally enough,

But ideally a pre-study should be conducted to assess the optimal number of plots and their size. Because the harvest is destructive, 2 successive harvests can not be done at the same place. The method of successive cuttings of the same stand is specious because cutting leads to a stimulation of the grass production.

The measure of biomass can be done regularly (every month, for example) or only at the maximum of vegetation (Singh *et al*, 1975, Sala and Austin, 2000). This last method is accurate only in the case of a low mortality and no grazing during the growing season (Long *et al.*,1989 ; Long *et al.* ,1992).

Non-destructive measurement of the above-ground biomass has been developed to avoid the bias of changing plots or for fragile ecosystem where plant harvest should be a problem such as arid grassland of Argentina (Guevara *et al.*, 2002; Flombaum and Sala, 2007). This method is based on allometric relationship between biomass and number of tillers and/or basal diameter and height of tillers and/or plant cover. The relationships depend on the lifeform of the grass (tussock or rhizomatous) and the species (Guevara et al, 2002).

The vegetation cover was estimated on 100 transects of 100 cm length where were noted green and dead interceptions by species (Flombaum and Sala, 2007). On the contrary, number of tillers and basal diameter and height of tillers were measured on one square-meter plots (Guevara *et al.*, 2002).

Measurement of H.

The measure of the quantity of grass grazed is difficult. The only way to estimate it is to compare biomass of grass inside and outside of plots protected from livestock grazing. But it has been proved that grazing increases plant production. The comparison of the grass production of the two plots leads to underestimate the grazing.

A2312- Remote sensing based methods

An assessment of the above-ground biomass integrated on a larger scale is nowadays accessible through the utilisation of remote sensing. As there is only one layer in the grassland, the remote sensing based method is particularly suitable as there is no problem of “hidden” under-storey vegetation.

Moderate Resolution Imaging Spectroradiometer (MODIS) data have a high temporal resolution and are freely available at EOS-Geogateway webpages (http://edcimswww.cr.usgs.gov/ pub/imswelcome) (Mutanga and Rugege, 2006). A field work is still necessary in order to establish the relationship between the MODIS data and the above-ground biomass. The field work has to be done over a rather large area, with a large scale of above-ground biomass (diachronic and/or synchronic variabilities). The samples have to be geo-referenced with GPS for example to be connected with the remote sensing data. When applied at the same conditions (plant species and biomass, annual rain and/or soil) than those used for the establishment of the relationship between MODIS and biomass, this method allows an estimation of the biomass on a larger scale than this conceivable with harvest based method. But a field work is still necessary to be sure that the relationship is accurate.

A232- Below-ground Biomass

The same methods than those described at the paragraph A222 are used to estimate the belowground biomass of the grassland i.e. extraction, mapping, in situ imaging method (rhizotrons) and other imaging methods.
The differences between forest and grassland are the more homogeneous distribution of the roots (as there is in general a lot of tillers of a square-meter and not a distance of 3 meters between tillers unlike for trees at a plantation) and a majority of fine roots.

The most used technique is the harvest of soil cores on the plots used for the estimation of the above-ground biomass. For one square-meter plot, one (at the center), four (at ¼ and ¾ of each diagonal) or five cores (at the center and at ¼ and ¾ of each diagonal) can be taken and pooled. The standard diameter of the corer is 8 cm, so between 0.5 and 2.5% of the surface area of the plot is sampled. The depth of the cores is determined by a trial sampling in the order to retrieve at least 80% of the total below-ground biomass. The depth of the cores is divided in layers, corresponding to the pedological horizons. In case of large horizon, the most used layers are: 0-10 cm (top horizon), 10-30 cm, 30-50 cm, 50-70 cm, 70-100 cm. When sampling by corer is not possible (soil too hard for example), a monolith of soil can be sampled.
The soil samples are generally air-dried and sieved with a 2 mm mesh. The root can be collected by manual sorting and/or by flotation. The roots are then divided in live and dead roots according to root color, elasticity or other parameters. This procedure is the major source of errors with a large operator effect. The fine roots are also separated from the larger roots. The threshold is often a diameter of 1 or 2 mm, depending of the authors. The roots are dried and weighted in order to estimate the dynamic of the biomass during the year.
The root biomass is generally expressed on a soil surface area basis (kg.m^{-2}) as the sum of the root biomass of the different layers divided by the surface area of the corer (or 4 or 5 times the surface area of the corer, depending on the sampling) or of the monolith. The biomass can also be expressed as a density as root mass divided by the soil volume for each layer. The density allows the study the vertical repartition of the roots in the soil.

For the assessment of the turn-over of the grassland roots, please see the paragraph A222 and Delitti *et al.* (2001)

A24- Models for interpolation and simulations

A241 Growth models

There is a wide variety of models available to predict growth of forest plantations. These include process-based, architectural and growth and yield models, each of which deals with a particular aspect of the forest production. Process-based models focus on forest ecosystems functioning (H_2O, carbon, and nutrients fluxes). Some example are BIOMASS followed by G'Day - McMurtrie *et al.* 1990, Hingston *et al.* 1998a, 1998b, Corbeels *et al.* 2001, 2005a; ProMod -Battaglia and Sands 1997; 3PG – Landsberg and Waring 1997, Landsberg *et al.* 2003, Esprey *et al.* 2004; CenW – Kirschbaum 1999; TRIPLEX – Peng *et al.* 2002, Zhou *et al.* 2004, 2005; CABALA - Battaglia *et al.* 2004; CASTANEA Dufrêne *et al.* 2005, Davi *et al.* 2005). These models describe the interactions between the water, carbon and nutrient cycles. They are mainly used to simulate (i) the water and CO_2 exchanges between the stand and the atmosphere, and (ii) gross and net primary production, using input meteorological data (e.g. rainfall, incident radiation, air temperature, ...), and other information about the soil (e.g. soil texture), the canopy structure and physiological properties. Architectural models deal with the botanical tree growth. They focus on the bud growth, ramification, and mortality. Resulting models are stochastic but they can accurately simulate the 3D architecture of plants (AMAP, L-SYSTEMS, a review is given by Godin 2000). They are used for different applications such as biomechanics (Fourcaud *et al.* 1996) or landscape studies (Auclair *et al.* 2001). Growth and yield models are designed to simulate the tree and stand growth under different silviculture regimes. They are based upon a series of basic relationships where diameter increments, height growth, and mortality are a function of site potentiality and silvicultural practices. These models are dedicated to the forest management for both plantations and natural forests (examples for even-aged forest: PTAEDA2 – Burkhart *et al.* 1987; NITGRO – Candy 1997; FAGACEES – Dhôte *et al.* 2000, Le Moguedec and Nepveu 2004; GLOBULUS – Tomé *et al.* 2004, E-DENDRO – Saint-André *et al.* 2002a, 2004, 2005; Gomat *et al.* 2007).

Because process-based models are often C and H20 coupled, they are described in section B of the present document. Here, we will focus on growth and yield model giving the example of E-DENDRO which is currently developed in Congo and in Brazil for Eucalyptus plantations.

A2411 E-DENDRO, a Growth and Yield Model

This chain is calibrated for the most planted clone in Congo. It includes three main modules that are linked into a single model. The growth module is a single tree distance-independent model, a classical approach in dendrometry as described below (Assman 1970, Dhôte 1996). For the tree properties module, a generic stem taper equation was constructed (Saint-André *et al.* 2002a and improved by Gomat *et al.* 2007). It explicitly takes into account the global taper of the bole, the butt swell and the decrease in diameter within the crown. The equation allows accurate estimations of diameters and volumes along the bole. Allometric relationships were also fitted for evaluating the biomass of roots, branches, stem, bark and leaves throughout the whole rotation (Saint-André *et al.* 2005). This model was successfully validated on an independent sample collected over the whole forest area to cover the widest range of site conditions. For the biogeochemical module a model was built to assess the distribution of nutrient concentrations (N, P, K) in individual rings within the bole and their changes with the ring age (Saint-André *et al.* 2002b). Furthermore, different allometric relationships estimated the nutrient contents within the branches, roots, leaves and bark (Laclau *et al.* 2000). Since 2004, nutrient cycling is being integrated into the chain of models in order to simulate nutrient input-output budgets (Saint-André *et al.* 2003). A litter fall sub-model was introduced (d'Annunzio *et al.* 2007a) and a litter decomposition model, initially calibrated for beech forests (d'Annunzio *et al.* 2007b), was transposed to eucalypt plantations under the tropics.
We only give details on the growth module to illustrate how such growth and yield model are working. We use four main relationships (Figure 2).
-Firstly, the dominant height is modelled as a function of stand age. Dominant height is widely used by foresters to assess the "Site Index" which includes the soil chemical and physical properties, the topography and the average climate of the plot. The use of the dominant height for this purpose is based upon the fact that the growth of dominant trees is less sensible to forest management and then better reflects site growing conditions than mean height or stand basal area growth. "Site Index" was defined in E-DENDRO by the maximum dominant height reached by the stand (asymptote of the curve). This avoids the complications of polymorphic curves but necessitates a large number of measurements for its evaluation. Classically, SI is usually inferred from past growth of the tree crop on that site.

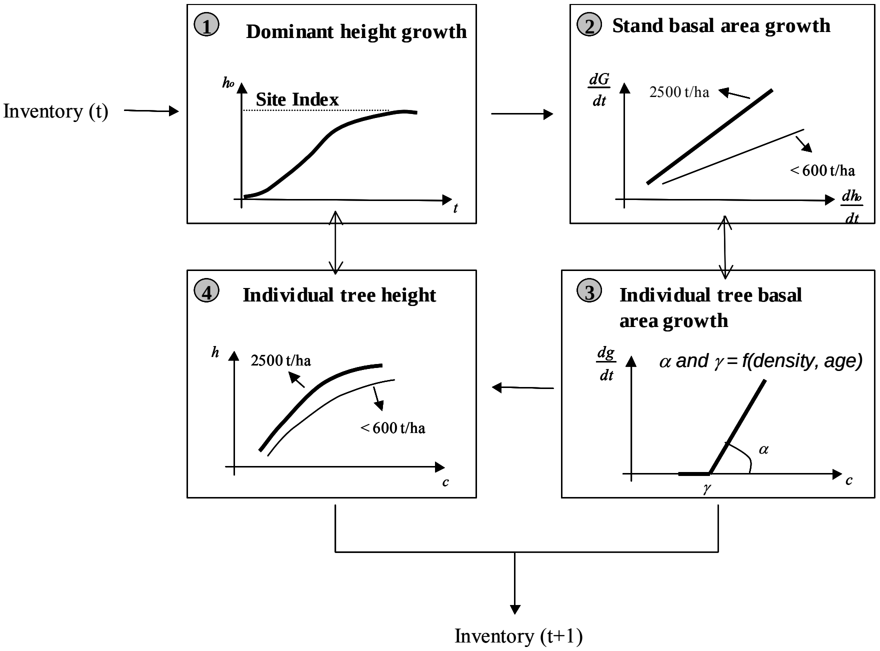


Figure 2: Overall description of Eucalypt-Dendro's growth module (Saint-André et al. 2002). Four equations are used: 1) dominant height growth as a function of stand age and site index; 2) Stand basal area increment as a function of dominant height increment and stand density; 3) Individual tree basal area growth as a function of tree circumference, stand density and indirectly stand age; 4) Individual tree height as a function of tree circumference, stand density and dominant height.

-Secondly, the stand basal area increment was modelled as a function of the dominant height increment. Such relationship is known as the Eichhorn law (Assmann, 1970) which assumes that for even-aged and pure stands, wood production is solely dependant on dominant height growth. This relationship has been verified for a large span of thinning regimes (provided that the canopy closure is rapidly reached).

-Thirdly, the individual tree basal area growth was modelled as a function of the tree circumference. It gives indications on between tree competitions within stands. The relationship is a linear segmented model. Below a given threshold that varies with stand age and forest management, trees do not grow. Above this threshold, tree basal area is a linear function of tree circumference. The slope of this relationship is directly proportional to stand basal area increment (dG) because the sum of individual tree basal area growths is strictly equal to dG.

-Quarterly the height of the trees was obtained from a height – girth relationship. Such kinds of equations are widely used by foresters and allow exploring slash and litter management effects on allocation rules between tree growth in height and circumference.

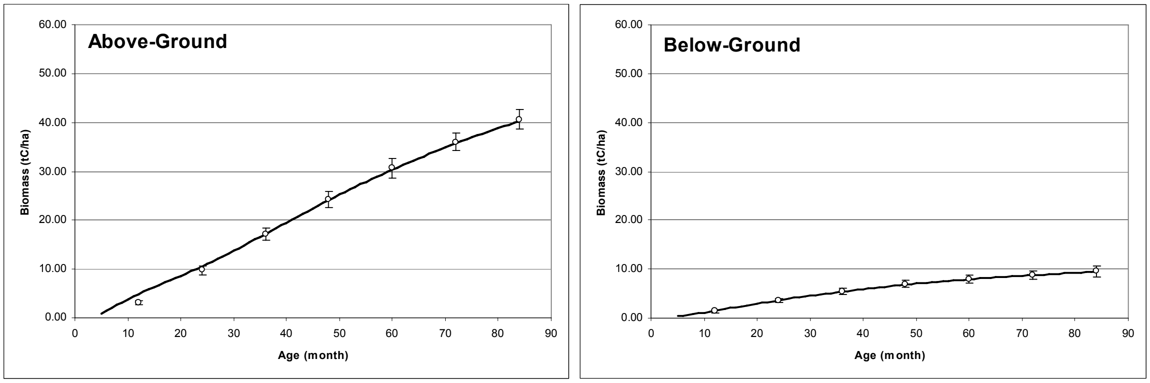
-Once new values of height and diameter are obtained for each tree, tree volumes are assessed using a stem taper equation (Gomat *et al.* 2007) and biomass compartments are given by a specific set of biomass equations (Saint-André *et al.* 2005). Confidence intervals are calculated by Monte Carlo simulations and account for: (i) the variance of the model parameters (for mean and for the variance), (ii) the correlation matrix between parameters (within a given compartment and between compartments), (iii) the residual error for each compartment, and (iv) the correlation matrix between residuals of compartments. Time courses of carbon stocks (Figure 3) can be simulated for a wide range of site index, planting densities (from 500stems/ha to 1300 stems/ha corresponding to the range of local practices in the site of Congo) and one clone (the most planted one).

Strength of the model

This modelling approach is relatively simple and requires a limited number of parameters and input data (one stand inventory). Competition between trees and silviculture practices are explicitly taken into account in modelling stand and tree growth and the within-trees wood properties. Although the model must be calibrated for each species or each clone, we have attempted to apply the constraints of generic form (equation remains the same whatever the clone), of easy access (parameters should be meaningful for an easier comparison between clones), of easy calibration (based upon a limited number of field trials) and of easy use (integration within decision tools for the manager).

Weakness of the model

Our modelling approach does not account for three major issues: (i) long term climate change (CO_2, temperatures), (ii) short term climatic effects (seasonality of growth) and (iii) feed back of the nutrient input/output budget on tree and stand growth (in Congo, nitrogen is the most limiting nutrient factor). The site index, which reflects site nutrient availability and the average climatic conditions of the area, is assessed from an inventory and is fixed for the whole simulation. This assumption is valid for forest ecosystems where site index varies a little within one rotation. However, it has been noticed, for both temperate and tropical forests that site index may change between two rotations cycles (from 30 to hundred years and more for temperate forests, 7 to 40 years for tropical plantations; Laclau 2001; Spiecker 1999; Dhôte and Hervé 2000). By including the feedback of the nutrient input/output budget on tree and stand growth, we would be able to simulate soil fertility variations (for one or two rotation) and also to integrate the effects of fertilisation practices into the simulation. Alternatively, site index could be estimated from physical, topographical, and plant diversity characteristics of the stand (Ryan *et al.* 2002; Louw and Sholes 2002, Seynave et al 2006).



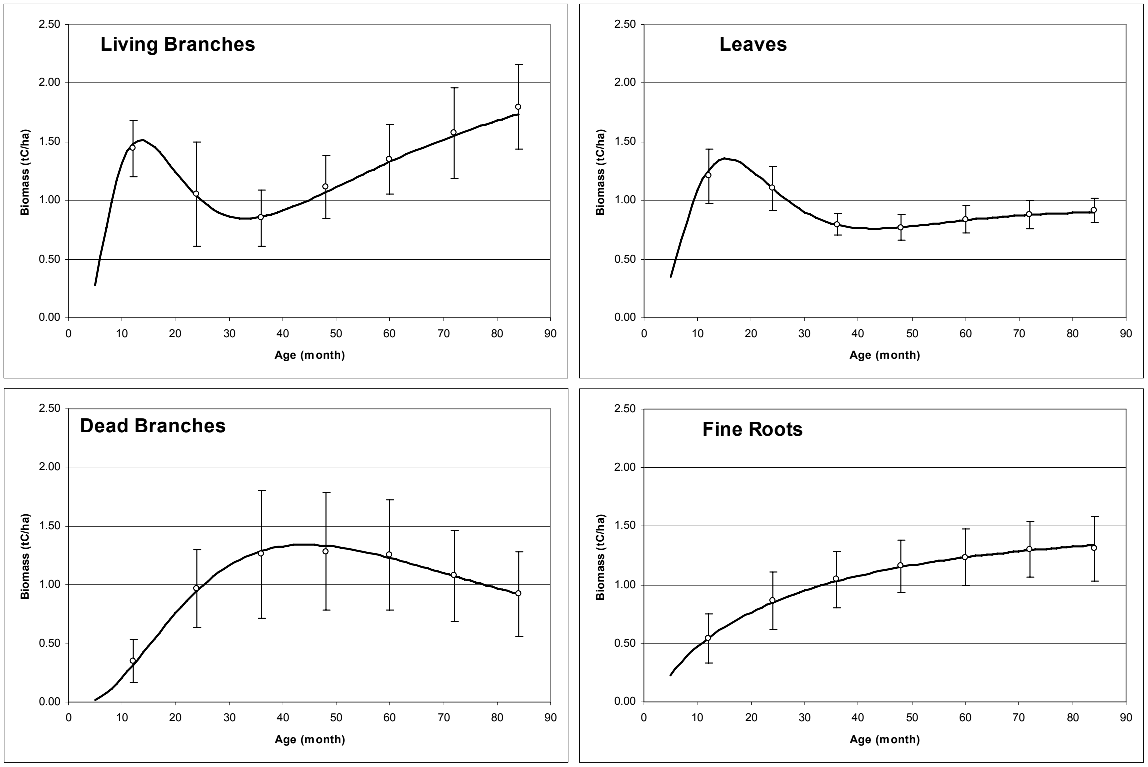


Figure 3 : Above-, below-ground, living branch, dead branch, leaf and fine root carbon stocks as a function of age for clone PF1 1-41. Confidence intervals correspond to the limits at 95%

A242 Soil carbon dynamics

The IPCC developed a computational method for estimated SOC stocks changes that can be used at the national and sub-national scale - Land Use, Land-Use Change and Forestry (LULUCF) sector (IPCC, 2004). The method computes the change of C stocks for a period of 20 years, assuming a linear rate, what is a non-negligible drawback. It uses information on climate, soil type and land use, and introducing three hierarchical tiers of methods. The tier 1 use default coefficients held by the IPCC, but much of the coefficients available have been fixed using studies mainly from North America and Europe, thus, typically more available for temperate area and not adapted for Africa. The other option is to use, when available, country specific data (Tier 2). At least, the third tier recommends the use of SOC dynamics models to accommodate national circumstances. These models must have a climate dependency, and thus provide source estimates with inter-annual variability. Models should undergo quality checks, audits, and validations. Ideally, they are linked to spatially explicit databases as in the GEFSOC Modelling System (Milne *et al.*, 2007).

Over the last decades, many models have been developed to simulate SOM dynamics and to predict possible response of SOM to global change or to land-use management. Most of them are regarded as process-oriented models, which focus on the processes involving the movement and transformations of matter or energy (Fang *et al.*, 2005). Process-oriented models are usually run at a monthly time step. They consider different pools (or quality) of OM characterized by their turnover rate. The limitation of those models is the difficulty to link the different pools to measurable fractions of soil organic matter, and to explain short term process as priming effects whose dynamics is probably not first order kinetics. Indeed, the microbial component of SOM is mainly simulated as a substrate and its impact on the turnover constant k is implicitly included. Therefore, models are independent of temporal and spatial variations in the soil microbial communities (Schmidt, 2007). Another type of model is organism-oriented model, which simulate the flows of matter or energy through different groups of soil organisms (Fang *et al.*, 2005). At least, a third kind of models reckon the importance of the vertical structure of a soil profile and try to consider the differences in terms of SOC inputs and dynamics within the profile. The three types of modelling approaches are detailed below.

A2421- Process-oriented models

In soils, microbial biomass is considered as non-limitant, but organic matter is (Jenny, 1941). About 90% of models are based on this assumption, which can be considered as correct in topsoils (Smith at al, 1997). As a result, they usually describe SOC stocks in the first 30 centimetres. These models are often muti-compartment models, and mainly empirical in nature. All of them contain a slow or inert pool or organic carbon. Decomposition is driven by first order kinetics.

$$\frac{\partial C_i}{\partial t} = -k_i . C_i . f_1().f_2() \qquad \textbf{Eq. 18}$$

with k_i the decomposition rate, $f_1()$, $f_2()$: functions describing environmental factor impacts (soil moisture, clay content...). The multi-compartment models were reviewed by Powlson *et al.* (1996) and Smith *et al.* (1997). The reviews pointed out that among nine of the leading SOM models (RothC (Jenkinson *et al.*, 1987) CANDY (Franko, 1996), DNDC (Li, 1996), CENTURY (Parton *et al.*, 1987), DAISY (Jensen *et al.*, 1994), NCSOIL (Nicolardot *et al.*, 1994), SOMN (Chertov *et al.*, 1997), ITE (Thornley and Verberne, 1989), Verberne (Verberne, 1992)), RothC and Century are the most reliable. These two models were able to simulate long term experimental data sets consistently over a range of different land uses.

The CENTURY model

Century is an ecosystem model that emphasizes the decomposition of soil organic matter and the flux of C and N within and between different compartments (Parton *et al.*, 1994). The grassland/crop and forest systems have different plant production submodels that are linked to a common soil organic matter and nutrient cycling submodel (Parton *et al.*, 1994). The model considers two fractions of litter (metabolic and structural) and three SOM pools (active, slow and passive), which differ in their potential decomposition rates. The active pool represents microbes and microbial products which turn over relatively rapidly (annual time scales), the slow pool consists of partially stabilized soil organic matter constituents with an intermediate turnover time (in the order of decades), while the passive pool represents recalcitrant materials that turn over on time scales of centuries. Separate pools for surface versus soil locations are maintained for the two litter fractions and the active pool, while the slow and passive pools are represented only within the soil (Cerri *et al.*, 2007). Although Century was originally developed for grasslands (Parton *et al.*, 1987), the model has been expanded to include agricultural crops and temperate and tropical forest systems.

The RothC model

The RothC-26.3 Model (Coleman *et al.*, 1999) simulates organic C turnover in non-waterlogged top soils according to soil type, temperature, moisture content and plant cover. It uses a monthly time step to calculate total C, microbial biomass C and δ^{14}C on a year to century timescale. SOC is split into four active fractions and one small inert organic matter (IOM) fraction. The active fractions are: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). Each fraction decomposes by a first-order process with its own characteristic rate. The IOM fraction is considered to be resistant to decomposition. RothC differs only a little from Century. The structure is the same, parameters are slightly different, and Century is able to consider N dynamics.

Analytical modelling

These pluri-compartments models are usually solved using discrete formulation on the monthly time step. This method might be critical from a mathematical point of view. Hence, some simple compartmental models with only few pools have recently proposed. Due to their simplicity, the differential equations on which they are based can be solved analytically, and parameter optimizations can be made using generally available nonlinear regression programs. The ICBM model (Andren et Kätterer, 1997) is one of them. A two-component model was devised, comprising young and old soil C, two decay constants, and parameters for litter input, "humification," and external influences.

Reliability of process-oriented models and practical measurement of their pools

The process-oriented models, that aim to predict the fate of SOC over the next decades, have been extensively calibrated from total carbon stocks, usually on the short term scale, using laboratory incubations, pluriannual litterbag experiments. There are much less data available on the time scale of decades. Especially, experiments involving isotope labeling (^{13}C natural labelling or ^{14}C bomb tracing) that have proven their efficiency are much scarce. Another limitation of these models is the difficulty to link the different pools to measurables fractions of soil organic matter. There have been a lot of attempts to characterize physically or chemically the conceptual pools introduced in the models, but without a lot of results (Balesdent, 1996; Pujet *et al.*, 2000; Ludwig *et al.*, 2003; Skjemstad *et al.*, 2004; De Gryze *et al.*, 2006; Zimmermann *et al.*, 2007).

At least, these models have shown limitation in explaining short term process as priming effects whose dynamics is probably not first order kinetics. As a result, another type of modelling approach has been developed, based on the microbial dynamics.

A2422- Micro-organisms oriented models

Most SOM models assume that SOM decay only depends on the SOM pool and disregard the roles of the size and the diversity of microbial populations (Fontaine and Barrot, 2005). Although some current models already separate microbial biomass into two or more functional types these biomasses are mostly treated as organic matter pools and are not considered to control the SOM decay. However, there is striking evidence that models should take microbial dynamics into account:

- Changes in microbial biomass and activity are observed depending on nutrient limitation.
- Changes in microbial biomass and activity are observed over the year (Schmidt *et al.*, 2007).
- The old age of SOM in deep soil horizon (Rumpel *et al.*, 2002) is diffcult to explain considering a linear relation between SOC and microbial biomass.
- SOM is mineralized faster by micro-organisms when their growth and activities are stimulated by the input of fresh organic matter - the so-called priming effect (Kuzyakov *et al.*, 2000; Fontaine *et al.*, 2003; Schimel et Weintraub 2003).
- Considering climate change, experiments had shown that there was not a linear relation between SOM decomposition rate and microbial pool, and they highlighted the existence of various feedback effects. For example an increase in temperature can induce a decrease in C mineralization, due to a reduction in microbial biomass (Fang *et al.*, 2005).

As a result, there is an increasing trend to try to include microbial dynamics aspects in SOM models. The authors who incorporate micro-organisms as decomposers into models to stimulate soil organic matter decomposition use the following formalism:

$$\frac{\partial C_i}{\partial t} = -K_B.B.f(C).f_1().f_2() \qquad \textbf{Eq. 19}$$

with KB the biomass growth rate, f(C): function describing microorganims dependance on OM, f1(), f2(): functions describing environmental factor impact (soil moisture, clay content...)
Fontaine and Barrot (2005) presented C-based models describing the dynamics of the SOC depending on microbial growth-death system. They showed that these models can predict the lack of SOM decomposition in deep soil and the steady accumulation of SOM in ecosystems. Ågren and Bosatta (1996) proposed a more complex model, taking into account the impact of the chemical quality (or recalcitrance) of the metabolized compounds on the microbial communities growth rate. There have been also few attempts to propose models at the population or at the community level able to reconcile the microbiologists' insights with the soil organic matter decomposition process (Neill and Gignoux, 2006 ; Raynaud *et al.*, 2006). They gave mechanistic description of diffusion of solutes in the soil, organic matter solubilisation or complexation by microorganisms, bacterial activity or bacterial predation... (Using the Fick law, the Michaelis Mentens equation, the Monod kinetics...) There are not soil organic matter models in themselves, but are intended to be used as a microbial-growth based kernel in any soil organic matter model.

A2423- The Z-dimension, deep soil layers

The micro-organisms oriented models have been developed to try to overcome limitations of the process-based models, especially, to overcome their incapacity to describe what happens in deep soil layers. However, at this stage, microbial oriented models do not yet work at the scale of the soil profile. Integrating the vertical dimension 'z' into SOC model requires indeed to consider another set of processes, and to be able to describe them accurately, what is still a challenge.
Vertical distribution of organic matter (OM) within the soil profile is mainly a consequence of differences in OM inputs at different depths, vertical relocation and decay of OM. Aboveground biomass leads to OM inputs at the soil surface, whereas roots and rhizo-deposition lead to inputs in deep soil layers. Movements of OM in the soil profile are a result of different mechanisms, including bioturbation, reloaction of dissolved OM and organomineral colloids by percolating water, transport of OM associated with clay in illiviated soils and macropore transport of particulate OM (Bruun *et al.*, 2007). These movements can be considered as diffusive or/and advective transfers.

OM transfers in the soil

The movement of carbon at the rate of the surrounding fluid is an advection process, while the relative movement of the organic carbon related to the surrounding fluid is a diffusion process. The advective flow is the quantity of carbon moved by the material in advection in each unit of time, i.e. the velocity ν of the flow multiplied by the carbon content of the elementary volume:

$$\frac{\partial C}{\partial t} = -v.\frac{\partial C}{\partial z} \qquad \textbf{Eq. 20}$$

The diffusive flow is independent on the movement of the matter. It is proportional to the gradient of carbon.

$$j = -D.\frac{\partial C}{\partial z} \qquad \textbf{Eq. 21}$$

The equation of continuity gives:

$$\frac{\partial C}{\partial t} = -div(j) \qquad \textbf{Eq. 22}$$

And from Eq. 20 and Eq.21, it comes that

$$\frac{\partial C}{\partial t} = D.\frac{\partial^2 C}{\partial z^2}$$

Organic matter input

Litter input to soil can be easily estimated. The quantification of belowground input is much more difficult to quantify. Some authors neglected it (Feng *et al.*, 1999), some others proposed an exponential distribution decreasing with depth (Balesdent and Elzein, 1995; Wynn *et al.*, 2005).

Organic matter decay

The decomposition of carbon is assumed to follow first oder kinetics. Different pools with different turnover times can be distinguished.

$$\frac{\partial C}{\partial t} = -k.C \qquad \textbf{Eq. 23}$$

The resulting equation describing the C distribution in the soil profile reads as follow:

$$\frac{\partial C}{\partial t} = D.\frac{\partial^2 C}{\partial z^2} - v.\frac{\partial C}{\partial z} - k.C + I(z) \qquad \textbf{Eq. 24}$$

with *I(z)* the input of organic matter.

Different strategies were adopted to solve this equation. For example, Wynn *et al.* (2005; 2006) presented models based on diffusive movement only, whereas Feng *et al.* (1999), considered that their soil was too dry for diffusion and considered advection only. Elzein and Balesdent (1995) and Bruun *et al.* (2007) took both into account. The various models proposed were fitted on total carbon stocks, and sometimes on 13C - taking into account the potential 13C fractionations.

Such models are still scarce. One of the main limitations to their calibration is the lack of data. However, they will certainly be developed in the forthcoming years as the scientific community is getting more and more aware of the importance of the carbon behaviour in deep soil layers.

A2424- Conclusions on the SOM modelling

Process-based models have been developed for the last 30 years and, despite their drawbacks, they have been used successfully to simulate SOC stocks changes at a subnational scale, the scale that is of interest in the CDM activities, in Brazil, India, Kenya… (Cerri *et al.*, 2007 ; Bhattacharyya *et al.*, 2007 ; Kamoni *et al.*, 2007).

They have been coupled to regional-scale databases often organized in geographic information systems (GIS) (Easter *et al.*, 2007). Basic data required to simulate carbon changes with these models are:

-the native vegetation,
-the historic, recent, current and future land use,
-the climate,
-the soil,

-the latitude (to estimate the potential evapotranspiration from climate data).

Recently, there are attempts to move away from the black box representation of soil organic matter and to propose modelling approaches describing more accurately some specific mechanisms that happen in soil, as micro-organisms dynamics or heterogeneity of the SOC dynamics and the movement of particles within a whole soil profile. These models, still not very numerous, have been calibrated on specific sites but still require validations. Moreover, they deal usually with a scale that is not the regional scale needed for CDM activities. As a result, they are not really useful by themselves in a carbon management perspective.

A3 - The carbon sequestration from carbon budget methodology

A31 - Eddy-covariance methodology

The eddy covariance technique produces a direct measure of net CO_2 and water vapor exchanges across a canopy-atmosphere interface using micrometeorological theory of the covariance between fluctuations of the vertical wind speed velocity and of CO_2 and water vapor concentrations. Water vapor and CO_2 concentrations are measured at a high frequency (20 Hz = 20 measures per second) using an IRGA (Infra-Red gas analyser), such as the Licor7500, whereas fluctuations of vertical wind speed velocity are measured using a three-dimensional ultrasonic anemometer. These data are processed on-line for computing semi-hourly averages and summed to obtain daily, monthly and yearly estimates of energy balance, evapotranspiration, and net ecosystem production (NEP ~ carbon balance of the ecosystem). The area sampled with the eddy covariance technique (the flux footprint) possesses longitudinal dimensions of about several hundred meters. As a consequence, this method is scale-appropriate for monitoring fluxes at the standscale, from 100 to 200 ha. Due to its high temporal resolution, the method is also particularly adapted for studying the ecosystem physiology, e.g. for quantifying the whole-ecosystem response to diurnal and seasonal changes in the micro-climate, and other environmental variables.

To use this method, a large number of precautions have to be respected. The major hypothesis for the measure is that the flux of CO_2 is only vertical and is due to eddy movements of the air.

Height of the tower:

To make valid measurements, the anemometer and the analyser must be installed in the surface boundary layer. The position of the surface boundary layer depends on the vegetation height and type, the wind speed and the distance to the hedge of the vegetation (for example, the edge between grassland and forest).

Position of the tower:

The eddy covariance system measures the flux of CO_2 between a surface of vegetation and the atmosphere. The portion of vegetation “shown” by the system, called the footprint, varies in function of measurement height, the vegetation height, the wind stability, the wind speed and the wind direction. Some models, analytical or lagrangian, give possibility to estimate the footprint (Gash, 1986; Horst and Weil, 1992; Hsieh, 2000; Leclerc and Thurtell, 1990). Inside the footprint, the vegetation has to be homogeneous.

In case of low wind, especially during the night, horizontal advection of the air can occur. To limit this lose of CO_2 not measured by the eddy covariance system, the terrain has to be as flat as possible (no slope and no talweg). Heterogeneity of the vegetation also leads to horizontal advection (Aubinet *et al.*, 2000).

Computation and correction of the data.

With the eddy covariance system, twenty measures are done each second. These raw data have to be treated before integration to a period of one half-hour. A long chain of corrections is needed to have good data (Figure 4).

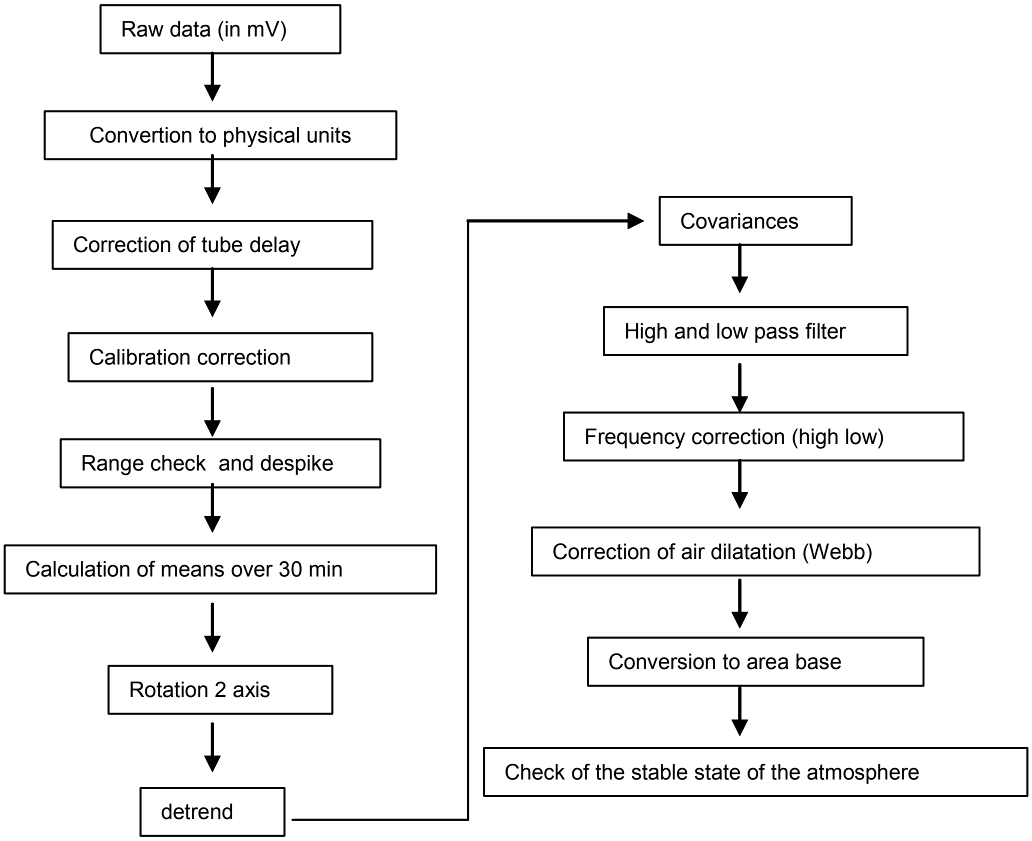


Figure 4: Diagram of the data processing

A quality check has to be done on the fluxes expressed on a half-hourly basis. For example, the basic hypothesis of the eddy covariance technique is that the air is moving vertically through eddy movement, as we already said. This occurs when the atmosphere presents non-stable conditions. In case of stability over half an hour, the mean flux can not be use. Another problem is the rain with the open-path analyser. Drops on the analyser leads to wrong results. These low quality data have to be rejected. Sometimes, the lack of data is also du to technical problem or stop for the calibration. On average, only 65% of the data are available over a year (Falge *et al.*, 2001). To be able to make annual budget of the carbon fluxes, operators have to gap fill the data. This part is really tricky as it can lead to a totally wrong estimation of the annual carbon budget, at the opposite of the results obtained through biomass survey, for example (Baldocchi, 2003). As the researchers are creating networks of research on carbon budget (such as Ameriflux, CarboEurope, CarboAfrica, AsiaFlux…), standardized methods of gap filling are created to allow the comparison of the budget over a large number of site (Falge *et al.*, 2001, Moffat *et al.*, 2007). Basically, gap filling is possible through the calculation of relationship between existing flux values and meteorological or plant parameters such as solar radiation, temperature, vapour pressure deficit, wind speed, vegetation height and/or phenology. This relationship varies in function of the period of the day (night or day) and the period of the year (wet season/ dry season or winter/growing season). To be valuable, a sufficient number of good quality data is necessary.

By summing the half-hourly values of flux (and gap filled values) over a full year, we can calculate the net ecosystem exchange (NEE). NEE is the difference of the net primary production and the ecosystem respiration (heterotrophic and autotrophic respirations).

$NEE=GPP-R_{eco}$

Two ecosystems with the same NEE can have high GPP and high R_{eco} or low GPP and low R_{eco}. To break down NEE, it has been assumed that the flux observed during the night (if the eddy covariance technique is applicable) is the ecosystem respiration. The ecosystem respiration is supposed to be linked only to soil temperature through exponential relationship. However, a unique relationship all over the year is not possible as respiration varies also in function of soil moisture and quantity of available carbon for heterotrophic respiration and growth activity for autotrophic respiration. For temperate climate, the relationship was calculated for each period of 30 days, starting at 1 January. The exponential relationship found for night value is applied for the calculation of the ecosystem respiration during the day (Falge *et al.*, 2002). A limit of this method is that the autotrophic respiration is supposed not to be limited by carbon during the night (when plants do not assimilate carbon). A comparison with Reco measured with a large number of chambers measurements extrapolated to stand scale should be useful to estimate the bias of this methodology. On the opposite of the first method, an other method based on the analysis of the light response can be used (Gilmanov *et al.*, 2007).

A32- NPP assessment

A321- Biomass increment

For this part, the reader can refer to chapter A221 and A222. All methods described there are applicable to assess biomass increments. As underlined in GPG-LULUCF 2003, a key component of a project is to monitor, and estimate the quantity of carbon accruing on the project area over separate time periods and over the whole duration. For trees, it is recommended to use permanent plots instead of temporary ones because these plots undergo repeated measurements allowing to account for autocorrelation in the statistical analysis. The main problem is that sampled plots should be subject to the same management as the rest of the project area and, if they can be clearly identified on the field, there are risks of bias (these plots could be better managed than elsewhere, for example by eliminating herbs and shrubs).

A322- Litter Falls

Annual patterns of litter production usually show two distinct phases: various studies found that annual litterfall increased with stand age until they reached a plateau where they remained constant with a strong inter-annual variability (Malhotra et al 1987, Trofymow 1991, Lebret *et al.* 2001). This variability was ascribed to environmental factors such as rainfall, wind, droughts, flooding or diseases (Pedersen et al 1999, Whitehead *et al.* 2004, Arreola-Lizarraga *et al.* 2004, Starr *et al.* 2005, Corbeels *et al.* 2005). At a finer scale, monthly litter production also shows a strong variability and can present various patterns, depending on climatic and edaphic conditions. Under temperate climates, unimodal patterns are usually observed in broadleaved forests (with litter being mainly shed at the autumn) whereas litter is generally shed evenly throughout the year in coniferous forests (Pedersen *et al.* 1999). Bimodal patterns are reported in different ecosystems (Roderstein *et al.* 2005, Xu *et al.* 2004, Corbeels *et al.* 2005) ranging from eucalyptus plantations under hot Mediterranean climate to tropical or subtropical broadleaved forests. The factors that influence monthly litter production patterns are a combination of internal physiological processes that lead to abscission and of external factors like seasonality and climatic accidents (Kozlowski *et al.* 1997) that unleash shedding. Internal factors are expressed through organs life span which is mainly determined by genetic origin (Addicott 1991, pp. 273-300), whereas periodic or accidental climatic factors can be very site-specific: regular tidal flooding periods in arid mangroves (Arreola-Lizarraga *et al.* 2004), exceptional droughts in eucalypts Australian forests (Pook *et al.* 1984a, 1984b), typhoon occurrences in broad-leaved coppice in Japan (Sato 2004).

Litter falls can be assessed by way of litter traps, large enough to capture branches, high enough to avoid wind hazards, and depth enough to avoid losses of material. Usual sizes range from 50 cm x 50cm to 1m^2. The number of litter traps should be important enough to catch all the variability (about 15 for each stand). Methods of sampling described in A21 are applicable. Litter should be collected regularly (for example weekly) so as to avoid leaching of nutrients. Monthly fall are then computed by adding the weekly fall for all weeks of the month. When a week was astride two months, the corresponding weekly litterfall value was assigned to the month having the majority of the days of the concerned week. If nutrient restitution is an objective of litter collection, it is then necessary separate the different fractions between leaves, branches, bark, fruits and miscellaneous.

A323- Fine root production and turn-over

A3231 Definitions and importance

Root production and root turn-over

The production of an organ or a population is defined by the sum of its biomass increase between two dates and the necromass produced during the same period. Fine root production was found to be equivalent to, or greater than, above-ground litterfall in a high number of forests, and may account for more than the half of the net primary production (Keyes and Grier, 1981; Burke and Raynal, 1994; Fahey and Hughes, 1994). For example, in northern America, more than 66% of the net primary production (NPP) of conifer stands was attributed to root production (Grier *et al.*, 1981). A good characterization of growth dynamics is therefore an important subject in view of a best estimation of root production and turnover.

Root turnover is an important component of carbon and nutrients cycle (Aber *et al.*, 1985; Aerts *et al.*, 1992 ; Hendrick *et al.* 1993; Ruess *et al.*, 1996 ; Gill and Jackson, 2000 ; West *et al.* , 2004). It is differently defined. Often confused to the production (Van Praag *et al.*, 1988), this term expresses generally the replacement of senescent old roots that died and decomposed by new roots during plant growth and development (Picard, 1981; West *et al.*, 2004).

Root turnover is differently appreciated according to whether it concerns annual or perennial plants, large or fine roots, primary or secondary or tertiary roots. Although representing only a low proportion of total root biomass (Saint-André *et al.*, 2005; Kern *et al.*, 2004) fine roots account for a high proportion of carbon flow in forest ecosystems (Hirano *et al.*, 2007). It is mainly the production and the turnover of this root type that was largely studied (Gill and Jackson, 2000).

Fine roots

Root system architecture of perennial plants is a complex network with lateral branching often associated to fine root (Madji *et al.*, 2005). Several researchers had used simplistic approaches to classify plants roots. A first approach assumed that all roots have the same function independently of their diameter and their position in the structure. The second approach is based on a classification of roots according to their basal diameter and that some processes as the production are assumed to be identical within a given class (Baddeley and Watson., 2005, Hirano *et al.*, 2007). Thus, several fine roots classes have been defined according to authors. The most used are: 0-2mm, 0-3mm and 0-5mm (Fogel, 1983; Gill and Jackson, 2000).

However others authors suggest that this arbitrary size-classification does not consider the root function and physiology. Hishi and Takeda (2005) showed a difference of roots lifespan according to their anatomical structure. Pregitzer *et al.* (2002) have shown that the root specific length and the nitrogen content depend on the position of roots in the structure. Root system topology could then be a better indicator of function than the root diameter.

Factors affecting fine root production and turn-over

Several factors controlling the root production were shown, including mineral nutrition (Kern *et al.*, 2004), the soil topography (Noguchi *et al.*, 2007), the atmospheric CO_2 concentration (Pregitzer *et al.*, 1995), the soil temperature (Kern *et al.*, 2004), the soil structure and texture (Lecompte *et al.*, 2003 ; West *et al.*, 2004), the plant environment (Lopez *et al.*, 1998), the soil microorganisms (Wells *et al.*, 2002), the stage of plant development (Kern *et al.*, 2004), and the soil pH (Godbold *et al.*, 2003).

A significant exponential relationship between the root turnover and the soil temperature was shown. This relation was variable according to the ecosystem type (Gill and Jackson, 2000): for example, the temperature explained 55% the variability of the root turnover in shrublands. However, this relationship was weaker in forests (R^2= 0.19).

Another positive correlation was shown between root turnover and the ratio precipitation/ maximum of mean annual temperature. However, the root turnover is not sensitive to the annual precipitation. The relationship between the root turnover and the potential evapotranspiration is also low.

Others studies are then necessary to elucidate the effect on root production of factors such as: root pathogens, maintenance respiration, solar radiation and the rate of nitrogen mineralization (Lauenroth and Gill, 2003).

A3232 Methods to estimate root production

Methods of root biomass and production estimation were differently classified. Schuurman and Goedewaagen (1971) classify them in three categories: (i) methods based on total root mass variations (ii) semi - quantitative methods with appropriate devices and (iii) method based on the carbon balance. A more recent classification distinguishes direct (sequential soil coring, ingrowth cores) and indirect methods (Vogt *et al.*, 1998). Because of the time-requirement of the direct methods and the difficulty to separate live and dead roots, at least six indirect methods were developed. They allow the prediction of root biomass and the production by using variables strongly correlated with root growth dynamics (Vogt *et al.*, 1998). Among these methods, there are: the nitrogen balance (Aber *et al.*, 1985 ; Nadelhoffer *et al.*, 1985, Hendricks *et al.*, 2006), the carbon balance (Agren *et al.*, 1980, Hendricks *et al.*, 2006), the carbon flow approach (Raich and Nadelhoffer, 1989), the correlation with abiotic variables (Vogt *et al.*, 1996). More recently, Gaudinski et al (2001) have developed radioactive carbon method that provides an estimation of the average age of the organic matter by comparing its content in radioactive carbon (14C) to levels of known atmospheric radioactive carbon which have drawn in years 1960 because of tests of thermonuclear weapons.

Sequential soil coring

The most commonly used direct method is sequential soil coring. This method is based on changes of living and/or dead root biomass sampled during at least one year (Nadelhoffer *et al.*, 1985 ; Ostertag, 2001). According to Bakker (1998), root sampling frequency is function of root mass variability during a year. The biomass unimodal distribution over a year allows to limit the samples to some periods corresponding to the maximum and the minimum (Vogt *et al.*, 1986; McClaugherty *et al.*, 1982; Burke and Raynal, 1994). In case of a multimodal distribution of the biomass, the sampling must be more frequent (Persson, 1983). From the sequential soil coring method, there are at least three ways of calculating root production. These methods consider either root biomass, or root biomass and the necromass, or a combination of biomass, necromass and the decomposition.

The 'maximum-minimum' method is only based on the seasonal biomass variations. Root production is defined as the difference between the maximal and the minimal value of biomass during of a period of study (one year in general).

$$NPP_{Fine-roots} = MaxB - MinB$$

Eq. 25

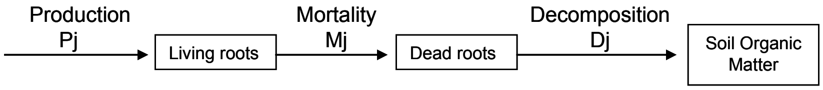
The balancing transfer method is a matrix of decision based on the variation of the biomass and the necromass between two dates of measurement (Fairley and Alexander, 1985, Hendricks *et al.*, 2006).

		Biomass		
		Increase	Decrease	
Necromass	Increase		ΔBdead > ΔBlive	ΔBlive > ΔBdead
		P = ΔBlive + ΔBdead M = ΔBdead D = 0	P = ΔBlive + ΔBdead M = ΔBdead D = 0	P = 0 M = -ΔBlive D = -ΔBlive - ΔBdead
	Decrease	P = ΔBvivant M = 0 D = -ΔBmort	P = 0 M = -ΔBvivant D = ΔBvivant - ΔBmort	

Table 3 : Matrix of decision illustrating the different equations used to estimate root production (P), mortality (M) and decomposition (D) (Fairley and Alexander, 1985).

The compartment-flow model is composed of two compartments (live and dead) and three flows (production, mortality and decomposition, Santantonio and Grace,1987). This approach is justified by the fact that the fine root growth, mortality and decomposition occurred simultaneously in some ecosystems.

This model can summarize as follows:



The root decomposition Dj that occurred during a given time interval *j* (defined from *i* to *i+1*) is given by:

$$D_j = y_i\left(1 - e^{-k_i j}\right)$$

Eq. 26

With y_i the quantity of dead root at time i and k_i the decomposition coefficient.

The production P_j and the mortality M_j for interval j were deduced from the decomposition D_j, the biomass and the root necromass by the following equations:

$$M_j = y_{i+1} - y_i + D_j$$

Eq. 27

$$P_j = x_{i+1} - x_i + M_j$$

Eq. 28

With x_i and x_{i+1} the quantities of living roots at time *i* and *i+1*.

Ingrowth cores method

An other commonly used direct method is the ingrowth cores method that consists in sampling soil cores in holes refilled with soil without root after an initial sample and to evaluate the production at different intervals of time (Persson, 1983 ; Cuevas and Medina, 1988 ; Steele *et al.*, 1997). Two sampling methods using ingrowth cores are often used (Neill, 1992 ; Hendricks *et al.*, 2006). The 'long term' sampling consists in installing a number of soil cores at the beginning of the study, and to collect a precise number of them at regular intervals. The 'short term' sampling consists in installing a limited number of soil cores over time and to collect them at a regular interval. Root production can then be estimated by using different approaches (Hendricks *et al.*, 2006) including (i) the sum of mean biomass of 'short term' ingrowth cores, (ii) the maximum of mean biomass of 'long term' ingrowth cores and (iii) the mean biomass of the last series of 'short term' ingrowth cores

Minirhizotron

During the last decade, minirhizotron techniques were largely developed, becoming the favourite method of fine root production estimation for some researchers (Lopez *et al.*, 1998, Rytter, 2001 ; Tierney et Fahey, 2002, Hendricks *et al.*, 2006). It is a visual study method for root growth dynamics through a transparent tube inserted into the soil. This tube is often inclined to 45° as compared to the horizontal. A great portion of the tube is inserted into the soil, while the external part is covered by an opaque plastic to avoid rain filling and lightening. The minirhizotron images (living and dead roots) are therefore captured with a camera. Different softwares were developed ('Rhizogen' for agricultural plants and 'Root' for forest plants) for the analysis of these images (Hendrick and Pregitzer, 1992). This method gives a root length production. It is then necessary to apply a correction factor to convert the length to root mass (Steele *et al.*, 1997). This method has also been used together with others methods sequential soil coring (Aerts *et al.*, 1992 ; Rytter, 1999). The minirhizotron method gives several estimations of the root production:

$$Root\,\mathrm{Pr} = \frac{NewRootLength}{UnitofTubeArea} \qquad \textbf{Eq. 29}$$

$$Root\,\mathrm{Pr} = \frac{biomass(g.m^{-2})}{lifespan(year)} \qquad \textbf{Eq. 30}$$

A3233 Methods to calculate root turn-over

In general, the root turnover (R_{tu}) is considered as the ratio of root production by the mean biomass during a period of study (Aerts *et al.*, 1992). But others estimation models exist in the literature, making difficult the comparisons between studies:

$$R_{Tu} = \frac{AnnualRoot\,\mathrm{Pr}oduction}{MaximumRootBiomass} \text{ (Dahlman and Kucera, 1969 in Gill and Jackson, 2000)} \qquad \textbf{Eq. 31}$$

$$R_{Tu} = \frac{AnnualRoot\,\mathrm{Pr}oduction}{MeanRootBiomass} \text{ (Burke and Raynal, 1994)} \qquad \textbf{Eq. 32}$$

$$R_{Tu} = \frac{AnnualRoot\,\mathrm{Pr}oduction}{MinimumRootBiomass} \text{ (Hendrick and Pregitzer, 1993)} \qquad \textbf{Eq. 33}$$

$$R_{Tu} = \frac{fine\ root\ production\ during\ growing\ season}{fine\ root\ biomass\ at\ the\ end\ of\ growing\ season} \text{ (Le Goff and Ottorini, 2001)} \qquad \textbf{Eq. 34}$$

$$R_{Tu} = RootNPP \text{ (Van Praag \textit{et al.}, 1988)} \qquad \textbf{Eq. 35}$$

$$R_{Tu}(Minirhizotron) = 1/meanRootAge \text{ (Fahey \textit{et al.}, 1999)} \qquad \textbf{Eq. 36}$$

$$R_{Tu}(Minirhizotron) = \frac{Root\,\mathrm{Pr}}{RootLength} \qquad \textbf{Eq. 37}$$

A3234 Conclusions on root production and root turn-over

There is no consensus between researchers on methods to be used for estimating root production. The main used methods often give contradictory values when they are used together in the same stands (Steele *et al.*, 1997, Rytter, 1999; Burke and Raynal, 1994; Tierney and Fahey, 2002; Hertel and Leuschner, 2002; Ostonen *et al.*, 2005; Hendricks *et al.*, 2006). For example, Steele *et al.* (1997) obtained, with minirhizotrons, a root production 2-4 times higher than with ingrowth cores method. According to Vogt *et al.*, (1998), this lack of consensus is due (i) to the strong variability of the carbohydrates allocation to fine roots (4-69% of total carbon fixed by the plant), (ii) the sensitivity of the root production and the root turnover to environmental conditions, and (iii) to the fact that several methods are tedious and time consuming. Therefore, several interrogations remain on the appropriate study method to be used for each type of ecosystem.

A33- Soil respiration and its heterotrophic and autotrophic components

Heterotrophic respiration (R_h) represents the part of ecosystem CO_2 efflux which is not directly emitted by living plants. It originates from the decomposition, by various macro and micro organisms, of organic matter accumulated in and on the soil.

Soil carbon processes are highly complex, as they involve many different actors which interact finely (Kuzyakov and Larionova, 2006). Respiring organisms can be classified into autotrophs (plant roots, which degrade carbon substrates directly produced by the plant itself) and heterotrophs, i.e. soil macro and micro fauna, bacteria and fungi that decompose soil organic matter (SOM). SOM is the result of the incorporation into the soil of above-ground vegetal detritus and litter-fall and of below-ground fine root mortality, and can be classified into different pools according to its velocity of decomposition (Parton *et al.*, 1987, Epron *et al.*, 2001).

The exact limit between heterotrophic and autotrophic organisms is not simple to define, because of the complexity of the rhizosphere, i.e. the interface between the root system and the surrounding mineral soil. Plant roots produce rhizodeposits (root secretions, sloughed root cap cells and exudates (Nguyen, 2003; Vogt *et al.*, 1991), which are the substrate of a range of rhizospheric organisms including ecto and endo mycorrhizae, fungi, bacteria. Although these rhizosphere organisms are strictly speaking heterotrophs, their respiration ('rhizomicrobial respiration' (Kuzyakov, 2006)) should not be included in Rh, as the carbon involved comes straight from the tree and has not actually transited through any of the SOM pools. However, rhizospheric processes can have a strong influence on the activity of surrounding heterotrophs, through competition and priming effects between the different microbial communities (Kuzyakov, 2006; Subke *et al.*, 2004).
Root, rhizomicrobial and heterotrophic respiration are of about the same order; they have been reported to represent about 30, 30 and 60%, respectively, of total soil CO_2 efflux of subtropical forests (Yi *et al.*, 2007).

Because of the interactions between different soil carbon pools and respiring organisms, the experimental determination of Rh is not easy. Soil respiration (CO_2 efflux from the soil surface) measurements can be made relatively easily: currently the standard method implies the uses of a chamber inserted into the soil superficial layer, or placed on previously inserted collars, and linked to a gas analyser in an open or closed circuit (Epron *et al.*, 2004; Ryan and Law, 2005; Yim *et al.*, 2002). But the separation of the total soil CO_2 efflux into the heterotrophic flux and the other components (which will hereafter be lumped together as rhizospheric respiration) must then be carried out using one of a variety of techniques, each with its underlying assumptions and simplifications (see reviews by Hanson *et al.* (2000) and Subke *et al.* (2006)).

The methods which have been used so far can be grouped into the following categories:

1) Extraction
2) Subtraction of root respiration
3) Root exclusion
4) Isotopic methods
5) Modelling

A331- Extraction method

This method consists in extracting volumes of soil and manually sorting out its different components, which are then incubated separately. Heterotrophic respiration is estimated per unit of soil mass as the CO_2 efflux of the soil from which roots have been extracted (Tyree *et al.*, 2006). This method presents the advantage of allowing a good separation and subsequent chemical analysis of different components, for example different soil horizons. The respiration rates obtained are on a volume or mass basis, and a series of assumptions must be made in order to translate them into rates per unit surface. Another major disadvantage of the method resides in the very strong disturbance of soil environment that it involves. As well as perturbing the biological links between the rhizosphere and the surrounding soil, the extraction process changes the structural and physical properties of the soil, which can have a strong influence on the heterotrophic respiration flux.

A332- Subtraction of root respiration

Total surface soil CO_2 efflux and root (± rhizosphere) respiration are estimated separately, and the difference between the two fluxes is supposed to represent Rh.
Root respiration can be estimated using respiration measurements made on root segments (usually excised, but on intact roots still attached to the root system in some cases (Kutsch *et al.*, 2001; Marsden *et al.*, in press)), combining them with

root biomass measurements in order to obtain an estimation per unit of soil surface (Yi *et al.*, 2007; Uchida *et al.*, 1998; Maier and Kress, 2000; Bahn *et al.*, 2006). Root excision is not a very satisfactory method because of the immediate effect on gas fluxes through the root (there may be a post-trauma flush of CO_2 escaping from the severed tissues and sap) and of the possible more long-term effect on root tissue activity. Yet it is often applied, because experiments for measuring respiration on intact in-place root systems are quite tricky to design and carry out.

In most of these cases, as roots are separated from the surrounding soil and often washed or even sterilised, rhizosphere respiration is not measured, and the estimation of Rh is therefore likely to be overestimated. The meta-analysis approach by Subke *et al.* (2006) on different techniques for estimation of the proportion Rh/Rs did indeed show that root excision methods tended to produce estimations which were higher than the mean.

Root respiration has also sometimes been estimated using a growth rate and a theoretical maintenance and construction cost (Wit *et al.*, 1978; Penning de Vries *et al.*, 1989; Navarro *et al.* 2007):

$$R_a = R_g + R_m = \alpha NPP + 0.4\beta B \qquad \textbf{Eq. 38}$$

where R is was the respiration (gC m^{-2} day^{-1}), subscripts ‘a’, ‘g’, ‘m’ were for autotrophic, growth, and maintenance, respectively, α (gC gDM^{-1}) is the growth respiration coefficient computed from organ composition (Penning de Vries *et al.*, 1989), NPP is expressed here in gDM m^{-2} day^{-1}, 0.4 is the C:CH_2O molecular mass ratio, β is the maintenance rate of respiration (gCH_2O gDM^{-1} day^{-1}; 25°C) and B is the biomass of the organ (gDM m^{-2}). According to de Wit et al (1978), β can be computed as follows:

$$\beta = 6.25 \cdot 0.036 \cdot NIT + 0.07 \cdot MIN \qquad \textbf{Eq. 39}$$

where 6.25 is the coefficient for the transformation of nitrogen into proteins, 0.036 the coefficient for protein turnover, NIT is as the dry matter content in nitrogen, 0.07 is the coefficient related to the cost induced by ionic gradients and MIN is the dry matter content in minerals. Total nitrogen can be assessed by the Dumas method, mineral elements by inductively coupled plasma emission spectrometry (ICP: Varian vista model), and lignin by TAPPI procedure (N = 4 replicates per organ, as an average). Air temperature measured above the canopy can be used for aerial parts and soil temperature belowground.

Another technique which has been applied quite commonly is the regression of soil respiration against root biomass (Behera *et al.*, 1990; Wang *et al.*, 2006). This technique is based on the hypothesis that R_h is constant spatially on a given plot, and that spatial variation in R_s is due to differences in root biomass. This is a strong hypothesis which is not always valid, as R_h and root biomass are likely to be strongly correlated. However, this technique does present the advantage of including rhizosphere respiration in the estimate of root respiration.

A333- Root exclusion

Heterotrophic respiration can be estimated as the soil CO_2 efflux measured on plots deprived of living roots. This can be achieved in several different ways, of which the main ones are: root removal, gaps, trenching, clipping, or girdling.

Root removal (Wiant, 1967) involves digging out a large volume of soil, sorting out and removing all root fragments, and replacing the soil. This method makes sure that no roots are present, but presents the same disadvantage as the extraction method, namely that it causes the disruption of the soil’s physical and biological environment.

Gaps (in forests) can be natural clearings or man-made by felling of a certain number of trees. The latter solution is preferable, as it ensures that the sampled area was equivalent to the rest of the forest before the beginning of the experiment. This technique, which has been used in several studies (Brumme, 1995; Nakane *et al.*, 1996), induces minimal soil disturbance, and allows an estimation of R_h which is not confounded with R_{rh}. However, it presents some disadvantages, because of the large size of the gap which is required in order to make sure that the central zone (where soil CO_2 efflux measurements are made) is root-free. On a practical side, this means that many trees must be felled, which is not possible on all experimental sites. In addition, the creation of the gap changes environmental conditions: increased incoming radiations, reduced water extraction by roots, lack of carbon inputs from fine root turnover and litter-fall. Another important problem is that after the felling of the trees, their root system remains in the soil and begins to decompose, thus constituting a large artificial source of heterotrophic respiration. The same problems arise in studies that measure heterotrophic respiration on recently clear-cut tree stands. In order to obtain a plausible estimation of R_h, several corrections need to be applied (Epron *et al.*, 2006b), and all of them increase the uncertainty of estimations. The most important correction is made to counter the effect of the increased CO_2 efflux due to the decomposition of the root system:

$R_h = R_{s,TP} - D$ **Eq. 40**

where $R_{s,TP}$ is the soil CO_2 efflux measured on the trenched-plot, and D is the CO_2 efflux caused by the decomposition of the dead root system. D is estimated either by using measurements of initial and final root biomass and assuming some form of decrease between the two dates, or by using only initial root biomass and a calibrated decomposition model.

Soil water content should also be considered: the removal of trees stops water extraction by roots and the soil water content can increase significantly in comparison with the surrounding soil (Epron *et al.*, 1999). As decomposition is related to soil water content (Thorburn *et al.*, 2001), R_h can be significantly affected.

In the case of trenching, the root-free plots can be smaller than forest gaps, because a barrier is introduced to prevent root growth into the plot. A trench is dug around a plot of variable size (some designs even involve pipes inserted vertically into the soil (Saiz *et al.*, 2006) containing or not a central tree, and lined for example with a thick plastic film. In this less intrusive method, the trenched-plot presents almost the same shade and litter-fall conditions as its immediate surroundings. The two major problems associated with the technique have already been cited for gaps: the need to take into account the decomposition of the killed root system, and the increased soil water content. In addition, although the problem of above-ground litter is partially solved, that of the cessation of fine-root turnover remains. Thanks to its relative simplicity, this method has been widely applied, on a range of ecosystems (Misson *et al.*, 2006; Epron *et al.*, 1999; Yi *et al.*, 2007; Tedeschi *et al.*, 2006; Boone *et al.*, 1998; Bond-Lamberty *et al.*, 2004; Buchmann, 2000; Rey *et al.*, 2002) but there is no standard practice for the necessary corrections.

Clipping is used for grasslands: all above-ground green parts of the plants are cut, and in this way the roots remain physically intact but are starved of their substrate.

Girdling is the equivalent technique for forests. The phloem flow of photosynthates to the root system is prevented by the removal of a ring of bark and cambium on the tree trunk. The roots remain alive and still perform water extraction, and the relations between the rhizosphere and decomposers are preserved (Scott-Denton *et al.*, 2006; Hogberg *et al.*, 2001; Olsson *et al.*, 2005 ; Frey *et al.*, 2006), but their metabolic activity is thought to be greatly reduced because of the lack of substrate. This method requires the effective killing of a relatively large number of trees, and what's more does not always produce satisfactory results for the estimation of R_h, as in some species the roots continue to respire, using previously accumulated below-ground carbon reserves (Binkley *et al.* 2006).

A334- Isotopic methods

The use of carbon isotopes for the separation of the different sources of total soil CO_2 efflux is promising as it is a completely non-intrusive method. Gas is sampled during soil respiration measurements and the difference in $\delta^{14}C$ between this air, atmospheric air, and soil organic matter, can be interpreted to derive by mass balance the "age" of the carbon respired. This approach however does not give an estimation of R_h, but of the proportion of R_s which is derived from "old carbon" in contrast to R_s derived from recent photosynthates (<1 year).

Some studies have used radiocarbon, either by pulse-labelling plants or by relying on a more or less recent bombing event which released ^{14}C into the atmosphere (Trumbore *et al.*, 2006; Cisneros-Dozal *et al.*, 2006; Schuur and Trumbore, 2006; Hahn *et al.*, 2006).

It is also possible to use the stable isotope ^{13}C, either in labelling experiments or using natural abundance. Some studies have been made on the sites of FACE (Free Air Carbon Enrichment) experiments, where the air enriched in CO_2 has a high $\delta^{13}C$. A mass balance approach is applied to deduce how much of the soil CO_2 efflux was emitted by roots. This approach has several limitations: firstly the results are difficult to interpret on the long term because the ^{13}C signature of some of the soil carbon pools changes fairly rapidly with the input of litter and rhizodeposits; and secondly the effects of the CO_2 enrichment itself on heterotrophic respiration are unknown.

Different plant and soil processes are known to be associated with different isotopic discrimination, so it is tempting to use the isotopic signature of soil respired CO_2 and that of phloem sugars to deduce R_h/R_s. It is nevertheless generally very difficult because the $\delta^{13}C$ of CO_2 respired from different sources are in fact very close, and because different soil pools have different signatures, of which some are higher and others lower than that of roots. The method works well in certain conditions, when there has been a change of photosynthetic pathway from C4 to C3 plants, which exert a different isotopic discrimination. The organic matter present in the soil is derived from the old C4 crop or plants and has a different isotopic signature from that of the photosynthates produced by the new C3 crop (Rochette *et al.*, 1999).

Another possible approach uses the fact that isotopic discrimination by plants depends on stomatal opening, which in turn depends on air relative humidity. After incorporation of a time-lag, a linear relation between air relative humidity and the $\delta^{13}C$ in soil CO_2 efflux appears, which can be used to calculate the root contribution (Ekblad and Hogberg, 2001).

Isotopic techniques are powerful, but very difficult (in the case of labelling experiments) and costly to apply because of all the necessary isotopic analyses. The interpretation of the data also relies on numerous assumptions on the age and dynamics of different soil carbon pools and on plant processes, so results can be significantly affected by the interpretation process (Subke *et al.*, 2006).

Whatever, tracking ^{13}C in respiratory fluxes for resolving residence and transfer times in the atmosphere–plant–soil system requires high frequency measurements of the isotopic composition of evolved CO_2. Up to now, the cost and the time required for analysing air samples using mass spectrometer in the lab limit the measurements frequency and duration following a labelling pulse or during the season for natural abundance. The recent development of a Tuneable Diode Laser Spectrophotometer (TDLS) allow simultaneous in situ measurements of fluxes of $^{13}CO_2$ and $^{12}CO_2$ at a high frequency and is recently used to examine ecosystem functioning (Bowling *et al.* 2003, Griffis *et al.*2004; Barbour *et al.* 2007)

A335- Modelling

Some studies have used a bottom-up approach to estimate Rh, relying on a detailed model of soil carbon dynamics (such as SECRETS (Sampson *et al.*, 2001) or CENTURY (Parton *et al.*, 1987)) and input meteorological information (Epron *et al.*, 2001; Eliasson *et al.*, 2005). Modeling approaches are very valuable because they reduce experimental requirements to the measurement of meteorological variables, and allow the simulation of Rh in various management or climatic conditions. However, the model first needs to be very carefully calibrated and validated, using one or several of the experimental techniques mentioned above.

A336- Conclusion on soil respiration

None of the presented methods is perfect, and probably the best way to gain confidence in estimates of Rh is to cross different techniques, and always to compare the flux estimates with biomass and other flux measurements to verify their compatibility. New techniques can also help to increase accuracy of our Rh estimates. Progress is expected in the short term in the domain of isotopic methods, with the beginning of the use of tunable diode lasers which allow high frequency measurement of fluxes of different isotopes.

In the aim of estimating NEP, Rh is compared to NPP, and must therefore be estimated on the same spatial and temporal scale. Temporal and spatial extrapolations of measured fluxes are probably the largest source of uncertainty on estimations of Rh and must therefore be addressed with particular care.

Spatial interpolation of measured data must be based on a carefully considered sampling scheme that accurately represents the spatial variability of the Rs flux, since estimations of Rh are generally based on Rs measurements. Soil respiration displays high spatial variation, due to the irregular distribution of tree roots and soil organic matter, and locally different soil water content, temperature, compaction and composition (La Scala *et al.*, 2000; Epron *et al.*, 2006a; Epron *et al.*, 2004; Khomik *et al.*, 2006; Longdoz *et al.*, 2000; Rayment and Jarvis, 2000). Management practices can induce a structuration of spatial variability (higher root density in lines than in interlines, presence of more organic matter in slash rows, soil compaction on lines of tractor passage (Epron *et al.*, 2004)) which needs to be taken into account in the spatial sampling strategy.

Generally NPP estimates are available on an annual basis, using inventory data which integrate growth over a large period, whereas the kind of measurement used for the determination of Rh is punctual in time. Temporal interpolation and often extrapolation is therefore necessary to obtain annual estimates, and is usually based on quite simple functions of soil temperature or/and water content. Possible daily variations of soil respiration have rarely been taken into account, and different conclusions are reached in different ecosystems/ seasons as to the possible significance of an over- or under-estimation produced by measurements at a particular hour (Liu *et al.*, 2006; Betson *et al.*, 2007). It is also possible that the functions used for interpolation should be calibrated on a more short term basis than what is often done, as large seasonal variations of the temperature sensitivity of soil respiration have been observed (Janssens and Pilegaard, 2003). However such seasonal variations are probably largely linked to seasonal changes in plant production, and could be more due to root activity than to heterotrophic organisms.

Considering that NEP and GPP can be assessed by eddy covariance (Baldocchi *et al.*, 1996; Falge *et al.*, 2001), NPP + Ra provides a valuable and independent source for inter-comparison, when Ra is measured directly (with huge difficulties) on plant organs, or, alternatively, estimated from the growth and composition of organs, construction costs (Penning de Vries *et al.*, 1979), and maintenance coefficients (de Wit *et al.*, 1978).

B- EVALUATING WATER BUDGETS AFTER AFFORESTATION

B1- Aim

The aim of this part of the report is to review a few relevant alternatives for assessing the H_2O balance of afforestation projects, as a complement to CDM carbon sequestration assessments.

The report was meant for general application. However, as a support, we will specifically develop one case study, a large (40 000 ha) eucalypt afforestation over grassland in Congo-Brazzaville. In this example, the whole planted area should be considered as a patchwork of different clones with different ages and densities, so that the water balance of the plantation is dynamically changing with time and requires to be assessed after a spatialisation exercise.

The most important requirements were: (i) to review methods which were suitable from the level of plot to the level of the whole plantation (spatialisation goal); (ii) methods suitable for comparison between baseline scenario and afforestation (CDM goal); (iii) to distinguish methods which were treating water balance independently of C and nutrient balance modules, or methods which were inter-compatible (flexibility goal).

We started with a review of general findings linking water balance and afforestation (mainly from meta-data analysis), then proposed definitions and concepts, field methods (from organ to landscape), models (idem), and ended with a comparison of models and discussed about their applicability for the present case study.

B2- Review of general findings

In the context of the CDM, afforestation has been suggested as a way to simultaneously sequester carbon, increase wood and paper supplies, and diversify rural incomes. However, converting grasslands or shrublands to plantations will likely affect many other ecosystem processes, notably water yield from rivers and streams (e.g. Farley *et al.*, 2005; Jackson *et al.* 2005; Nosetto *et al.*, 2005; Sun *et al.*, 2006);

Water yield is altered through changes in transpiration, interception, and evaporation, the first two terms tending to increase when grasslands or shrublands are replaced with trees. Planting trees is often assumed to increase infiltration (e.g. Ilstedt *et al.*, 2007). Transpiration rates are influenced by changes in rooting characteristics, leaf area, stomatal response, plant surface albedo, and turbulence (Brooks *et al.*, 1997; Hoffmann & Jackson, 2000; Jackson *et al.*, 2001; Vertessy, 1999). Although transpiration is traditionally considered the most important component of forest evapotranspiration (ET), interception and subsequent evaporation from the canopy can also increase substantially, particularly with conifers (Pearce & Rowe, 1979; Cannell, 1999). Evaporation of intercepted precipitation is generally low in grasslands, but can account for 10–20% of rainfall for broadleaf trees and 20–40% for conifers (Le Maitre *et al.*, 1999). In tropical plantations of broadleaf trees where rainfall events of large intensity are dominant, evaporation of intercepted precipitation is usually lower than 10% (Whitehead and Beadle, 2004). The sum of the changes in evaporation and transpiration in plantation catchments leads to an increase in ET (Holmes & Sinclair, 1986); for example, ET from a catchment planted with eucalyptus could be 40–250mm higher than from a grassland catchment (Zhang *et al.*, 1999).

The impact of afforestation on water resources is likely to vary with the climate (rainfall of the zone), the soil water reserve, the type of plantation and its age. Considering potential climate feedbacks associated with reforestation, Jackson *et al.* (2005) simulated for eastern USA that plantations would increase evapo-tranpiration and decrease air temperature, hence likely decreasing precipitations, as compared to crops or pastures (the simulation is presented for temperate zones, the conclusion can be different under the tropics). Dolman et al (2004) stressed that in general, ETR would be larger above forests, forests having a lower albedo than crops or grasslands (10-15% for forests but 20-25% for grasslands), hence more available energy, more sensible heat flux, creating a "forest-breeze" above forests. Combined with other phenomena, this would generally lead to increased precipitations over forests.

Few systematic global analyses of the effects of afforestation on water yield have been proposed. Farley *et al.* (2005) proposed a relevant meta-analysis, quantifying the change in streamflow associated with afforestation globally. They assessed the direction, range, and extent of changes in total annual streamflow and low flow (both measured in the catchment) associated with afforestation, examined the interactions with original vegetation type (grassland or shrubland), tree species planted, plantation age, and climate, and provided a predictive framework for modelling the effects of afforestation on water yield for carbon sequestration scenarios. According to Farley *et al.* (2005), runoff (defined here, as the sum of surface and subsurface flow) decreased consistently and substantially with afforestation across their entire meta-analysis. More than one-fifth of the catchments experienced reductions of 75% or more during at least 1 year and 13% of the catchments experienced 100% runoff reductions for at least 1 year.

B21- Impact of afforestation after grassland or shrubland

Both the original vegetation type at a site and plantation species significantly influenced proportional changes in streamflow. When averaged across ages, annual runoff reductions were greater after grassland afforestation (44%) than after shrubland afforestation (31%). Eucalypts had a greater impact than pines in sites that were originally grasslands, with runoff (defined here, as the sum of surface and subsurface flow) reductions of 75% and 40%, respectively, according to Farley *et al.* (2005).

The reason for observed higher runoff reductions in afforested grasslands compared with shrublands may be inherently higher runoff with herbaceous cover (although this might not be true starting from shortgrass steppes and ending with shrublands). Contributing to this effect is the difference in the depth and distribution of roots among vegetation types, which is altered by the shift from grasses or shrubs to trees (Jackson *et al.*, 2000). Shrubs have greater similarity to trees, in terms of total root biomass and maximum rooting depth, than to grasses (Jackson *et al.*, 1996); for this reason, the change in access to water and the change in transpiration rates are not likely to differ as much between shrubs and trees as they do between grasslands and trees.

The two primary causes of the increase in ET following afforestation are the greater capacity for water loss associated with higher leaf area indexes (LAI) of the higher stature vegetation (Calder, 1986) and better access to water sources, through accessing of deep water or drawing on stored soil water (Calder *et al.*, 1993; Zhang *et al.*, 2001; Engel *et al.*, 2005). When grasslands are afforested, deep water access likely plays an important role, as there should be a large change in rooting depth (Jackson *et al.*, 1996).

What would be the shift in water balance (transpiration, evaporation, interception, surface run-off, soil water content and dynamics) when savannas or grasslands are afforested with eucalypts in Congo, at the plot level and at the plantation level?

B22- Effects of afforestation according to the drought index

According to Farley *et al.* (2005), afforestation reduced runoff across a broad range of climates. Reductions in runoff were significantly related to mean annual precipitation (MAP) for afforested grasslands in both proportional (% of MAP) and absolute terms (mm yr^{-1}). For grasslands, the wettest sites (MAP>1500 mm yr^{-1}) had the largest absolute reductions (287 mm) but the smallest proportional reductions (27%). In contrast, proportional losses were far greater at the driest grassland site (62%), suggesting that the effects of afforestation on water yield will be more severe in drier regions. Afforestation on shrublands behaved in a similar way.

The effect of afforestation on low flow of the catchment is also an important component of this framework. Changes in low flow may be even more important than changes in annual flow, as the dry season is when reduced water supply will have the most severe effects for users, particularly in arid and semiarid regions (Smith & Scott, 1992; Scott & Smith, 1997; Sharda *et al.*, 1998; Robinson *et al.*, 2006).

At last, there are many examples where trees rely on water tables, especially for riparian communities or phreatophytic species planted in African agroforestry parklands (e.g. Roupsard *et al.*, 1999).

B23- Effects of afforestation according to stand age or development

Although the effects of plantation age and rotation length are important for predicting the consequences of afforestation on water yield, these effects are lacking in most studies (Best *et al.*, 2003). According to Farley *et al.* (2005), runoff reductions are attained very rapidly after afforestation, with losses of more than 10% of streamflow occurring in the first 2–3 years after tree establishment for most catchments. This indicates that the time-lag between planting and runoff response is usually short, although the full effect on runoff may not occur for one or more decades.

Farley *et al.* (2005) showed that streamflow response to afforestation can be expected to be very rapid (within 5 years of planting), maximum runoff reductions can be expected between 15 and 20 years after planting, and runoff reductions will likely be larger and more sustained when grasslands are afforested than when shrublands are.

What is the shift in water balance (transpiration, evaporation, interception, soil water content and dynamics) according to plantation age, stand development including rotation effects at the plot level?

B24- Effects of afforestation on water balance associated with changes in rooting depth, LAI, canopy structure, and stomatal conductance

Interception storage and evaporation from the canopy are thought to be greater for needle leaved than for broad-leaved trees (Zinke, 1967; Cannell, 1999); the dense canopies of conifers allow for higher canopy storage of rainfall and can lead to large interception losses (typically ranging from 15% to 24%, and in some cases reaching as much as 60%; Le Maitre *et al.*, 1999). For eucalypts, which tend to establish deep roots at a young age (Dye, 1996), higher transpiration is likely the most important component of increasing ET following afforestation (Vertessy, 1999). Therefore, in dry regions, where transpiration is the more important contributor to absolute increases in ET following afforestation (Scott & Lesch, 1997), eucalypts are likely to cause more severe runoff reductions. In wet regions, where interception plays a more important role, pines may cause more severe runoff reductions.

In the present report, we propose to review definitions, equations, field assessment methods and models suitable for comparing the terms of the water balance of Congolese grasslands, savanna and eucalypt plantations.
From this review, we will analyse the performances of the various tools, in order to select an appropriate strategy for implementing the comparison. Special emphasis will be devoted on methods which are suitable for spatialisation purposes (from plot to whole plantation). The implementation of the comparison itself is out of the scope of the present review, it will be performed during the next 2 following years of the project.
The present review could also be proposed further as an example for incorporating water balance issues into general afforestation projects, such as CDM.

B3- Definition of terms and equations of the water budget

B31- The complete equation of ecosystem water balance

The general soil water balance equation is including a total of 10-12 parameters (FAO 1998 p. 12):

$$\Delta\theta = P + Ir + Cr + \Delta SF - In - Ro - T - Es - Dp$$ **Eq. 41**

Where (all expressed in mm): $\Delta\theta$ = variation of the soil water stock; P = precipitation; I_r = Irrigation; C_r = Capillary rises; ΔSF: difference between entering and outgoing lateral subsurface flow; I_n = Interception; R_o = surface Run-off; T = Transpiration; E_s = soil evaporation; D_p: deep percolation

$$In = P - T_f - S_f$$ **Eq. 42**

Where (all expressed in mm): P = precipitation; I_n = Interception; T_f = throughfall; S_f stemflow
Beware that the definition of "runoff" can vary much between the papers. For pure hydrologists, it means generally surface + deep drainage and corresponds to everything that is not evaporated (e.g. Farley *et al.*, 2005). For ecophysiologists, runoff rather means surface runoff.

B32- Soil water content, dry bulk density, porosity

-Soil gravimetric water content (θ_g) refers to the mass of water per unit of dry soil ($g_{H2O}\ g^{-1}{}_{drysoil}$). It can be computed as:

$$\theta_g = \frac{(M_{wetsoil} - M_{drysoil})}{M_{drysoil}}$$ **Eq. 43**

with M, the mass of soil
-Dry bulk density (ρ_{db}: unit $g_{soil}\ cm^{-3}$): it is the density of undisturbed dry soil (sampled horizontally along the profile of a trench, using a cylinder of known volume, V):

$$\rho_{db} = \frac{M_{drysoil}}{V_{cylinder}}$$ **Eq. 44**

-Soil volumetric water content (θ_v) refers to the volume of water per unit of soil volume ($m^3{}_{H2O}\ m^{-3}{}_{soil}$). θ_g is converted into θ_v following:

$$\theta_v = \theta_g \cdot \rho_{db}$$ **Eq. 45**

-Water filled porosity (WFP) is the percent saturation of the soil by water, where P_{tot} is the total porosity of the soil ($m^3{}_{air}\ m^{-3}{}_{soil}$):

$$WFP = \frac{\theta_v}{P_{tot}}$$ **Eq. 46**

$$P_{tot} = 1 - \frac{\rho_{db}}{\rho_{solid}}$$ **Eq. 47**

with ρ_{solid} to be computed from soil texture (Hillel, 1982; Campbell, 1985; Müller, 2000).

$$P_{air} = P_{tot} - \theta_v$$ **Eq. 48**

with P_{air}: air porosity of soil ($m^3_{air}\ m^{-3}_{soil}$).

B33- Soil water potential, pF, field capacity and wilting point

The soil water potential (Ψ; unit Pa) concept at a particular point in the soil profile is expressed as the difference in 'free energy' per unit volume or mass of water in comparison with water held in a reference pool of free water (set to zero) (Marshall and Holmes, 1998). The energy content of the soil water is usually below that of the reference pool, which means the soil water potential is negative.

The potentials result from the following:

-gravitational potentials (Ψ_g): related to height from surface

-matric potentials (Ψ_m): result from adsorptive forces and decline in negative values during soil drying

-osmotic (Ψ_o):

-overburden potential (Ψ_p): resulting from overlying soil matrix

Sometimes, the term hydraulic potential (Ψ_h) is used, which refers to the sum of gravitational and matric potentials.

pF is an ancient notation, still much in use, though:

$$pF = LOG_{10}(h)$$ **Eq. 49**

where h is the water height (or pressure) expressed in cm, and LOG_{10} is the logarithm in base 10.

MPa Ψ	cm h	pF	
-0.032	316	2.5	**Field capacity**
-0.100	1000	3.0	
-1.585	15849	4.2	**Wilting point**

Table 4 : equivalents in Ψ (MPa), h (cm) and pF for three levels of soil water, including common estimates field capacity and wilting point.

Field capacity (θ_{fc}) is the soil water content for which a maximum of water is retained in the soil, without drainage. It corresponds to the highest (less negative values) of soil water potential. It is often assumed to correspond to pF values around 2.5.

The wilting point is the soil water content for which herbaceous plants usually start to wilt (θ_{wp}). As this term is dependent on the type of species, surrogates are often preferred: either the soil water content for which pF = 4.2 (more objective choice) or for which the minimum value of Ψ (Ψ_m) has been observed, during the year for instance (more site specific, according to the actual drought stress index locally or annually).

B34- Soil Relative Extractable Water (REW), critical REW and soil water deficit (SWD)

The extractable water (mm) is the difference between the current θ and the wilting point value, or else the minimum value of θ, (θ_m), z being the height:

$$EW = (\theta - \theta_m)\, z\, 10^3$$ **Eq. 50**

The maximum extractable water (mm) is the difference between the field capacity θ and the wilting point or else the minimum value of θ:

$$EW_M = (\theta_{fc} - \theta_m) z 10^3$$ **Eq. 51**

The relative extractable water (0 < REW < 1) is defined by the ratio between EW and EW_M:

$$REW = \frac{EW}{EW_M} = \frac{(\theta - \theta_m)}{\theta_{fc} - \theta_m}$$ **Eq. 52**

The critical REW (REW_c) can be defined as the threshold value for which the ratio between actual transpiration and potential evapo-transpiration (PET), i.e. T/PET, starts to decrease with decreasing REW. Above REW_c, T/PET is assumed to remain relatively constant with REW. REW_c has often been reported to be around 0.4, e.g. Granier *et al.* (1999).

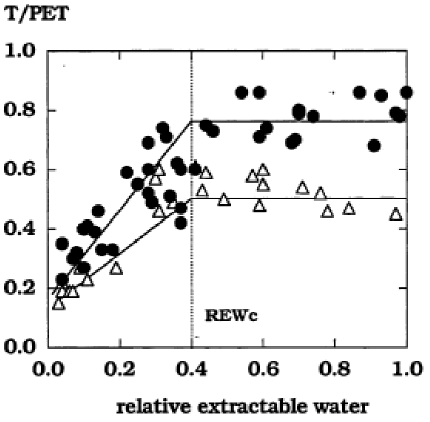


Figure 5 ***copied from Granier et al (1999):*** *Ratio T/PET calculated from sap flow measurements in an oak stand as a function of relative extractable water (REW) calculated from neutron probe measurements (from Breda and Granier, 1996). Two data sets are reported: LAI=6 (black circles) and LAI=4.5 (open triangles). The dotted line shows the critical REW (REW_c).*

B35- Water movement in the soil: potentials, soil moisture characteristics curve, hydraulic conductivity, continuity equation

B351- Soil moisture characteristic curve

Soil volumetric content (θ_v) and matric potential (Ψ_m) are related to each other by what is called the soil moisture characteristic curve". This relationship is unique for every soil type. It is fitted to a power function (e.g. Campbell, 1985, but numerous other models are available, like Van Genuchten, Brooks and Corey, Driessen, Rogowski, Power function, exponentiel function) for modelling purposes.

$$-\psi_m = e^a \cdot \left(\frac{\theta_v}{\theta_{v\_sat}} \right)^b$$ **Eq. 53**

where Ψ_m is expressed in m; e^a is referred to as the air-entry suction for the soil (the potential where the largest pores begin to drain); θ_{v_sat} is the saturate θ_v ($m^3\ m^{-3}$); a, b are empirically-adjusted parameters
For all volumetric contents larger than the air-entry suction, the soil is saturated and therefore at its maximum matric potential ($\Psi_m = 0$).
It should be noted that the soil moisture characteristics are different if they are determined during the wetting or drying processes of soil. This is called hysteresis.

B352- Hydraulic conductivity

The flow of water in the soil (F_w: unit m s^{-1}) occurs in response to soil water potential gradients. The proportionality term is the soil hydraulic conductivity (K_w: unit m s^{-1}). The basic equation is referred to as the Darcy's law.

$$F_w = -K_w \cdot \frac{d\psi_h}{dz}$$ **Eq. 54**

where Ψ_h is the sum of gravitational and matric potentials (m); z is the flow distance (m).
The K_w values vary approximately between 10^{-4} and 10^{-9} m s^{-1}.
Analogous to the equation for the soil moisture characteristics, it is also possible to calculate hydraulic conductivity as a function of volumetric water content (e.g. Campbell, 1985, but numerous other methods available).

$$K_w = K_{w\_sat} \cdot \left(\frac{\theta_v}{\theta_{v\_sat}} \right)^m$$ **Eq. 55**

with m = 2.b + 3
where K_{w_sat} is the hydraulic conductivity under saturated conditions (unit m s^{-1}) which can be measured or derived from textural data (Campbell, 1985), and b is a fitted parameter, ranging from 2 (clay soil) to 24 (sandy soil).

B353- Continuity equation

Combining equations 55 and 56 we obtain the common form of the continuity equation (Richard's equation) for water flow:

$$\frac{d\theta_v}{dt} = \frac{d(-K_w \cdot d\psi_h)}{dz}$$ **Eq. 56**

A sink (S: e.g. plant water uptake) can be added to this equation in the form (e.g. Sansoulet, 2007):

$$\frac{d\theta_v}{dt} = \frac{d(-K_w \cdot d\psi_h)}{dz} - S$$ **Eq. 57**

S being a function of Ψ (or θ)

B36- Drought and flooding

There are many definitions and indexes of drought, including:
- **Climatic indexes:** e.g. ombrothermic diagrams, comparing temperature and rainfall
- **Soil indexes:** based on soil water content or hydraulic potential.
- **Plant indexes:** including organ (leaf) relative water content (RWC_l), organ (leaf) water potential, leaf temperature, chlorophyll fluorescence etc.
- **Plant and soil indexes:** based on Relative Extractable Water (REW) (see definition above and Granier *et al.*, 1999). The soil water deficit (SWD, expressed in mm) can be defined by (Granier *et al.*, 1999)

$$SWD = (0.4 * EW_M - EW)$$ **Eq. 58**

And can then be cumulated monthly, seasonally or annually in mm. Alternatively, the number of days with EW < 0.4*EWM can be computed.

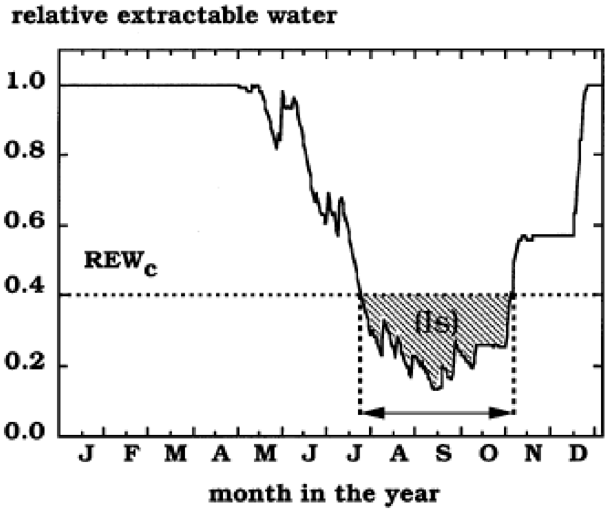


Figure 6 ***copied from Granier et al (1999):*** *Seasonal time course of relative extractable water (REW) in a soil, illustrating the number of days of water stress (segment with arrows) and the water stress index (Is, dashed area), REW$_c$-critical REW.*

- Plant and soil and climatic indexes
Entire books of conferences were dedicated to drought and it I not the purpose to review them here

B4- Quantifying the terms of water budget

B41- Soil

In annex 1, we have summed up Principles, Methods, Pros and Cons and examples of instruments and brands for assessing:

-Soil Volumetric humidity
-Soil Matric potential
-Soil Penetrometry
-Soil Texture
-Soil Sedimentometry
-Soil Infiltrability
-Water quality

B42- Roots

The profile distribution of fine root biomass is of major importance for many models, in order to couple transpiration of plants (including evaporation of the top soil) with their root water-uptake. Many models assume that the percentage of roots in each layer is driving the percentage of the total transpired water (T) which is actually extracted from the corresponding layer.
Rooting profiles can be assessed simply measuring impacts frequencies per layers in trenches (and the horizontal variability intra-plot can be assessed by stratified repetitions, or else using trenches with logarithmic spiral shapes around the trunks for instance). Alternatively, root biomass, separated by classes of diameter, can be obtained from trench experiments.
A major difficulty is then to account for seasonal variations in the root water extraction efficiency, which can be very variable, especially in the upper soil layers where roots can even dry-up. For continuous surveys of root status, rhizotrons and mini-rhizotrons can be used (Hendrick *et al.*, 2006). Belowground carbon allocation, including fine root growth and senescence, is subject to many biotic and abiotic factors that vary spatially and over time. These factors include stand or tree age, tree species, soil temperature, moisture, and nutrient availability, as well as impacts by insects, fungi, and other soil organisms (Gill and Jackson 2000; Haynes and Gower 1995; Hendrick and Pregitzer 1993; Nadelhoffer *et al.* 1985).
The high labour-intensive requirements of most techniques to measure root biomass means that any attempt to build consensus on different approaches has been difficult because few studies have been designed to measure and compare different methods at the same time (Vogt *et al.*, 1998) and in the same place. In our study, we particularly focused our

objective on this comparison between different methods for biomass estimation that occurred in the same area, within the same plot and on the same trees. The experiment took place in large plantations of eucalypt trees near Pointe Noire, Congo. We limited our observations to excavations techniques commonly used: Auger coring, monolith coring, half and full trench excavation technique (e.g. Jourdan *et al.*, subm.).

B43- Leaf and Plant

In Annex 2, we have summed up Principles, Methods, Pros and Cons and examples of instruments and brands for assessing:

-Plant Hydraulic potential
-Sapflow
-Leaf evaporation and stomatal conductance

B44- Stand and Ecosystem

In Annex 3, we have summed up Principles, Methods, Pros and Cons and examples of instruments and brands for assessing:

-Climate
-Air humidity
-Canopy analysis, gap-fractions, LAI
-Stand evapo-transpiration and canopy conductance

Of particular importance is to cross-validate field methods, for instance eddy-covariance and sapflow (Saugier *et al.*, 1997; Granier *et al.*, 2000; Wilson *et al.*, 2001; Roupsard *et al.*, 2006) or to partition the flux above and below the canopy (Roupsard *et al.*, 2006 Misson et al 2007).

B45- Landscape: spatialising LAI, fAPAR, energy balance, as a pre-requisite for spatialising evapotranspiration

Spatialising LAI could be done alternatively by:

- coupling a growth and yield model (such as E-DENDRO) with the H_2O model: in this case, the G&Y model is supposed to yield LAI as an output, with its time and space variability (both static and dynamic approaches possible). This method is probably suitable for the case-study of eucalypt afforestation in Congo, since the E-DENDRO will be made available (see A2411 E-DENDRO, a Growth and Yield Model)
- Estimating LAI from remote-sensing. This method is more general and is probably not applicable to our case study, due to the difficulty in obtaining cloud-free images. The dynamic aspects may only be achieved if several images can be used along the seasons, or if vegetation is simulated dynamically (e.g. through LPJ).

B451- Fraction of absorbed PAR (fAPAR)

The fraction of incident PAR absorbed by the canopy (fAPAR), which related to LAI through the Beer's law, is central for eco-physiology: it drives most Soil-Vegetation-Atmosphere Transfer (SVAT) models (e.g. Ruimy *et al.*, 1995), and allows interpretation and gap-filling of eddy-covariance measurements of GPP (Gross Primary Productivity) at the scale of the ecosystem (Baldocchi, 1997; Falge *et al.*, 2001). fAPAR can also be estimated by remote sensing in order to run regional models of Net Primary Productivity (Monteith, 1972; Gower *et al.*, 1999; Nouvellon *et al.*, 2000b). For simplicity, fAPAR is often approximated by fIPAR (the fraction of intercepted PAR, the complement of PAR transmittance below the canopy), which can easily be measured at the scale of the ecosystem using indirect optical gap-fraction methods, such as e.g. LAI-2000 Plant Canopy Analyser (Welles and Norman, 1991; Weiss *et al.*, 2004) or Hemispherical Photography (Frazer *et al.*, 2001; Jonckheere *et al.*, 2004). In addition, the actual fAPAR requires the modelling of light scattering (reflection + transmission of intercepted light by the canopy and reflection by the soil) and light re-interception (of scattered light by the canopy and by the soil), e.g. Nouvellon *et al.*, (2000a).

B452- Remote sensing tools for LAI and energy balance

Some state variables of spatialised models can be related to remote sensing observations by mean of radiative transfer (RT) schemes. Two canopy RT models are generally used. The first one is the Markov chain reflectance model (MCRM), which simulates two-layer canopy reflectances for different solar zenith angles (SZA) (Kuusk, 2001). This model has a demonstrable usefulness in most canopies, except needleleaf forests (Fang & Liang, 2003; Kuusk, 1998). The second model is the GeoSAIL model (Huemmrich, 2001), which validation results show is suitable for needleleaf forest and works very well in the boreal area (Huemmrich, 2001). Alternatively, the nonparametric methods (e.g. neural networks, NN and projection pursuit regression, PPR) provide a direct relationship between the simulated reflectance and the corresponding biophysical variables of interest, are ideal for LAI extraction (Fang and Liang, 2005).

The Moderate Resolution Imaging Spectroradiometer (MODIS) science team in the Earth Observing Program (EOS) is producing an LAI product globally (Justice *et al.*, 1998; Myneni *et al.*, 2002). The MODIS LAI product, a 1- km global data product updated every 8 days, is available for the general user community through the Earth Resources Observation System (EROS) Data Active Archive Center (DAAC). The operational MODIS LAI algorithm uses vegetation maps as a priori information to constrain the vegetation structural and optical parameter space (Myneni *et al.*, 1997). Six major biomes were used: grasses and cereal crops (biome 1), shrubs (biome 2), broadleaf crops (biome 3), savannas (biome 4), broadleaf forests (biome 5), and needleleaf forests (biome 6). For each land pixel, numerical solutions to a three-dimensional radiative transfer (RT) equation are used to account for the bi-directional reflectance factors (BRF) of the biomes for varying sun-view geometry and canopy/soil patterns. A look-up table (LUT) is constructed including a suite of canopy structures and soil characteristics of each biome. The present version of the LUT contains 25 patterns of effective ground reflectances evaluated from the soil reflectance model. By comparing the observed and modeled BRFs, LAI is retrieved. The solution is usually not unique; therefore, the mean values of LAI averaged over all acceptable values and their dispersions are taken as the retrievals and their uncertainties. Should this main algorithm fail, a back-up algorithm is triggered to estimate LAI using the NDVI (normalized difference vegetation index). The backup algorithm makes use of the pixel NDVI and the straightforward NDVI-LAI relationship for each biome. The LAI product has a value between 0.0 and 8.0 assigned to each 1-km cell of the global grid database. One important aspect of the MODIS LUT method is that some variables, such as soil reflectance and leaf reflectance and transmittance, need to be fixed with a priori constants. Soil and leaf optical properties are allowed to vary only with biome types by MODIS algorithms in order to facilitate its global application. However, most of these variables vary dramatically. Fixing them with constants carries large uncertainties—notably for soil and leaf optical properties. In addition, land biome type is indispensable for this algorithm; misclassification will lead to accumulated errors in the final LAI products.

MODIS can also be used for energy balance or for estimating the latent heat flux.

B5- Modelling the terms of water budget

According to Dufrêne (2005), hydrologic processes control drought effect on photosynthesis soil carbon and nitrogen dynamics (Parton *et al.*, 1987), and thus some of the forest models also couple the carbon budget with a model simulating the water cycle. The rainfall reaching the ground is shared out into soil evaporation, transpiration, interception, infiltration or runoff. According to the application domain, the hydrology models are more or less sophisticated. For example, the evapotranspiration can be calculated as function of a potential evaporation (Granier *et al.*, 1999) or estimated following Monteith (1965) or Shuttleworth and Wallace (1985). The soil can be divided into numerous layers (Braud *et al.*, 1995) or parameterized into one or several buckets (Eagleson, 1978). Nevertheless, detailed SVAT models are difficult to use for the investigation of the spatial and temporal variability of land surface fluxes. The large number of parameters they involve requires detailed field studies and experimentation to derive parameter estimates (Boulet *et al.*, 2000). Simple water balance models using simple soil and stand parameters and basic climatic data are often sufficient to predict temporal variation in soil water content (Granier *et al.*, 1999).

In the literature, one can find a very large amount of models dedicated to water balance, or including at least a water balance module. Our purpose is not to review all those models in extenso, but only to sum up a few categories of models, and to give also a few examples that would be promising for our specific case study. This specific choice of models might appear rather arbitrary, so we tried to give also alternative choices in the form of references, in order to orientate the reader.

In table 5, we summed up the characteristics of the different selected models, according to main compartments being modelled (climate, soil, plant, or balanced), the compliancy with the modules for complement compartments, with spatialisation goals, with photosynthesis module, with C4 photosynthesis module, with nutrient module, for comparison between baseline scenario and afforestation.

B51- General energy balance model

$$R_n = H + \lambda E + G + Q \qquad \textbf{Eq. 59}$$

where: R_n: net radiation; H: sensible heat flux; λ: latent heat flux for water evaporation; E: evaporation; G: soil heat storage; Q: air and plants heat storage

B52- Potential Evapo-transpiration models (PET)

B521- Empirical formulas (e.g. Turc; Priestley-Taylor):

From Turc

$$PET = \mu \cdot (R_g + 50) \cdot \left[T_a / (T_a + 15) \right] \qquad \textbf{Eq. 60}$$

where: PET: potential evapotranspiration (mm month^{-1} or mm 10day^{-1}); µ:constant (0.13 for decade and 0.4 for month); R_g: global radiation (cal cm^{-2} time^{-1}); T_a: mean sheltered temperature for the period (°C).

From Priestley-Taylor

$$PET = \alpha \cdot \frac{\Delta}{\lambda(\Delta + \gamma)} \cdot R_n \qquad \textbf{Eq. 61}$$

where: PET: evapo-transpiration; a: coefficient with average value of 1.26 (covering crops, bare soil and ocean); λ: latent heat flux for water evaporation; Δ: slope vapour pressure curve; γ :psychrometric constant; R_n: net radiation at the crop surface.

B522- Physical formulas (e.g. Penman, 1948):

This formula was built initially to estimate evaporation by water surfaces, or by surfaces saturated in H_2O and without stomatal resistance.

$$PET = \frac{\left[\Delta \cdot (R_n - G) + \gamma f(u)(e_s - e_a) \right]}{\left[\lambda(\Delta + \gamma) \right]} \qquad \textbf{Eq. 62}$$

where: PET: reference evapo-transpiration; Δ: slope vapour pressure curve; R_n: net radiation at the crop surface; G: soil heat flux density; γ :psychrometric constant; f(u): a wind function with the form f(u)=a + b(u); e_s-e_a: vapour pressure deficit.

B523- Biophysical-formulas: Penman-Monteith reference evapo-transpiration (ET_0) (FAO, 1998)

The FAO Expert Consultation on Revision accepted the following unambiguous definition for the reference surface:
"A hypothetical reference crop with an assumed crop height of 0.12m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23".
The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water.
The FAO Penman-Monteith reference PET equation is a simple representation of the physical and physiological factors governing the evapotranspiration process. From it, one may calculate crop coefficients, K_c, i.e. K_c=ET_c/ET_0.

Daily time-step (FAO, 1998, p. 24)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad \textbf{Eq. 63}$$

where: ET_o: reference evapo-transpiration (mm d^{-1}); R_n: net radiation at the crop surface (MJ m^{-2} d^{-1}); G: soil heat flux density (MJ m^{-2} d^{-1}); T: mean daily air temperature at 2 m height (°C); u_2: windspeed at 2 m height (m s^{-1}); e_s: saturation vapour pressure (kPa); e_a: actual vapour pressure (kPa); e_s-e_a: vapour pressure deficit (kPa); Δ: slope vapour pressure curve (kPa °C^{-1}); γ :psychrometric constant (kPa °C^{-1}).

Hourly time-step (FAO, 1998, p. 74)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr}+273} u_2 \left(e^0(T_{hr}) - e_a\right)}{\Delta + \gamma(1+0.34u_2)} \qquad \textbf{Eq. 64}$$

where: ET_o: reference evapo-transpiration (mm h^{-1}); R_n: net radiation at the crop surface (MJ m^{-2} h^{-1}); G: soil heat flux density (MJ m^{-2} h^{-1}); T: mean hourly air temperature (°C); u_2: average hourly windspeed at 2 m height (m s^{-1}); $e^0_{(Thr)}$: saturation vapour pressure at air temperature (kPa); e_a: average hourly actual vapour pressure (kPa); Δ: slope vapour pressure curve (kPa °C^{-1}); γ :psychrometric constant (kPa °C^{-1}).

B53- Soil water models (to be coupled with plant and rainfall interception models)

Soil water transfer models can be classified into three categories: (i) stochastic models (probabilistic approach, models very specific to the local conditions and poorly transferable), (ii) functional deterministic models (capacitive models, using two values of θ_v, the wilting point and the field capacity), and (iii) deterministic mechanistic models which couple several phenomenons (Sansoulet, 2007). Deterministic mechanistic models offer the possibility to study interactions between phenomenons, or sensitivity to phenomenons. However, their potentialities are restricted by the number of parameters and initial conditions required for simulation. Their validation is also difficult. Some successful cross-comparison of functional models FAO (Doorenbos and Pruitt, 1977) or Ritchie (1985), with a mechanistic model (Maraux and Lafolie, 1998) are available in the literature (eg. Maraux *et al.* 1998).

There is an increasing demand for large scale (region, continent) and for long term studies on forest–site–climate interactions, as much for hydrological as for forest management purposes. Such extensive applications require robust water balance models using simple soil and stand parameters and basic climatic data, in order to run simulations over many years.

B531- Example of soil water model: Hydrus (Šimůnek *et al.*, 2005), see also Annex 4a for detailed description

Hydrus 1D has already been implemented at the scale of our case study plots (Laclau *et al.*, 2005), hence justifying our choice to present it here. It is an interactive graphics-based user interface, which may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The flow region may be composed of non uniform soils. Flow and transport can occur in the vertical, horizontal, or a generally inclined direction. The software package can be freely downloaded with the code from www.hydrus2d.com (or www.pc-progress.cz). However, plant transpiration and soil evaporation are input variables in Hydrus1D and have to be assessed from ecophsyiological models.

The Hydrus1D program numerically solves the Richards' equation for variably saturated water flow and convection-dispersion type equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The flow equation may also consider dual-porosity-type flow with a fraction of water content being mobile, and fraction immobile. The heat transport equation considers transport due to conduction and convection with flowing water. The solute transport equations consider convective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase.

The Hydrus1D software package also includes modules for simulating carbon dioxide and major ion solute movement. Diffusion in both liquid and gas phases and convection in the liquid phase are considered as CO_2 transport mechanisms. The CO_2 production model is described. The major variables of the chemical system are Ca, Mg, Na, K, SO_4, Cl, NO_3, H_4SiO_4, alkalinity, and CO_2. The model accounts for equilibrium chemical reactions between these components such as complexation, cation exchange and precipitation-dissolution.

The water flow part of the model can deal with prescribed heat and flux boundaries, controlled by atmospheric conditions, as well as free drainage boundary conditions. The governing flow and transport equations are solved numerically. Hydrus1D also includes a parameter optimization algorithm for inverse estimation of soil hydraulic and/or solute transport and reaction parameters from measured transient or steady-state flow and/or transport data.

A description of Hydrus 2D/3D models can be found on the site: www.hydrus2d.com. These models are adapted to predict the spatial variability of water transport in porous media provided that the available data make it possible to estimate the input parameters. These softwares are not free and the large number of parameters required to simulate the spatial variability of soil water transport make them unsuitable for large scale estimations of drainage.

B532- Example: PASTIS (Lafolie, 1991)

The mechanistic model PASTIS is described in detail in Lafolie (1991) and Maraux and Lafolie (1998) especially in this latter case for maize-sorghum sequence. The model is based on Richards' equation for describing water flow in the soil profile with a sink term accounting for plant water uptake. At the soil surface a flux-type boundary condition corresponding to either rain intensity or actual evaporation is imposed. Provision is made in the model to handle surface pounding if the rain intensity exceeds soil intake capacity. A water potential type boundary condition varying with time is imposed at the bottom of the soil profile. Potential evaporation is imposed at the soil surface up to the time the surface soil water potential reaches a prescribed threshold. When this threshold is reached, evaporation is reduced and this threshold is imposed as the boundary condition at the soil surface. In this case, the application of Darcy's law at the soil surface gives the actual evaporation. The root density and the maximum rooting depth increases linearly with time to a maximal root depth up to a prescribed time at which root growth is stopped. In addition the root density decreases exponentially with depth. When a difference exists between the potential and actual transpiration of the crop a plant water stress appears that may modify the growth of aerial and underground organs of the plant, and parameters are introduced to account for this effect.

The model predicts the upward water flux into the root zone and its important contribution to plant uptake during the dry season. It also predicts the transpiration rate during months without rain and the amount of water remaining in the soil profile at the end of the crop.

B54- Leaf transpiration models

In analogy with the Fick's law relative to diffusion in the gas phase:

$$E_l = 10^{-3} \cdot \frac{\delta w}{r_s + r_a} = 10^{-3} \cdot g_{s,a} \cdot \delta w \qquad \textbf{Eq. 65}$$

where E_l: leaf transpiration (mmol m^{-2} s^{-1}); δw: difference of H_2O molar fraction in the gas phase between mesophyllian evaporating surfaces of the leaf (at leaf temperature) and ambient air (at air temperature) in unit (mmol mol^{-1}); r_s: stomatal resistance to H_2O (s m^2 $mmol^{-1}$); r_a: aerodynamic resistance to H_2O (s m^2 $mmol^{-1}$); $g_{s,a}$: leaf conductance to H_2O (mmol m^{-2} s^{-1}).

E_l can be measured with an IRGA (Infra Red Gas Analyser) using either open or closed systems, δw can be assessed by leaf and air thermocouple or thermistors and reference + chamber molar fraction (open-path) or RH probe (closed path).

Leaf evaporation can be measured directly (see above), or else, be computed as the solution of energy and radiative balance at leaf scale.

$$R_n = H + \lambda E + \Delta S \qquad \textbf{Eq. 66}$$

where: R_n: net radiation; λ: latent heat flux for water evaporation; E: leaf evaporation; ΔS: leaf heat storage

In order to model the stomatal conductance independently of photosynthesis, one can propose the Jarvis (1976) approach (requires g_{smax}, empirical functions of PAR, T_a, VPD, soil water content or Ψ). In this case, a large range of conditions of simultaneous recording and repetitions of g_s, PAR, T_a, VPD, Ψ is required in order to calibrate and/or validate the model.

If coupling is desired, two solutions are commonly used: Jarvis (1976) + Farqhuar *et al.* (1980) or else Ball et al (1987). Both options offer numerical solutions for the coupling between stomatal conductance and photosynthesis: Wang and Jarvis (1993) and Baldocchi (1994), respectively.

B55- Plant models (to be coupled with soil models)

B551- Liquid phase

Van den Honert's law is relative to water flux in the liquid phase:

$$F_d = g_L \cdot (\Psi_s - \Psi_l) = g_L \cdot \Delta\Psi \qquad \textbf{Eq. 67}$$

where F_d: flux density, expressed per unit total leaf area or sapwood area (mmol m^{-2} s^{-1}); g_L: total (soil-to-leaf) hydraulic specific conductance per unit total leaf area or sapwood area (mmol m^{-2} s^{-1} MPa^{-1}); Ψ_s: soil water potential (MPa); Ψ_l: leaf water potential (MPa).

F_d can be measured with sapflow systems or by gravimetric methods, δΨ can be assessed by Scholander pressure chamber.

B552- Gas phase

Transpiration can be modeled directly and empirically as a function of R_n, T_a, VPD, Ψ
In order to model the canopy conductance, two solutions can be proposed:
-to upscale from stomatal conductance and LAI: in this case the stomatal conductance can be modelled using a Jarvis (1976) approach
-to invert g_c from Penman-Monteith, using measured values of T and climate (see below)

B56- Soil-Vegetation-Atmosphere Transfer models (SVAT) models

Caution: many SVATS appear rather unbalanced, in terms of modelling effort allocated rather to the climate, the soil or the plant. In this case, it would be recommended to couple the module of interest with complementary modules, originating from complement models. The main focuses of the following SVATs is summed up in Annex 4.

It is of particular importance that SVAT models include a retro-action loop between soil water availability and stomatal conductance, in order to limitate transpiration when soil dries out. All models presented below propose a form of retroaction, or allow including one.

B561- Reference SVATs (Multi-layer and 3D architectural models)

Soil-Vegetation-Atmosphere Transfer models (SVAT) can be classified into (i) “reference” models, such as multi-layer (e.g. Baldocchi and Harley, 1995), discrete 2D and 3D models (de Reffye *et al.*, 1988; Sinoquet *et al.* 2001; Dauzat *et al.*, 2001), or else (ii) “simplified models”, such as single-layer Big-leaf models (Sellers *et al.*, 1992; Amthor 1994; Lloyd *et al.*, 1995) or Sun-shade models (single-layer with two leaves: Sinclair *et al.*, 1976; Norman 1980, de Pury and Farqhuar, 1997; Wang and Leuning, 1998; Leuning *et al.*, 1998). The respective (dis)advantages of those models were often discussed (e.g. Raupach and Finnigan, 1988; de Pury and Farquhar, 1997, Leuning *et al.*, 1998). It is generally assumed that reference multi-layer and 3D models are accurate but require a number of calculations, which becomes a drawback for their inclusion into Global Circulation Models (e.g. Sellers *et al.*, 1992) and Regional Transport Models. 3D models for instance, rely upon a detailed representation of canopy architecture. They are inherently the most promising for solving recurrent theoretical problems affecting non-ideal canopies: e.g. row structure with large gaps, azimuthal heterogeneity, complex leaf angle distribution function (LADf), distinction between green and non-green elements or aggregation (clumping) at different scales (Weiss *et al.*, 2004). However, with regard to their complexity and to the number of parameters required, 3D models were made available only for few plant species, and their applications remained seldom so far. We argue here that 3D models do offer an outstanding reference for testing the performances or for validating simplified models to be applied in non-ideal conditions, the latter models being more promising for general applications.

B5611- Example of a complete SVAT model: CASTANEA: (Dufrene *et al.,* 2005; Davi *et al.,* 2005). See also Annex 4b for detailed description

CASTANEA is a physiologically multi-layer process-based model with the aim to bridge the gap between soil–vegetation–atmosphere(SVAT) and growth models. It is aiming to predict the water and carbon balance of an even-aged monospecific deciduous forest stand. CASTANEA describes canopy photosynthesis and transpiration, maintenance and growth respiration, seasonal development, partitioning of assimilates to leaves, stems, branches, coarse and fine roots, evapotranspiration, soil heterotrophic respiration, water and carbon balances of the soil. Its outputs are compliant with eddy-covariance experiments (NEE, GPP, Re, NPP, NEP, Rsoil, Rh).
No variability between trees is assumed and then one “averaged” tree is considered to be representative of the stand. The main output simulated variables are (i) the evolution of leaf area index, the standing biomass, the soil carbon and water content which are state variables, and (ii) the canopy assimilation, the maintenance and growth respirations, growth of organs, soil heterotrophic respiration, transpiration and evapotranspiration which are flux densities variables. Half-hourly rates of gross canopy photosynthesis and transpiration are calculated from incident radiation and photosynthetic characteristics of individual leaves and can be aggregated daily.
The canopy is assumed to be homogeneous horizontally and vertically subdivided into a variable number of layers (i.e. multi-layer canopy model), each of them enclosing the same amount of leaf area. Tree structure is a combination of five functionally different parts: foliage, stems, branches, coarse and fine roots. A carbohydrate storage compartment is also considered but is not physically located in the model.
Phenological stages (budburst, end of leaf growth, start of leaf yellowing, etc.) and leaf growth are based on day-degrees.

Water fluxes

Rainfall interception by the canopy

The canopy is regarded as having a surface storage capacity, recharged by rainfall and discharged by evaporation and drainage. The storage capacity of leaves and woody parts (i.e. stems and branches) are considered separately. During the leafy period, leaves intercept a fraction of rainfall, depending on both leaf area index and gap fraction. If the amount of water intercepted exceeds the leaf capacity storage, the excess is lost by throughfall and can either be intercepted by woody parts or reach the soil surface. If the amount of rainfall intercepted by woody parts exceeds the storage capacity of the bark then water can both run out along branches and stems or throughfall on to the litter layer. Evaporation rate occurs according to the Penman–Montheith equation (Monteith, 1965) assuming a zero stomatal resistance.

Canopy evapotranspiration

The canopy evapotranspiration is calculated by adding water evaporated from the wet parts of the canopy and transpiration from the dry parts. The Penman–Monteith equation (Monteith, 1965) is applied at the canopy level to calculate both transpiration and evaporation. Heat storage and soil heat flux are assumed to be negligible. The canopy conductance gc is calculated by averaging leaf stomatal conductance over the canopy. For water evaporation calculation, an infinite conductance gc is assumed (no resistance) and equation is simplified to the Penman formulation. Net radiation is driven by energy balance, air vapour pressure deficit (VPD) is an input meteorological variable and the canopy aerodynamic resistance is calculated assuming a logarithmic wind profile above the canopy and an exponential decrease inside the canopy.

Soil evaporation

Soil evaporation is calculated in the same way as canopy transpiration using Penman–Monteith equation. It differs from canopy evaporation only by the available energy for evaporation, the aerodynamic resistance from soil to atmosphere and the water vapour soil conductance. Soil conductance to water vapour depends on water status both in the upper part of soil and in litter.

Soil water balance

The soil water balance model is basically a bucket one with three layers (litter, a top-soil layer and a total-soil root zone including top-soil layer). Current water contents (RWlit, RWtop, RWsoil) are the state variables corresponding to the three compartments. For each layer, water content is calculated daily as the difference between inputs (stemflow, throughfall and drainage from above layer) and outputs (evaporation, transpiration and drainage). The way to arrange in time the different fluxes is different for litter and soil compartments: Litter*:* three steps are considered. Soil*:* 2 steps are considered. It should be noticed that two water balances are calculated independently; one for the top-soil layer and another one for the total soil root zone (including top soil layer). Both are used to calculate the soil water stress, which controls both transpiration and photosynthesis.

Effect of soil water status on canopy gas exchange

During water stress period the slope (*g*1) of the relationship, proposed by Ball *et al.* (1987) between leaf assimilation (*A*) and stomatal conductance (*g*s), is assumed to decrease linearly when soil water storage decreases. The effect of soil water stress on photosynthesis translates into g1 through a reduction factor. On the contrary when both soil layers (top and total) are below this threshold, the soil water stress increase linearly with decreasing soil water content until zero. Stress is a threshold parameter for soil water stress.

B562- Simple SVATs

B5621- Big-leaf for closed canopies and modifications for sparse canopies:

Big-leaf models represent the canopy like a single layer, with one source and with a unique instant value for transpiration, photosynthesis and for light absorption.

Stand evaporation can be computed as the solution of energy and radiative balance at stand scale.

According to the Penman-Monteith equation adopted by FAO standards (FAO, 1998, p. 19), evapo-transpiration by a cropped surface submitted to stomatal resistance is:

$$E = \frac{\left[\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}\right]}{\lambda\left[\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)\right]} \qquad \textbf{Eq. 68}$$

where: E: evapo-transpiration (mm s^{-1}); Δ: slope vapour pressure curve (Pa $°C^{-1}$); R_n: net radiation at the crop surface (W m^{-2}); G: soil heat flux density (W m^{-2}); ρ_a: mean air density at constant pressure (1.33 kg m^{-3}); C_p: heat volumetric capacity (1000 J kg^{-1} $°C^{-1}$); e_s: saturation vapour pressure (Pa); e_a: actual vapour pressure (Pa); e_s-e_a: vapour pressure deficit (Pa); r_a: aerodynamic resistance (s m^{-1}); λ: latent heat flux for water evaporation (2.5 10^6 J kg^{-1}); γ :psychrometric constant (66 Pa $°C^{-1}$); r_c: canopy resistance (s m^{-1}).

Interestingly, Stewart (1988) proposed to inverse this formulation in order to compute the canopy conductance when evapo-transpiration and climatic parameters were known. In order to model the canopy conductance, two solutions can thus be proposed:

-to upscale from stomatal conductance and LAI: in this case the stomatal conductance can be modelled using a Jarvis (1976) approach (requires g_{smax}, empirical functions of PAR, T_a, VPD, Ψ)

-to invert g_c from Penman-Monteith (requires, E or T, g_{cmax}, empirical functions of PAR, T_a, VPD, Ψ).

For closed canopies, it works reasonably well for estimating transpiration, and in this case, a Penman-Monteith model (see description above) is generally used, with possible inversion in order to retrieve the canopy conductance. However, even in this simple case, the approach is limited, due to photosynthetic concerns, if it desired later to couple with a C module. As a matter of fact, the assumption of a canopy functioning like a big leaf for C would only be valid if the vertical profile of leaf photosynthetic capacity (i.e. mainly of nitrogen distribution) would be proportional to the profile of light absorption (Farquhar, 1989), a condition which is not necessarily met at daily time-step and never met at instant time-step. The relationship between leaf photosynthesis and light absorption is non-linear (Farquhar *et al.*, 1980) and displays three portions: the first one which is approximately linear (at low light, typically corresponding to the situation of shaded leaves); a transition zone, which is non-linear, hence resulting in biased averaging by big-leaf models; and the last one at light saturation, corresponding to the situation of sunlit leaves. It comes that only the first and last portions allow light averaging for estimations of photosynthesis without introducing significant biases, thus supporting the simplifications assumed by Sun-shade models (Sinclair *et al.*, 1976; Norman 1980).

For non-closed canopies, such as for sparse and row crops, Shuttleworth and Wallace (1985) proposed a modified Big-leaf model, in order to account for the relative contribution of soil and sparse crop to evapo-transpiration, according to varying LAI or canopy coverage of the crop. The Shuttleworth and Wallace model represent covers with two layers (with distinct microclimatic conditions and an aerodynamic resistance in-between) and two sources (soil and canopy).

B5622- Sun-shade

Sun-shade models represent canopies with one layer and two sources (sunlit and shaded leaves). The Sun-shade model proposed by de Pury and Farquhar (1997) proved to combine the advantages of simplicity and accuracy of big-leaf and multi-layer models respectively, after comparing the simulations of wheat photosynthesis displaying uniform (spherical) leaf angle distribution and homogeneous (intercepting elements distributed randomly) canopy. Other authors confirmed the validation of canopy photosynthesis and of the terms of energy balance for wheat, after comparing their own Sun-shade and multi-layer models (Wang and Leuning, 1998) or using field eddy-covariance measurements (Leuning *et al.*, 1998). Hence, Sun-shade models come out as simple and reliable approaches on low and dense canopies. We consider that they would deserve further developments over a range of canopies, such as tall, open, non-uniform (non-spherical leaf angle distribution) and non-homogeneous (non-randomly distributed elements), i.e. non-ideal canopies.

In order to model the canopy conductance with a sun-shade model, one solution can thus be proposed:

-to upscale from stomatal conductance and LAI of sunlit and shaded leaves: in this case the stomatal conductance can be modelled using a Jarvis (1976) approach (requires g_{smax}, empirical functions of PAR, T_a, VPD, Ψ)

B5623- Example of a balanced H_2O model : BILJOU: Granier *et al.* (1999). See also Annex 4c for detailed description

BILJOU (bilan jour) is a daily or infra-daily water balance model where the main aim is to quantify drought intensity and duration in forest stands. This simple and lumped water balance model aimed basically at quantifying drought intensity and duration in forest stands. It uses a small set of parameters and standard daily meteorological data (potential evapotranspiration and precipitation). It can also be run infra-daily. Evapotranspiration, which is generally the largest flux component, besides throughfall, is estimated here from ecophysiological relationships at stand scale. These relationships are driven by maximum leaf area index (LAI) to calculate canopy transpiration, understorey evapotranspiration and rainfall intercepted by tree canopies. It can be used for different sites and purposes, like long term (several years) or short term studies on the impact of drought on forest stands. This model estimates the main terms of the hydrological cycle in forest stands: soil water content, stand transpiration and interception, drainage. Runoff is neglected in the original version. It allows also computing seasonal and annual integrated water stress indices to characterize drought events affecting physiological processes and growth of trees from various species, over long term periods. Water stress is assumed to occur when relative extractable soil water (REW) drops below a threshold of 0.4 under which transpiration is linearly reduced due to stomatal closure. Day-to-day estimates of soil water content during the growing season allows to quantify duration and intensity of drought events, and to compute stress indexes.

Symbols	Variable
P	rainfall
Th	throughfall
In	rainfall interception
Is	water stress index Is
T	tree transpiration
Eu	evaporation from understorey plus soil
PET	potential evapotranspiration (Penman Formula)
ET	actual evapotranspirationT+Eu+In
r	equals T/PET
rm	equals Tm/PET in absence of water stress
W	available soil water
Wm	minimum soil water (i.e. lower limit of water availability)
WF	soil water content at field capacity
EW	extractable water
EWm	maximum extractable water
REW	relative extractable water
REWc	critical REW, at which tree transpiration begins to decrease
SWD	soil water deficit
Di	drainage at the bottom of soil layer i
mici	microporosity of soil layer i
maci	macroporosity of soil layer i
fi	water flow refilling soil layer i
LAI	leaf area index
K	extinction coefficient for PAR
fTPAR	fraction of transmitted PAR
Rn	net radiation
Tcor	Transpiration diminished by 20% of In
Rnu	net radiation of the understorey
AEu	available energy of the understorey
REi	root extraction in layer i
RfDi	fine root relative distribution in layer i
Th	throughfall = P-In
SWD	soil water deficit

Table 5 **:** *List of symbols and variables in BILJOU (Granier et al., 1999), completed for the purpose of the present review after coding the original model.*

This model is iterative and the variation in soil water content are calculated at a daily pace as:

$$\Delta W = P - In - T - Eu - D \qquad \textbf{Eq. 69}$$

where ΔW is the change in soil water content between two successive days.
Note here that runoff is considered negligible.

The BILJOU model combines several advantages of simplicity, few number of parameters required, and compliancy with spatialisation purposes (spatialisable parameters).
Its calibration requires soil water monitoring along a vertical profile, together with soil water potential (measured or calculated). The parameter “rm”, which represents Tm/PET in absence of water stress has to be calibrated for the stand

(using sapflow during the wet period for instance), unless the proposed relationship between rm and LAI is used (Granier *et al.*, 1999). Similarly, the relationship between “r” (T/ETP) and REW in conditions of water shortage, the critical value of REWc, as well as an empirical relationship between In and P have to be documented locally.

It is assumed that the fraction of water uptaken by the roots in every soil layer is proportional to their respective fine root density. Also the evapotranspiration of the understorey is a fixed fraction of its available energy.

Once calibrated and validated, we believe that this simple model offers good perspectives for a wide range of situations. It deserves to be adapted for multistrata systems.

B5624- Other examples of a balanced models: Lo Seen *et al.* (1997), Nouvellon *et al.* (2000c);

B563- Empirical SVATs, using observed variations of crop coefficient (FAO, 1998)

FAO (1998) proposes the crop coefficient approach, which is simple in principle, but requires important calibrations in practice and which are mainly empirical (suitable for local conditions but difficult to extrapolate). According to FAO (1998), 5 concepts of evapo-transpiration can be proposed:

. Climate + well watered reference grass =ET_o (see computation details above)

. ET_o x K_c (well watered crop, optimal agronomic conditions) = ET_c

. ET_o x (K_{cb} +K_e) = ET_c, which is similar to the previous condition, but with distinct coefficients for the crop (K_{cb}) and for the soil (K_e)

. ET_o x K_c (well watered crop, optimal agronomic conditions) x K_s (water and envir. Stress)= $ET_{c,adjusted}$

. ET_o x ($Ks.K_{cb}$ +K_e) = ET_c, which is similar to the previous condition, but with distinct coefficients for the crop (K_{cb}) and for the soil (K_e)

B57- Biome models or plot-to-biome upscaled models

Ecosystem models developed in the past to assess the effects of climate and land use changes have generally fallen into two categories:

-biogeochemistry models which simulate the carbon, nitrogen and water cycles

-biogeography models (e.g., MAPSS) which predict vegetation distribution under varying climates

The integration of biogeography and biogeochemistry models into transient models (Dynamic Vegetation Models) that could illustrate real time ecological effects of climate change has been an important next step in model development.

Two such models are under construction by the MAPSS research team:

MC

BIOMAP : a hybrid between MAPS and Biome-BGC

These new dynamic vegetation models will be useful for exploring management options at all scales from landscape to regional, national and global.

B571- Example: MAPSS (Mapped Atmosphere-Plant-Soil System: Neilson (1995). See also Annex4d for detailed description

MAPSS is a landscape to global vegetation distribution model that was developed to simulate the potential biosphere impacts and biosphere-atmosphere feedbacks from climatic change. Model output from MAPSS has been used extensively in the Intergovernmental Panel on Climate Change's (IPCC) regional and global assessments of climate change impacts on vegetation and in several other projects. Vegetation models developed by the MAPSS team are being continually enhanced. MAPSS was originally a steady-state biogeography model, able to simulate a map of potential natural vegetation under a long-term average climate. Emerging technology couples the biogeographical rule base of MAPSS with two different ecosystem nutrient cycling models and a process-based fire model in order to simulate the spatially explicit dynamics of vegetation at landscape to global scales under both stable and changing climates. These new dynamic vegetation models, MC and BIOMAP, will be useful for exploring management options at all scales from landscape to regional, national and global.

The principal features of the MAPSS model include algorithms for:

1) Formation and melt of snow,
2) Interception and evaporation of rainfall,
3) Infiltration and percolation of rainfall and snowmelt through three soil layers,
4) Runoff,
5) Transpiration based on LAI and stomatal conductance,
6) Biophysical 'rules' for leaf form and phenology,

7) Iterative calculation of LAI, and
8) Assembly rules for vegetation classification.

Infiltration, saturated and unsaturated percolation are represented by an analog of Darcy's Law specifically calibrated to a monthly time step (Hillel, 1982). Water holding capacities at saturation, field potential, and wilting point are calculated from soil texture, as are soil water retention curves (Saxton *et al.*, 1986). Transpiration is driven by potential evapotranspiration (PET) as calculated by an aerodynamic turbulent transfer model based upon Brutsaert's (1982) ABL model (Marks and Dozier, 1992; Marks 1990), with actual transpiration being constrained by soil water, leaf area and stomatal conductance. Stomatal conductance is modulated as a function of PET (a surrogate for vapor pressure deficit) and soil water content (Denmead and Shaw 1962). Canopy conductance (i.e., actual transpiration) is an exponential function of LAI, modulated by stomatal conductance.

Elevated CO_2 can affect vegetation responses to climate change through changes in carbon fixation and water-use-efficiency (WUE, carbon atoms fixed per water molecule transpired). The WUE effect is often noted as a reduction in stomatal conductance (Eamus 1991). Since MAPSS simulates carbon indirectly (through LAI), a WUE effect can be imparted directly as a change in stomatal conductance, which results in increased LAI (carbon stocks) and usually a small decrease in transpiration per unit land area.

MAPSS has been implemented at a 10 km resolution over the continental U.S. and at a 0.5^o resolution globally (Neilson 1995, Neilson 1993, Neilson and Marks 1994). The model has been partially validated within the U.S. and globally with respect to simulated vegetation distribution, LAI, and runoff (Neilson 1993; Neilson 1995; Neilson and Marks 1994). MAPSS has also been implemented at the watershed scale (MAPSS-W, 200 m resolution) via a partial hybridization with a distributed catchment hydrology model (Daly 1994, Wigmosta 1994).

Distributed hydrology-biogeochemistry model (DHB) in MAPSS

The distributed hydrology-biogeochemistry model (DHB) was created to study the effects of climate and land cover change at the watershed level in the Pacific Northwest. DHB was developed by incorporating components from DHSVM, a hydrology model (Wigmosta et al 1994, Storck *et al.* 1998), BIOME-BGC, a biogeochemistry model (Running and Gower 1991, White *et al.* 1998) and MAPSS (Neilson 1995), a biogeography model. DHB simulates interactions between hydrologic fluxes, soil moisture state, and vegetation growth and mortality at a grid scale of ~100m and on a daily time step. Simulation of vegetation includes lifeform competition for light, water, and nitrogen. Simulation of hydrology includes quasi-three-dimensional redistribution of surface water and shallow groundwater. Leaf area index, root distribution, and vegetation height are the key state variables linking physical and biological fluxes in the model.

B572- Example: ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms): Krinner *et al.* (2005). See also Tab. 5e for detailed description

ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems Environment) is a new “last generation” Dynamics General Vegetation Model (DGVM). It is a “last generation” model in the sense that it fully couples physical and biogeochemical processes and vegetation dynamics. It has been included in the IPSL global climate model. ORCHIDEE is in fact composed of three coupled submodels : SECHIBA an existing land surface scheme (Ducoudré et al, 1993), the plant dynamics core of LPJ (Sitch *et al.*, 2000), and a new biogeochemistry model STOMATE (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems). STOMATE uses the concept of plant functional types (PFT) to describe vegetation distributions. In its present version the model simulate 12 PFTs. In every grid cell all different PFTs may coexist. Photosynthesis is based on the Farquhar model (Farquhar *et al.*, 1980) and stomatal conductance on Ball&Berry (Ball *et al.*, 1982). Carboxylation rate Vmax is a function of PFT and of leaf age. Maintenance respiration is a function of biomass and linearly related to temperature (Ruimy *et al.*, 1996). Growth respiration is a fixed part of allocated photosynthates (30%). Heterotrophic respiration (decomposition) parameterization is essentially taken from CENTURY (Parton *et al.*, 1988). The most original parts of STOMATE are the parameterizations of phenology and allocation. Budburst is based on a new scheme calibrated from remote sensed data and based on parameters like the number of growing degree days and chilling days or changes in soil water content (Botta *et al.*, 2000). Leaf senescence is a function of leaf age modulated by water and temperature stresses. The allocation submodel is based on resource optimization (Friedlingstein *et al.*, 1999).

Orchidee “is a SVAT coupled to a biogeochemistry and a dynamic biogeography model. As such it explicitly simulates the phenomena of the terrestrial carbon cycle that are linked to vegetation and soil decomposition processes, but also changes in vegetation distributions in response to climate change as well as short-time scale interactions between the vegetated land surface and the atmosphere.” Krinner *et al.* (2005).

B5721- Conceptual Framework

It is based on the following three other models:
1. The SVAT Sechiba "describes exchanges of energy and water between the atmosphere and the biosphere, and the soil water budget." "In its standard version Sechiba contains no parameterization of photosynthesis. Time step of the hydrological module is of the order of 30 minutes."
2. The dynamic global vegetation model (DGVM) LPJ have been taken for "the parameterizations of vegetation dynamics (fire, sapling establishment, light competition, tree mortality, and climatic criteria for the introduction or elimination of plant functional types). The effective time step of the vegetation dynamics parameterizations is one year."
3. The model Stomate (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems) simulates "processes such as photosynthesis, carbon allocation, litter decomposition, soil carbon dynamics, maintenance and growth respiration, and phenology". "Stomate essentially simulates the phenology and carbon dynamics of the terrestrial biosphere. Treating processes that can be described with a time step of one day, Stomate makes the link between the fast hydrologic and biophysical processes of Sechiba and the slow processes of vegetation dynamics described by LPJ. Innovative features of Stomate comprise a completely prognostic plant phenology (leaf out dates, maximum LAI, senescence) and plant tissue allocation including a carbohydrate reserve, and time variable photosynthetic capacity depending on leaf cohort distribution."

Depending on the pursued objective, ORCHIDEE can be run in different configurations:

1. "Hydrology only. In this case, the carbon module is entirely deactivated and leaf conductance is calculated without using any parameterizations of photosynthesis. Vegetation distribution is prescribed and LAI is either prescribed (using satellite observations) or diagnostically calculated as a function of temperature".
2. "Hydrology and photosynthesis. In this case, the parameterizations of photosynthesis and stomatal conductance are activated, but vegetation distribution is prescribed and LAI is either prescribed or diagnosed as a function of temperature."
3. "Hydrology and carbon cycle with static vegetation. In this case, the carbon cycle is fully activated. Soil, litter and vegetation carbon pools (including leaf mass and thus LAI) are prognostically calculated as a function of dynamic carbon allocation. However, LPJ is de-activated; instead, the vegetation distribution is prescribed."
4. "Hydrology and carbon cycle with dynamic vegetation. In this case, all three submodels are fully activated and the model makes no use of satellite input data that would force the vegetation distribution, so that vegetation cover, with its seasonal and interannual variability and dynamics, is entirely simulated by the model."

B5722- Model Workings

1. It is built on the concept of plant functional types (PFT) to describe vegetation distribution
2. Distinguishes 12 PFTs (10 natural and 2 agricultural) that can coexist in each grid element
3. Grasses cannot grow below trees (as in MAPSS) to simplify several parameterizations (photosynthesis, transpiration and light competition)
4. Carbon dynamics is simulated as the exchange of carbon between the atmosphere and eight biomass pools in soil and plants
5. Turnover is simulated depending on temperature, humidity and quality
6. Nitrogen is implicitly represented in carbon and photosynthesis parameters
7. Natural disturbances included are fires and herbivory
8. The state of vegetation (for hydrology module) is identified by surface roughness and albedo by averaging PFTs properties
9. Stomatal conductance and photosynthesis are linked in the carbon module and used in for transpiration in the hydrology module

B6- Comparing the water budget of grasslands and eucalypt plantations in Congo

Annex 5 lists the main experiments achieved in the whole eucalypt plantation (around 40 000 ha near Pointe-Noire, Congo). Annex 6 sums up all the models presented above, with their required input parameters, and available or not available alternatives for running them at the scale:
-Required parameters:1 is for required; "No" is for insisting that it is not required)
-Available solutions: "1" is for available per plot or total area, "C" is for computable per plot; "E" is for estimable per plot).
Specific comments are included in the excel version in order to indicate possible methods for "C" and "E", according to the specific model. When alternatives are possible between different solutions (e.g. radiation can be obtained from direct

measurement or from computations using sunshine duration), letters a, b, c, are proposed per category of parameters (e.g. 1a is an alternative of required parameter in the category of climate parameters).
From Annex 6, one can easily see at glance what are the main requirements for every model, how similar, how complex they are, how complex it would be to fulfil them.

B7- Our methodological choices and recommendations

B71- Spatialisation objective and model choice

Models are assumed to be spatialisable if their required parameters are spatialisables, or, more precisely, if the parameters to which the model is highly sensible are spatialisables, or vary little across space. An initial sensibility study will allow identifying for which parameters the models are sensitive, and which of them are spatially variable. Then comes the time to assess the spatial/temporal variability of those specific parameters, to check if it can be assessed properly with the available tools and thus if the model will be spatialisable or not.

B72- Key variables

From our own analysis or Annex 6 for specific application to the case study of the whole eucalypt total plantation, including its neighbouring grasslands, we concluded that, for the minimum, we will have to spatialise the plots according to the next physical variables:

-rainfall
-vegetation (clones of eucalyptus and grassland),
-age (for eucalyptus, time since last fire for grassland),
-planting density (for eucalypts)
(-soil physics are relatively homogeneous and could be averaged)

The key variables that will necessitate coupling with G&Y model will be:

-LAImax,
-seasonal LAI (Leaf Area Duration),
-fine root profile density,
-SOM

The relationships that we could derive from previous experimental studies and apply to the whole plantation are:

-gs = f(PAR, Ta, VPD, soil moisture)
-In= f(LAI, Height, density, Rainfall, wind)
-rmax=Tmax/ETP= f(LAI)
-r=T/ETP= f(REW)
-REWc

We assume below that the models are sensitive to all those parameters, that they are spatially/temporally variable, and that their variability can be assessed or estimated. A major assumption here is that the dendrological model eucalypt-dendro coupled to the nutrient model is able to simulate properly LAImax, seasonal LAI (LAD) and fine root density.

Below are presented some more detailed recommendations per class or parameter (according to Annex 6)

B721- Climate parameters

Only a very few weather stations are available around the plantation (including airport), which means that PET models can be used with a maximum time resolution of one day. However, it will be possible to use Turc, Priestley-Taylor, Penman or reference ETo (P-M) for calculating potential evapo-transpiration, alternatively.
A major limitation is that we have few spatialised data for rainfall and radiation. We suggest to seek for interpolations models available in the literature (WorldClim ?)

B722- Interception, throughfall, stemflow

For all models it is necessary to spatialise rainfall interception, according to LAI, height, i.e. clone, age and density. We suggest developing empirical relationships (e.g. Laclau *et al.* 2000)

B723- Transpiration Parameters (stomatal conductance, T, E/ETP)

We suggest to use data available from 3 eddy covariance experimentations (P.I. Yann Nouvellon, Agnes de Grandcourt) in order to calibrate Jarvis (1976) models of stomatal (or canopy) conductance as a function of PAR, Ta, VPD, soil water. This is because a stomatal conductance submodel is required by many models, such as Big-leaf (Penman-Monteith), Shuttleworth and Wallace, Sun-shade, Multilayer, 3D, MAPPS and Orchidee
BILJOU is interestingly the only model which does not require a stomatal conductance submodel. However, in the case of BILJOU, it is recommended not to use the default REWc and relationship between T/ETP = f(PET), but rather calibrated relationships for the two clones, trying to incorporate age effects.

B724- Canopy Parameters (LAI, K, IPAR etc)

LAI is the key parameter which requires to be spatialised. We'll have to consider at least LAI of 2 clones of eucalypt of major importance in the forest, according to age and density.

Alternative 1: Dynamic vegetation model. We'll have to consider at least LAImax and to relate LAImax with age, clone, outputs of the G&Y model. We'll have to consider seasonal variations of LAI, or Leaf Area Duration model, i.e. develop a semi-mecanistic model for budburst, leaf area duration, leaf senescence, leaf shedding: we propose to get inspired from the solutions used for this purpose in the ORCHIDEE model.

Alternative 2: Static vegetation model. We can use remote sensing in order to calibrate the relationship between NDVI and fAPAR. fAPAR can be estimated from LAI given by the G&Y model, after inversion of the Beer's law, with calibrated values of the extinction coefficient and clumping factor.

B725- Roots (in particular fine root distribution in the soil)

The profile distribution of fine root biomass is of major importance for many models, in order to couple transpiration of plants and evaporation of the top soil with defined layers of water-uptake in the soil.
For our case-study, it is thus necessary to spacialize fine root distribution, according to clone and age.

B726- Soil Physics

For all models, it is necessary to spatialise soil physical characteristics in order to estimate EW, wilting point, field capacity. But interestingly, it is not necessary to have monitorings of soil humidity or potential, unless for calibration purposes.
Spatialisation of soil physics will most likely not be possible (in this case, one can use default values obtained within a few plots), or eventually using empirical relationships if they can be developed.
Slope might be important when affecting runoff, but neglectable in most cases
SOM is important for computing EW but might not vary so much at the spatial scale (SOM could be simulated from the G&Y model)

B73- Hierarchic modelling, cross-validation and time-step of models

It is much likely that models chosen for spatialising water balance of growing vegetation (dynamic modelling) will remain simple and balanced with regard to their climate, soil and plant sub-modules. In the following we will refer to "simple models for dynamic spatialisation".
It does not appear realistic to run them at hourly or semi-hourly time step, thus the minimum time step will be the month.
We propose:

-to calibrate and validate the reference models (e.g. Canoak or Hydrus) using field measured data, on an hourly or semi-hourly time step
-to calibrate and validate the simple models for dynamic spatialisation using measured values as much as possible, on a daily time step
-when it is not possible (data missing), to cross-validate them with reference models (e.g. Canoak or Hydrus) on a daily time-step.

Hence this hierarchical modelling approach will allow checking the reliability of the simple models for dynamic spatialisation, before spatialising them.

B8- Conclusions

Annex 4 and Annex 6 allow listing the number of required parameters per model, and checking their flexibility for spatialisation or for connections with C and nutrient modules

In terms of chosing a SVAT model for H_2O spatialisation purposes, without connecting with C and nutrient modules:
-BILJOU (Granier et al., 1999) combines many simplifications and advantages that would make it suitable for the spatialisation purpose. But it would gain from Leaf Area Duration sub-models developed in ORCHIDEE. Although BILJOU has no stomatal model, it is not likely that the default relationships between ET and PET, LAI and REW could be used without calibration. However, BILJOU would be directly compliant with the outputs of the G&Y model, would use their simulated LAI as an input and would yield the water-balance as a final product
-Big-leaf, Sunshade, CASTANEA and ORCHIDEE-hydrology models could also be spatialisable, but would require a stomatal sub-model and the benefit is not obvious.
-Hydrus-1D would be barely spatialisable, or would require huge efforts for spatialising soil water conductivity, root distribution and to connect with equivalent level of precision for the plant compartment.
-Multilayer would be barely spatialisable, due to non availability of many parameters on a spatial basis
-3D models are clearly not spatialisable.
-PASTIS, not spatialisable due to increased number of parameters that cannot be spatialised.

In terms of choosing a model which would be spatialisable and compliant with C and nutrient modules:
-BILJOU has no embedded C module, but it could be rather easily created, through water-use efficiency for instance. The derived photosynthesis (GPP) could be alternatively used as a final product (such as water balance), or else re-injected a growth+respiration+allocation model (NPP +Ra model). But in the latter case, it might be preferable to chose a ready-made model, such as CASTANEA or ORCHIDEE.
-Big-leaf, Sunshade, but mainly for computing GPP fluxes coupled with ETR
-CASTANEA and ORCHIDEE would probably be suitable for coupling with a NPP+Ra model

We propose a hierarchical modelling approach, with different steps of validation in the next future and in order to match the goals of the project:
1/ to calibrate/validate a few reference models (e.g. Canoak, Hydrus) at the plot level, using eddy-covariance +soil water experiments (e.g. Kondi, Hinda, Kissoko, Tchizalamou experiments) in different situations, (e.g. Hinda for calibration and Kissoko for validation) or else 2 different years on one site.
2/ to build a soil water model, the parameters of which should be spatialisable (most likely a functional bucket model) for eucalypt and for grassland
3/ to couple the soil and plant models into a "simple models for dynamic spatialisation": e.g. BILJOU or modified BILJOU
4/ to calibrate the simple model with field data, or else to cross-calibrate with the reference models when those data are not available
5/ To collect the spatialised data required for the selected model
6/ To simulate for the whole plantation using solely the "simple models for dynamic spatialisation"

A major limitation for the last step is the fact that we have no data for validation at the whole plantation level, such as catchment streamflow data, meaning that we have no absolute reference for comparing the outputs. So conclusions of the study might be restricted to feasibility, labour-efficiency and qualitative comparisons, with validations only at the plot level. However, the hierarchical modelling approach is expected to combine direct validations, and cross-validations, for a wide range of plot situations.

C - NUTRIENT BUDGETS IN FOREST ECOSYSTEMS

A general feature for plantation forests is that they are installed on soils with low agronomic potentialities and there is a growing concern about their sustainability in a context of enhanced productivity resulting from genetic improvement and more intensive management. Maintaining both, the soil capacity for production and the quality of the environment are central goals for sustainable forest management (Nambiar and Brown, 1997). The problem of maintaining forest soil fertility could theoretically be solved by using fertilizers as it has been done in agriculture. For obvious economic reasons, but also for ecological and environmental reasons, the systematic use of fertilizers is neither possible nor desirable: low production sites have their own ecological richness, and it is not desirable to make all environments uniform. A better understanding of ecosystem functioning is necessary to carry out an ecological intensification of forest management relying more efficiently on ecological processes to sustain the forest productivity.

The objective of the present chapter is to give an overview of the methods that can be used to study the effects of silvicultural practices on long-term nutrient availability in forest soils.

C1 - The biogeochemical cycles of nutrients

The production and the sustainability of forest ecosystems lies on a set of complex processes interacting called 'biogeochemical cycles'. These cycles tend to optimize the limited pools of bioavailable nutrients. It was defined by Duvigneaud (1985) as the permanent circulation of nutrients between the compartments of the system. It makes possible an efficient recycling of nutrients by vegetal species. At the scale of the ecosystem, the biogeochemical cycle includes 3 embedded cycles that are inter-dependent (Switzer and Nelson, 1972):

- ***The biological cycle***, often mixed up with biogeochemical cycle, represents the circulation of nutrients between the plants and the soil layers explored by roots.
- ***The biogeochemical cycle*** represents the retranslocations of nutrients within-plants throughout their development,
- ***The geological cycle*** (or geochemical) represents the inputs of nutrients in the ecosystem (atmospheric deposits, nutrient release by soil weathering, fertilization,…) and the outputs (biomass removal, deep drainage, run off,…).

The quantification of the main fluxes of these cycles requires in particular (Ranger *et al.*, 2002; Laclau *et al.*, 2005): i) a continuous monitoring of the chemical composition of solutions throughout their transfer in the ecosystem, ii) a water transfer model (see section B of the present document) to estimate water drainage at the depth where lysimeters are installed in the soil, iii) a quantification of nutrients contained in litter fall, iv) nutrient released by forest floor decomposition, and v) the dynamics of nutrient accumulation in trees. The quantification of nutrient fluxes and their dynamics over several years provide relevant information on the mineral functioning of forest stands as well as their ecological impacts on soil fertility and water resources.

C2 - Methods to assess the long-term changes in soil fertility

Soil fertility is the sum of physical, chemical and biological factors characterizing the capacity for biomass production, but only chemical soil fertility will be considered here. Soil physical properties can be greatly modified by management practices following logging in plantation forests (e.g. Rab, 1996; Ampoorter *et al.*, 2007), but most of forest managers take care of soil physical properties. Soil fertility decline in the tropics is mainly a result of nutrient depletion and imbalances that may account for low yields of crops. Secondary effects are the degradation in soil physical properties (e.g. structural degradation from resulting mechanical stress, which is more likely because of soil organic C decline) and the increased susceptibility to pests and diseases and competitive loss to weeds (Hartemink, 2003). Soil fertility has two components: the short-term component and the medium- to long-term component (figure 1, Ranger and Turpault, 1999). The short-term component is related to the present pool of nutrients available for plant nutrition. It is usually characterized by soil analysis, but it remains a potential which is used differently by different tree species. Moreover, the dynamic equilibrium characterizing medium- and long-term fertility is far more interesting than the current soil fertility, but far more difficult to investigate. It is usually described in the biogeochemical cycle of nutrients characterized by a set of mechanisms which together lead to the conservation of the limited pool of available nutrients for tree nutrition. The cycle is open and elements can enter (atmospheric deposits, mineral weathering, biological fixation, fertilizer inputs) or leave it (losses associated with deep drainage and biomass harvesting). The cycle tends to optimize the use of available resources for vegetation, which only represent a small part of the total nutrient reserves of the ecosystem in most soils under temperate climates (e.g. Fitcher *et al.*, 1998; Ezzaim *et al.*, 1999). By contrast, the potential of nutrient release by weathering in tropical soils can be very low and the major part of nutrients can be retained in the standing biomass and the forest floor (Fisher and Binkley, 2000; Nambiar *et al.*, 2004).

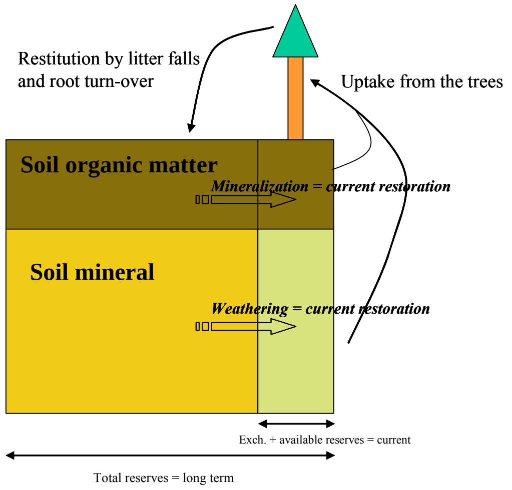


Figure 7 : Soil chemical fertility is based on a small amount of nutrient circulating rapidly in the ecosystem. Nutrient uptake by trees in native forest ecosystems come from two major pools: i) a pool issued from the mineralization of the soil organic matter restored by litter fall and root turnover; and ii) a pool issued from weathering of soil minerals. The partitioning of theses fluxes is site-dependant. In most of tropical soils, the amounts of nutrients released by weathering are negligible and the long term soil fertility is mainly a result of atmospheric inputs and N_2 fixation in natural ecosystems, and fertilization in crops and forest plantations.

C21 - Conceptual model

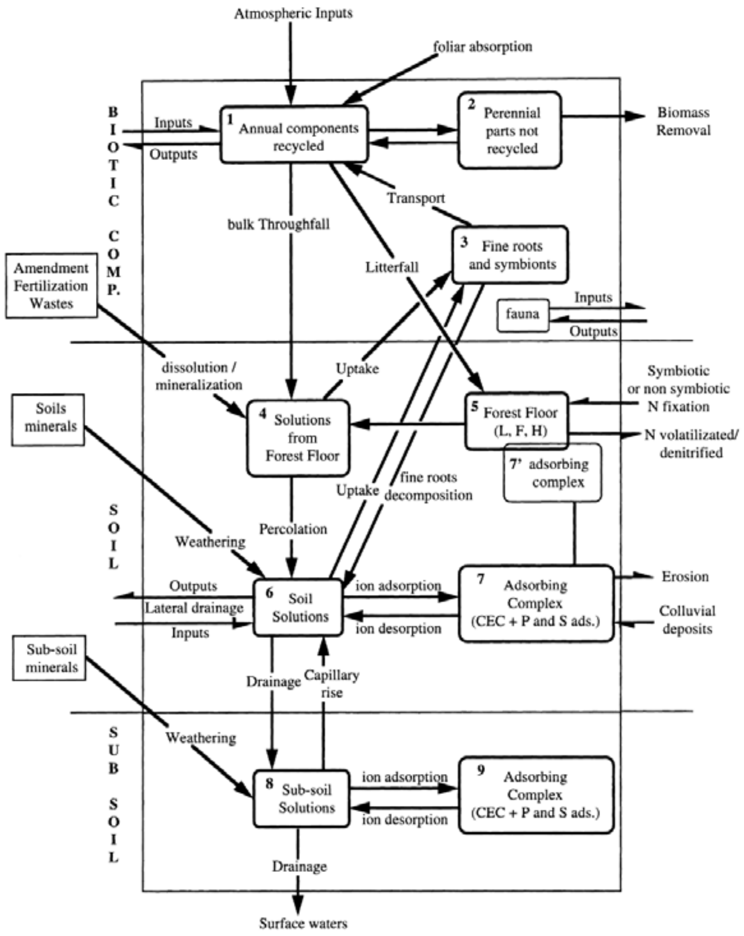


Figure 8: Conceptual model for the description of the biogeochemical cycle of nutrients.

A conceptual model describing the main compartments and fluxes in the ecosystem can be used. The principle is to decompose the ecosystem in compartments with a relatively homogenous behaviour and to quantify the fluxes between these compartments. This method make it possible to: (i) identify all the fluxes entering and leaving a compartment, (ii) calculate several fluxes impossible to measure directly, such as the uptake of nutrients by vegetation, and (iii) assess input-output budgets at a specific scale (Figure 2). The sustainability of an ecosystem is associated with stability of the biogeochemical cycle and with balanced nutrient budgets, at least in the mid-term. This does not mean that production of a species on a site is maximum, but that it is optimal according to the constraints of the environment and to the potentiality of the species to explore them (Ranger and Turpault, 1999). This point is of major importance for CDM projects because maintaining soil quality is important for many functions (production and therefore carbon sequestration; ecology (reserve of soil biodiversity); environment (sustainability, water and air quality) and soil is a non renewable and a relatively fragile resource. Consequently, inadequate forest management could lead to rapid soil degradation.

C22 - Input-output budgets of nutrients

The input-output nutrient budget is the simple algebraic balance between inputs and outputs of an ecosystem. Fluxes must be integrated over a specified time. A budget can be calculated on both total or available reserves. Information is far more relevant in the later case, especially for plant nutrition purposes but far most difficult to assesss.

Spatial scales have to be defined with precision because: (i) the mechanisms of soil function are scale-dependent, and (ii) information from nutrient budgets is closely related to the scale of investigation. The advantages and limits of each spatial scale (namely forest plot or catchment) are discussed by Ranger and Turpault (1999). We will present here studies at the forest plot scale, which are the most relevant to investigate the mechanisms involved in the long-term impact of forest management practices on soil fertility.

The equation of a budget at a certain scale is directly derived from the conceptual model presented in Figure 1. A simplification was made by considering that all available soil elements belong to the same compartment whether they were in the liquid or in the solid phase, as if calculations were made on dry soil. Formulas for calculating budgets are presented for the more general cases but, fortunately, simplifications can usually be made.

For the forest plot:

ΔBS = inputs (AD + FA + Sf + NSf + W + Lin + Cr + Bi + Ai) – outputs (BR + Dr + LL + NgL + Bl)

where ΔBS (bioavailable stock) is the exchangeable nutrient cations + organically bound nutrients + P and S adsorbed on the solid phase, AD the atmospheric deposition, FA the foliar absorption, Sf the symbiotic fixation of N, NSf the nonsymbiotic fixation of N,W the weathering, Lin the lateral inputs composed of lateral drainage + colluvium, Cr the capillary rise, Bi the biological input from the plot (flora, fauna), Ai the anthropogenic inputs (fertilization, wastes, etc.), BR the nutrient associated with biomass removal, Dr the drainage losses during the rotation and stand regeneration phase composed of liquid losses + solid losses, LL the lateral losses composed of liquid losses + solid losses, NgL the gaseous losses of N by denitrification and volatilization, and Bl the biological losses of the plot (flora, fauna).

C23 - Spatial and temporal scales

The budgets can also be established at different temporal scales that provide complementary information. They are highly dependant on the stage of development considered and a comparison of situations is only possible for the same stage of stand development. Budgets have to be calculated over many years in order to eliminate inter-year variability. A five-year monitoring seems to be a minimum duration when looking at the few sites monitored in the long term (Driscoll *et al.*, 1989; Ranger *et al.*, 2002). Seasonal budgets in deciduous forests are useful to assess the effect of tree nutrition on the main fluxes of nutrients entering or leaving the ecosystem, since the lack of leaves and the interruption of transpiration during winter provide qualitative information on the effects of foliar leaching and root uptake on the chemistry of solutions. An assessment of the nutrient fluxes at various stages of development representing the whole rotation is relevant both, for studying the dynamics of processes during stand development and for calculating nutrient budgets assessing the impact of management. The longevity of forest trees in temperate regions make it necessary to use a chronosequence approach, even if the underlying hypotheses (namely representing the different stages of development of a single stand: same genetic material, soil, climate, site history and silviculture) are never completely satisfied (Cole and Van Miegroet, 1989). The previous land use of each stand in the chronosequence has to be carefully checked because it can strongly affect the present behaviour of the ecosystem (Ranger *et al.*, 2002; Dambrine *et al.* 2007). More accurate input-output budgets for the whole rotation can be established in fast growing tropical plantations because the nutrient fluxes can be measured over a complete rotation in the same stand (Dambrine *et al.*, 2000; Toit and Scholes, 2002; Laclau *et al.*, 2005).

Sampling in each study stand has to be designed to assess the spatial and temporal variability in nutrient fluxes which are usually high, even in mono-specific forest plantations (Ranger *et al.*, 2002; Asano *et al.*, 2006). An extensive literature is available to establish reliable experimental designs making it possible to assess with a sufficient accuracy the main fluxes (i.e. atmospheric inputs, nutrients associated with biomass removal and losses by deep drainage) and then the input-output budgets.

C3 - Quantification of the main fluxes of nutrient budgets

Nutrient fluxes have been quantified for several decades in forest ecosystems and an extensive literature is available. For nutrient budgets, a simplification of the complete conceptual model can be performed (Figure 9). Inputs are reduced to atmospheric deposits and weathering, whereas outputs are nutrients losses by harvesting and by deep drainage. Of course this view is a simplification to be applied at a given scale (stand, watershed, etc..) and it is necessary to verify if some other fluxes can be significant in an ecosystem eg. Fertilization, N fixation, run-off etc… For this report, we will however concentrate on these four main fluxes and a brief synthesis of the methods currently used to estimate them is presented here.

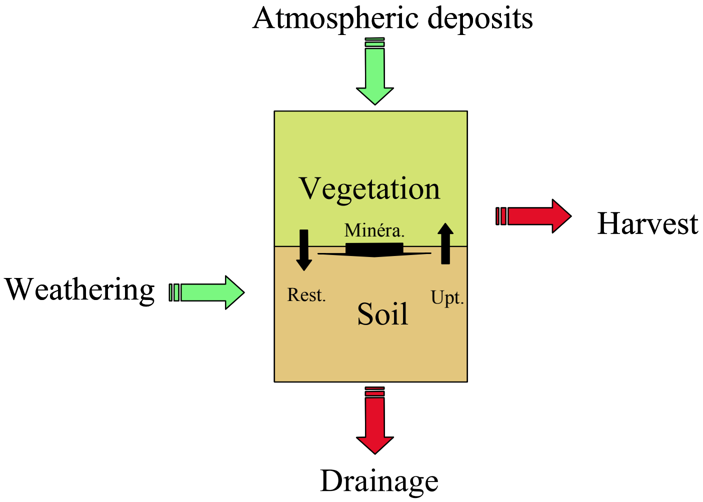


Figure 9: Main fluxes to be quantified for nutrient budgets in natural forest ecosystems.

C31 - Atmospheric deposits

Atmospheric deposition is a major input of nutrient in natural ecosystems. Total atmospheric depositions to forest ecosystems (*TD*) are separated into wet depositions (*WD*), dry depositions (*DD*), and cloud and fog droplet deposition (Ulrich, 1983). Fog droplet deposition as often considered negligible, except in specific areas with frequent fog (altitude forests for example) , *TD* for the chemical element *x* can be estimated by the equation:

$$TD_x = WD_x + DD_x \quad \textbf{Eq. 70}$$

An accurate estimation of dry deposition is difficult as a result of high spatial and temporal variability in air chemistry and large interactions between canopies and aerosol and gas depositions (Lindberg *et al.*, 1986; Lovett *et al.*, 1993; Levia Jr *et al.*, 2006). Wet deposition can be quantified with a wet-only rainwater collector designed to avoid the collection of dry depositions (area of collection opened automatically over the rainfall events). Different methodologies can be used to estimate dry depositions. Some inert surfaces can provide useful estimates of particle deposition; however, these may or may not be related to the flux to natural surfaces (Lindberg and Lovett, 1985). The critical problem is relating the deposition on inert surfaces with deposition on tree foliage. Indeed, dry deposition rates to leaves are subject to large uncertainties. Dry deposition can also be estimated from measured air concentrations, particle size measurements and parameterised dry deposition velocities (Sievering *et al.*, 2001). Gaseous uptake through stomata and fog deposition fluxes can be estimated from specific models and air concentration monitoring (Draaijer and Erisman, 1995). However, the high spatial and temporal variability in gas and aerosol depositions on forest canopies also leads to large uncertainties in the estimation of dry deposition with the latter methodology.

A classical method used in biogeochemical studies estimates roughly *TD* from bulk depositions in an open area and nutrient fluxes in throughfall and stemflow solutions. A specific device combining an open gauge and a filter gauge above the canopy (or in a nearby clearing) with samples collected on an event basis makes it possible to estimate dry deposition from the following set of equations (Moreno *et al.*, 2001):

$$NE_X = TS_X - BD_X \qquad \textbf{Eq. 71}$$

where TS_x is the flux through the canopy of the element x, considered to be total throughfall plus stemflow, NE_x is the net deposition of the element x, and BD_x is the bulk deposition of the element x in the open gauge.
Net deposition is regressed against the gain in the deposition resulting from aerosol deposition on the filter gauge. This method requires a constant interval of sampling time. To fulfill this requisite, each data item can be divided by the number of days elapsed since the previous rainy episode. This regression results in an intercept term representing the mean daily rate of canopy exchange. When the intercept term is positive, it represents the rate of canopy leaching and when it is negative, it can be understood as the rate of canopy uptake. Thus, DD can be calculated by the equation:

$$DD_X = TS_X - WD_X + Ce_X \qquad \textbf{Eq. 72}$$

where Ce_X is the canopy exchange processes.

When solutions are not collected on an event basis, the most common method consider Na^+ as a tracer, assuming that *Ce* are negligible for this element compared with *DD* (Parker, 1983). This hypothesis is commonly accepted in coastal area but should be checked inland when the depositions of marine aerosols are low. Dry deposition of Na^+ can be considered as *TS – BD*. For example, in the *Eucalyptus* stand of Pointe-Noire (Atlantic coast), *DD* for the element *x* was then calculated from the equation (Laclau *et al.*, 2005):

$$DD_X = \left(\frac{TS - WD}{WD}\right)_{Na} \times WD_X \qquad \textbf{Eq. 73}$$

C32 - Nutrient removal at the harvest

The methodology used to assess the biomass of tree components has been described in § A2.2. Nutrient contents in tree compartments are quantified together with the biomass sampling operations. The samples are dried at 65°C to prevent nitrogen volatilization and to estimate the dry matter of each sampled tree. Then they are ground and homogenized for chemical analyses. The methodology used to assess stand biomass from regressions and inventories applies for nutrient contents in each tree component. The inter-tree variability in biomass is usually much higher for nutrient contents as a result of the cumulated variability in biomass and nutrient concentrations. Genetic and environmental factors are likely to account for a large range in nutrient concentrations among trees. However, a bias resulting from the low representativeness of samples for the tree components or analytical errors are frequent. The assessment of nutrient content in forest stands requires a great care throughout the whole study, from field measurements to sample representatively tree components without pollution of the samples, to laboratory determinations and statistical analysis.

C33 – Biological fixation of atmospheric N_2

Several limitations occur for all the methods used to assess N_2 atmospheric fixation in field experiments (Boddey *et al.*, 2000). The most common methods are based on ^{15}N natural abundance and ^{15}N dilution. However, qualitative assessments of N_2 fixation by the accretion method (comparing the N content in N-fixing and non-fixing stands) or ARA measurements are useful to check the consistency with the order of magnitude of estimations made by isotopic methods (Bouillet *et al.*, 2007; Forrester *et al.*, 2007).

C331- ^{15}N natural abundance method

The percentage of N derived from atmospheric N_2 (%Ndfa) can be calculated according to the following equation (Shearer and Khol, 1986):

$$\%Ndfa = 100\ (\delta^{15}N_{REF} - \delta^{15}N_F) / (\delta^{15}N_{REF} - B) \qquad \textbf{Eq. 74}$$

where $\delta^{15}N_{species} = [(^{15}N/^{14}N)_{species} - (^{15}N/^{14}N)_{air}\ ] / (^{15}N/^{14}N)_{air}$, $\delta^{15}N_{REF}$ is the relative natural isotopic abundance of the reference non-fixing tree, $\delta^{15}N_F$ the relative isotopic abundance of the N-fixing species, and *B* the relative isotopic abundance of the same species growing on N-free medium.

Non-fixing reference plants likely to explore the same soil layers, and therefore to utilise the same pool of soil N, as the N-fixing species have to be selected (Galiana *et al.*, 2002). However, the mycorrhizal status of a given species has an influence on its access to different soil nitrogen sources and the fractionation associated with N uptake (Shearer and Kohl, 1986; Spriggs *et al.*, 2003). Högberg (1990) showed that tree species associated with ectomycorrhiza, (ECM) generally had a higher foliar $\delta^{15}N$ than species associated with endomycorrhiza (VAM). Low values of $\delta^{15}N_{REF}$, are likely to prevent efficient use of the ^{15}N natural abundance method (Domergues *et al.*, 1999). Högberg (1997) suggested that the mean ^{15}N abundance of reference species should be at least 5‰ higher than the *B* value to estimate N fixation by that method.

C332-^{15}N dilution method

This method requires an uniform application of ^{15}N-enriched fertilizer to the soil. Representative samples of the different biomass components (leaf, branch, stemwood, stembark, stump and coarse root) have to be collected for N-fixing trees and Non-fixing reference plants, as for the ^{15}N natural abundance method. For a given tree component %Ndfa is then calculated from the following equation (Fried and Middelboe, 1977):

$$\%Ndfa = 100\ [1 - (AE_F) / AE_{REF})] \qquad \textbf{Eq. 75}$$

where $AE = {}^{15}N*100/({}^{15}N + {}^{14}N) - 0.003663$, *AE* is the percentage atom excess of the N-fixing species and AE_{REF} is the percentage atom excess of the reference species. A weighted average AE for the standing trees can be estimated from the equation. The rate of N_2 fixation is then considered unchanged before and after soil labelling. The method is only valid if the percentage of N derived from atmospheric fixation is similar after soil labelling and over the period from planting to the date of ^{15}N-enriched fertilizer application. One way of avoiding bias is to apply fertilizer with a high $^{15}N/^{14}N$ ratio and to label the soil at young stand stages (Bouillet *et al.*, 2007).

High rates of ^{15}N enrichment (5 to 10% ^{15}N atom excess) are usually used in ^{15}N dilution experiments (Liyanage *et al.*, 1994; Parrota *et al.*, 1994a,b; Guinto *et al.*, 2000). High AE_{Ffinal} and $AE_{REFfinal}$ are then observed, and can be measured with a low sensitivity mass spectrometer. However, field experiments with fast growing tree species require the application of labelled fertilizer on dozens of square metres and ^{15}N enrichment is then limited by the cost of the application.

Several limitations appeared in this study for using the ^{15}N natural abundance and ^{15}N dilution methods to estimate N_2 fixation by *A. mangium*:

- %Ndfa is highly influenced by the *B* value considered for the N-fixing species and different strains might affect the ^{15}N abundance of legume shoot tissues (Boddey *et al.*, 2000).
- Possible variations in N_2 fixation and ^{15}N discrimination are likely to occur over the year (Watt *et al.*, 2003), which might bias the %Ndfa estimations.
- Variations in nitrate and ammonium availability is likely to occur with soil depth, leading to differences in $\delta^{15}N$ of the mineral nitrogen taken up by the N-fixing species and the reference species, as NH_4^+ is less depleted in ^{15}N than NO_3^- (Boddey *et al.*, 2000). Moreover, a different proportion of N derived from the ^{15}N-enriched fertilizer might be taken up by the N-fixing species and the reference species if the fine root densities of the two species differ in the upper soil layer.
- Fine root mortality of the N-fixing species is a major process in incorporating N in the soil but this flux is badly estimated in forest ecosystems (Gill and Jackson, 2000; Hendricks *et al.*, 2006).

There are few references for field estimates of atmospheric N_2 fixation by N fixing trees (Bouillet *et al.*, 2007). Marked variability in %Ndfa and fixed N is observed among species or sometimes for a given species. That finding may be explained by the limitation in using ^{15}N isotopic methods previously pointed out. Moreover, only leaves have been sampled in most of these studies and none of them have tested both natural abundance and dilution methods. Further studies need to be carried out to obtain reliable figures for N_2 fixation, which are essential for interpreting inter-specific interactions in mixed plantations with N fixing trees.

C34 - Weathering of soil minerals

Soil minerals are external to the available soil nutrient reservoir where trees take up their nutrients. Even if weathering of minerals release low amounts of nutrients in most of the soils, this process plays an important role for the sustainability of temperate forests managed in long rotations (Ranger and Turpault, 1999). Weathering is a natural process resulting from the changes of thermodynamic condition at the soil surface (if compared to what prevailed for mineral formation) and this flux buffers the protons flux from both natural and anthropogenic origins. Main factors influencing weathering rates are: the climate (the rate increases with rainfall and temperature); the minerals present in the soil, for example Goldich (1933) describes the sensitivity of minerals to weathering (quartz<felspaths<white micas<black micas<amphiboles<calcite etc…); the type of vegetation and of micro-organisms associated to the vegetation have large influence on the weathering rate by the humus and the rhizosphere effects. Mineralogy of the different particle size fractions and mineral bearing nutrients can be quantified according to Fichter *et al.* (1998) using identification of mineral by X ray diffraction, total and selective chemical analysis, thermogravimetric analysis and normative calculation. Hypotheses for their dissolution kinetics can be made according to literature (Sverdrup, 1990). The geochemical Profile model developed by Sverdrup and Warvfinge (1988) can be used to estimate the magnitude of this flux (Ezzaim, 1997).

C35 - Losses by deep drainage

The most suitable method to estimate nutrient fluxes in gravitational solutions at various depths in the soil requires: i) sampling an aliquot of solutions to measure nutrient concentrations (from a relevant lysimetry design) and ii) predicting the drainage fluxes from hydrological model (*e.g.* Marques *et al.*, 1997; Qualls *et al.*, 2000; Ranger *et al.*, 2007). Nutrient fluxes are then calculated multiplying the water fluxes at each soil depth by the mean concentration of nutrients in gravitational solutions. The methodology used to estimate water fluxes in forest soils from water transfer models was presented in section B.

The chemistry of soil solutions is highly dependant on the lysimeters used since the residence times of solutions in soils are different according to the type of solution sampled by the lysimeters. Whereas zero-tension lysimeters sample free water, tension lysimeters sample low energy capillary waters more influenced by tree uptake, root exudates and biological processes. Centrifugation of soil samples make it possible to study high energy capillary solutions, more representative of the solutions where tree roots take up nutrients (Ranger *et al.*, 2001, Jaffrain, 2006).

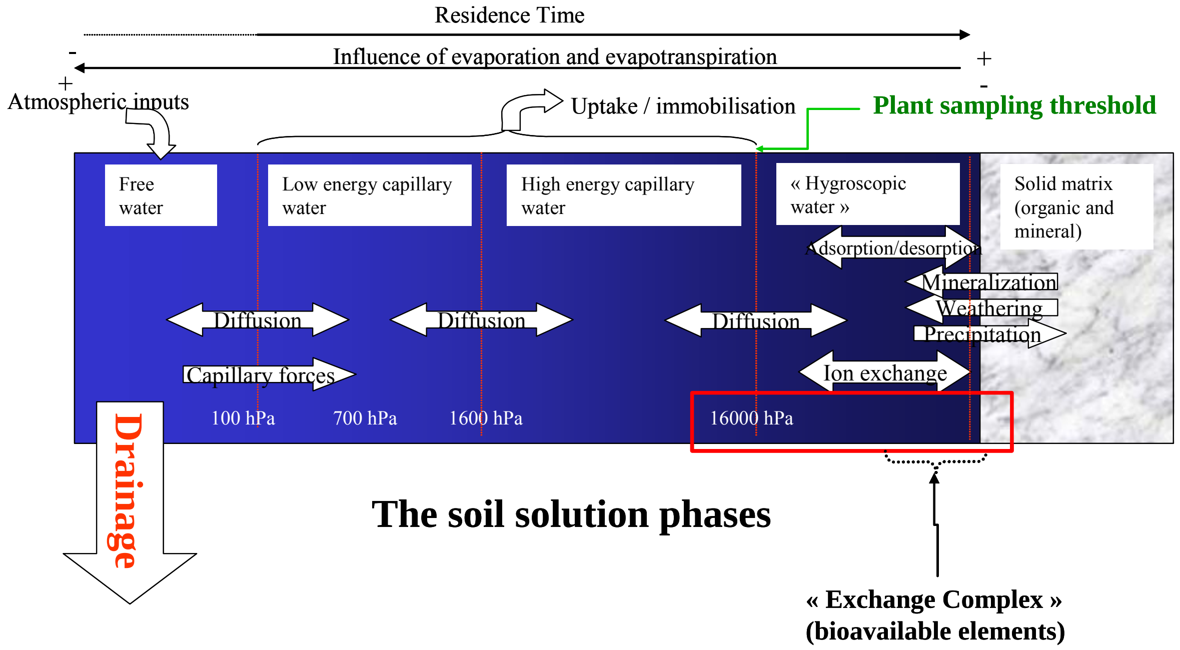
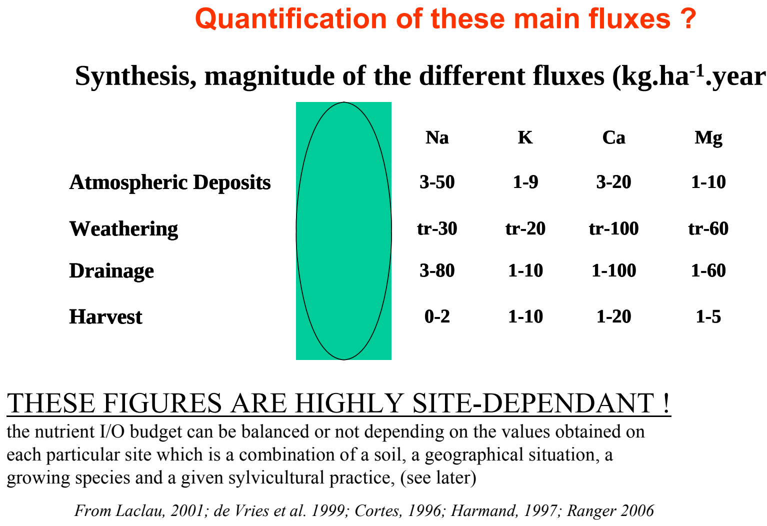


Figure 10: Ionic exchanges among the different soil solution phases (from Jaffrain, 2006).

The concentrations of nutrients used to calculate the fluxes lost by deep drainage in forest soils must be determined in gravitational solutions collected by zero-tension plate lysimeters (ZTL). However, in soils without preferential drainage ways ZTL can be unable to collect the amounts of gravitational solution necessary for chemical analysis, in deep soil layers. In that case, soil solutions collected by tension lysimeters can be used but a low suction should be applied (about -10 kPa). Soil solutions are frequently collected by tension-cup ceramic lysimeters in forest soil but these lysimeters sample capillary solutions, closer to the nutritive solution of the vegetation (Ranger *et al.*, 2007).
Solutions can be collected downhill in pits where they are protected from light and extreme variations in temperature. The number of replicates of lysimeters must be defined according to the spatial variability of soil solution chemistry in the study site.

C36 – Order of magnitude of the main fluxes

A great variability in nutrient fluxes occurs in forest ecosystems according both to the characteristics of the stands (in particular productivity and nutrient use efficiency) and to site conditions (soil mineralogy, amount and distribution of rainfall, aerosol contents, etc…).



Quantification of these main fluxes ?

Synthesis, magnitude of the different fluxes (kg.ha^{-1}.years^{-1})

	Na	K	Ca	Mg
Atmospheric Deposits	3-50	1-9	3-20	1-10
Weathering	tr-30	tr-20	tr-100	tr-60
Drainage	3-80	1-10	1-100	1-60
Harvest	0-2	1-10	1-20	1-5

THESE FIGURES ARE HIGHLY SITE-DEPENDANT !

the nutrient I/O budget can be balanced or not depending on the values obtained on each particular site which is a combination of a soil, a geographical situation, a growing species and a given sylvicultural practice, (see later)

From Laclau, 2001; de Vries et al. 1999; Cortes, 1996; Harmand, 1997; Ranger 2006

Figure 11: order of magnitude of the main fluxes in nutrient budgets established in tropical and temperate forest ecosystems.

Figure 11 points out that nutrient fluxes are highly site dependant and the main factors influencing the magnitude of the fluxes have to be studied before estimating nutrient budgets at landscape scales.

C4 - A Study Case: Influence of afforestation with Eucalypts in Congolese savannas on soil fertility

An experimental design was installed in a native savanna and in an adjacent 6-year-old *Eucalyptus* plantation to assess the effects of afforestation on the biogeochemical cycles of nutrients in Congo. P, K, Ca and Mg budgets established over three years in savanna were roughly balanced, which was consistent with the presence of that savanna for more than 3000 years in the region indicated by previous studies (Trouvé, 1992). An input of N by biological fixation is necessary to balance the N budget in that ecosystem (Table 6). The legume species *Eriosema erici-rosenii* R.E. Fries (Papilionoideae) found in all the savannas of the region must play an important role in the N input in this ecosystem, compensating for long-term losses. The budgets of K, Ca, Mg were also roughly balanced at the end of the *Eucalyptus* rotation (from age 6 years to age 9 years) considering the accuracy of determination of the fluxes (Laclau *et al.*, 2005). By contrast, the P budget was slightly negative and high N immobilization in stemwood led to a deficit of about 26 kg N ha^{-1} year^{-1} (Table 6).

	Savanna					***Eucalyptus* stand**				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Wet deposition	4.8	0.3	2.7	3.3	1.4	4.8	0.3	2.7	3.3	1.4
Dry deposition	0.0	0.0	0.0	0.0	0.0	6.5	0.3	3.8	4.5	1.8
Symbiotic Fixation (1)	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weathering	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Total inputs	26.4	0.3	2.8	3.3	1.4	11.4	0.6	6.8	7.8	3.2
Surface run off	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.1
Deep drainage	3.0	0.1	0.6	0.4	0.2	4.3	0.3	2.1	1.1	1.2
Immobilization (2)	-	-	-	-	-	32.7	3.7	4.8	3.9	2.5
Burning	23.4	1.5	2.4	2.6	2.9	0.0	0.0	0.0	0.0	0.0
Total outputs	26.4	1.6	3.0	3.0	3.1	37.0	4.1	7.1	5.4	3.8
Mean over 3 years	**0.0**	**-1.3**	**-0.2**	**0.3**	**-1.7**	**-25.6**	**-3.5**	**-0.3**	**2.4**	**-0.6**
Inter-annual range:										
Min	**0.0**	**-1.4**	**-0.4**	**-0.1**	**-1.8**	**-29.7**	**-3.9**	**-2.4**	**1.6**	**-0.3**
Max	**0.0**	**-1.2**	**0.0**	**0.5**	**-1.6**	**-21.6**	**-3.0**	**1.3**	**3.4**	**-0.7**

(1) Calculated to balance the nitrogen budget in the savanna, (2) Nutrient immobilization in stemwood.

Table 6 : Mean input-output fluxes of nutrients in the soil under an Eucalyptus stand (from six to nine years of age) and a native savanna (kg ha^{-1} year^{-1}).

Nutrient budgets were assessed for the whole *Eucalyptus* rotation for contrasted harvesting methods. The range of variation between the most conservative method (scenario 1) and the most costly in nutrients (scenario 4) was about 180 kg ha^{-1} for N, 25 kg ha^{-1} for P, 55 kg ha^{-1} for K and Ca, and 30 kg ha^{-1} for Mg (Figure 12).

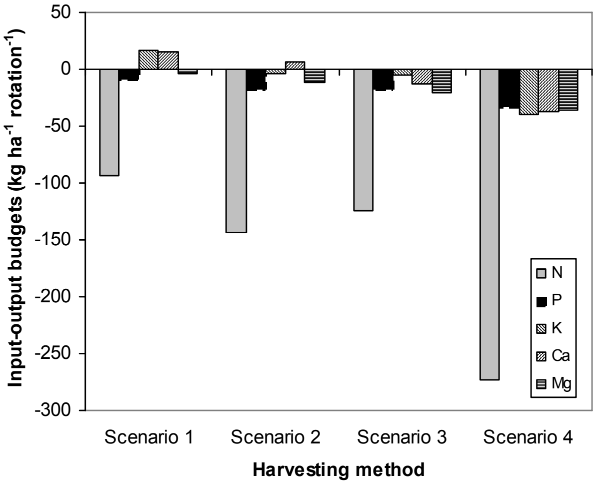


Figure 12 : Input-output budgets (kg ha^{-1}) of N, P, K, Ca and Mg for the whole Eucalyptus rotation, and for various harvesting scenarios. Scenario 1: de-barked pulpwood harvest; Scenario 2: de-barked pulpwood and firewood harvest; Scenario 3: pulpwood with bark harvest; Scenario 4: whole tree harvest. From Laclau et al. 2005.

De-barking the stems on site kept at the soil surface 31, 9, 21, 28 and 16 kg ha^{-1} of N, P, K, Ca and Mg, respectively. These values represented about 10% of the amount of N accumulated in the above-ground part of the trees at harvest, 20%

of that of P and K, and 35% of that of Ca and Mg. The removal of firewood for surrounding populations in Congo (scenario 2) led to further losses of 50, 8, 20, 9 and 7 kg ha^{-1} of N, P, K, Ca and Mg, respectively, relatively to the most conservative method where only de-barked pulpwood is harvested. The current silviculture in Congo led to a deficit of 144 kg ha^{-1} of N for the first rotation after afforestation. This deficit represented about 7% of the initial amount of total N in the A_1 horizon (0-50 cm) under savanna.

Even if certain fluxes were assessed with large uncertainty, input-output budgets demonstrate clearly that *Eucalyptus* plantations take advantage, during the first rotation after afforestation, of a N soil fertility inherited from the previous vegetation of savanna. Unfavorable qualitative changes add further to the quantitative deficit of the N budget: savanna organic matter is progressively replaced by *Eucalyptus* organic matter poorer in N (Trouvé *et al.*, 1994), and whose chemical composition (tannins, lignin, polyphenols) leads to a slower mineralization (Bernhard-Reversat *et al.*, 2001). For the other elements, the budgets for the whole rotation were well balanced relative to the amounts of available elements in the soil. This behavior is consistent with fertilizer field trials in this area, which show that tree responses to N inputs increase over successive rotations, whereas no response to P and K inputs is observed, even in replanted sites 20 years after savanna conversion (Bouillet *et al.*, 2004).

Low amounts of nutrients in the soils of this area (P excepted), and the high cost of fertilizer inputs make it essential to strictly limit nutrient losses throughout stand rotation. Several modifications in silvicultural practices were proposed to achieve this goal:

- *Field trials of fertilization.* The quantitative data from the budgets show that field trials should focus on N fertilization. Future plantations, with much more productive clones might lead to unbalanced budgets of K, Ca and Mg in the soils. It would then be important to check that these elements do not become limiting after several rotations.
- *Soil preparation and weed control.* Minimum cultivation is recommended to limit nutrient losses by erosion and planting must occur as quickly as possible after harvesting to reduce nutrient losses by drainage. Moreover, weed controls must be planned to take advantage of the temporary fixation of nutrients in the biomass of weeds during the early growth of the stands.
- *Harvesting method.* The effects of various harvesting scenarios on nutrient budgets were quantified. They show that current practices including de-barking on site is fundamental owing to the chemical paucity of the soil. This feature was confirmed by an experiment dealing with organic matter management in Congolese *Eucalyptus* plantations (Nzila *et al.*, 2002).
- *Fire prevention.* Nutrient budgets provide new light on the terrible effects of fires in these plantations. Large losses of N by volatilization during burning have clear negative consequences on the long-term production in this area where N is the first nutritional limiting factor. Effective fire prevention is therefore crucial for the sustainability of these plantations.
- *Introduction of a legume understorey.* Numerous studies showed that mixed plantations between *Eucalyptus* and legume species can have beneficial effects on soil N fertility (Forrester *et al.*, 2006). An understorey of *Acacia mangium* introduced in *Eucalyptus* stands exhibited a high rate of biological N_2 fixation in Congo and might be an attractive option to enhance soil fertility, through inputs of organic matter and atmospheric N (Bouillet *et al.*, 2007).

C41 – Complementary considerations for spatialising nutrient cycling in eucalypt plantations in Congo

This part of the report comes as a complement of chapters A2411 and B7 for the objective of simulating C, H_2O and Nutrient budgets after afforestation of a savanna in Congo. Among the four variables required for the nutrient budget (input: weathering and atmospheric deposits; outputs: harvesting and drainage), the following simplifications can be made in Congo:

- Release of nutrient by weathering is neglectible (Nzila *et al.*)
- Atmospheric depositions will be estimated from the relationships established between rainfall and nutrient concentrations and dry depositions from the foliar biomass of the stands and rough ratios between elements (Laclau *et al.*, 2003a).
- Because losses of nutrient by deep drainage are low in these forest plantations (Laclau *et al.*, 2003b), they will be fixed to an average value. Water and nutrients loss due to run off will be predicted from the amount of rainfall, the slope of the plot and the age of the stand.

The most important term is the nutrient losses by harvesting which depends on the whole chain of models described in A2411. For an accurate estimation of these losses, a spatialisation of the Site Index, which is the main input of the G&Y model, will be required. This will be achieved by selecting stands of contrasted site index. Trees will be measured in height and diameter. Leaves and fine roots will be collected on dominant trees to assess the current nutritional status of the trees. The specific leaf area and roots length are also calculated. Samples of soils will be collected at different depth up to 2m to assess physical (texture, bulk density) and chemical (pH, C, N, P, K, Ca, Mg, S, CEC) properties of the soils. They will be also analysed by way of NIRS techniques and if a good relationship could be found between Site Index and the spectra, we would have an easy and cheap way of assessing site index on the whole forest area.

GENERAL CONCLUSION

If there are well established methodologies for carbon budgets, this review provides a first basis of relevant alternatives for assessing the water and nutrient balance, as a complement to CDM carbon sequestration assessments. It can be used as a stand alone,

However, the following points can be highlighted so as to provide refined standards:

- Carbon: few methodological points need further clarifications:
    (i) Forest biomass data base. A large scan of available biomass equations for African species (such as the one provided by Zianis *et al.* 2005) is urgently needed for Africa so as to provide a reference document for A/R carbon projects.
    (ii) Fine root assessment – a reference method for biomass estimation is still missing (among the excavations techniques commonly used). Auger coring, monolith coring, half and full trench excavation techniques should be tested on the same sites and trees. Because such methods are tedious and costly, it is necessary to assess the accuracy of these methods in relation with the labour time and costs.
    (iii) a cost-benefit approach between Tier1, Tier 2 and Tier 3 should be proposed to help stakeholders in building their own carbon project: the main question is to quantify costs and benefits of using one or another tier level. This supposes the application of each method in a representative case of A/R project in Africa (the Congolese case study was chosen for this task)

- Water and Nutrient: this review provides a first basis for establishing standards. The discussion and methodological choices developed for the Congolese case study (parts A2411, B7 and C41) can be adapted to any ecosystems (as a function of available data and models). The work to be done in Congo includes the following aspects:
    (i) to calibrate/validate a few reference models (e.g. Canoak, Hydrus) at the plot level, using eddy-covariance + soil water experiments (e.g. Kondi, Hinda, Kissoko, Tchizalamou experiments) in different situations, (e.g. Hinda for calibration and Kissoko for validation) or else 2 different years on one site.
    (ii) to build a soil water model, the parameters of which should be spatialisable (most likely a functional bucket model) for eucalypt and for grassland
    (iii) to couple the soil and plant models into a "simple models for dynamic spatialisation": e.g. BILJOU or modified BILJOU
    (iv) to calibrate "simple models for dynamic spatialisation" with field data, or else to cross-calibrate with the reference models when those data are not available
    (v) To collect the spatialised data required for the selected model (including the determinant of soil fertility (Site Index as a function of indicators of soil functioning)
    (vi) to simulate for the whole plantation using solely the "simple models for dynamic spatialisation"

All these tasks are planned in the CarboAfrica project (WorkPackage 6 – Part A and B, see the first annual report).

ANNEX

Parameters	Method	Principle	Pros	Cons	E.g. Models and Brands
Soil Volumetric humidity	TDR (Time Domain Reflectometry)	Propagation speed of an electromagnetic impulse. Time depends much on soil water content. Has to be calibrated locally. Buriable probes or removable probes	Quick. Can be automated. Non hazardous.		Trase. Campbell. Sentek.
	FDR				Thetaprobe-Delta-T. SM 200 Delta T. Profile PR2 Delta T
	Capacitive				Echoprobe Decagon Devices
	Neutron Probe	Rapid neutrons emitted. Neutrons slowed down by H2O on their way back. Neutron count. Has to be calibrated locally.		Hazardous. Very difficult to transport and to pass borders.	Campbell Pacific nuclear Corp.
Soil Matric potential	Classic Tensiometer	range 0-1bar (for humid soils)			Soil Moisture Corporation
	Electronic tensiometer	range 0-1000 kPa (for dry soils). range -100 to +250 kPa (for wet soils)			Equitensiometer EQ2 Delta T. T range UMS
	Extraction pF	ceramic plates range 0-15bar . Cellulosic plates range 0-100 bars. Tempe: range 0-1 bar			Soil Moisture Corporation
	Hygrometric method	Potentiometer for soils and plants: range 0-40 MPa			WP4 Decagon Devices
	Resistive method	Gypse bloc	cheap	not very accurate	Soil Moisture Corporation
	Micro-Psychrometer	Thermocouple within porous cap, buried in the soil. The vapour pressure in the cap (measured) is a function of the soil water potential and of temperature. range -0.5 to -7 Mpa, plant tissue and soil.	Large range of potentials allowed. Quick	Poorly sensitive in humid soils. Expensive. Very sensitive to temperature fluctuations	PST 55 T WESCOR
Soil Penetrometry	Pocket	range 0- 5 bars			
	Static (CBR)	range 0- 667 N			
	Dynamic (TRL)				
Soil Texture	Manual sieves				
	Automatic sieves				
Soil sedimentometry	Andreasen Pipette	Manual			
	Robinson Pipette	Manual			
		Automatic			ASP 12-18 or 24
Soil Infiltrability	Surface Infiltrometry	Guelph permeameter: range 10-4 to 10-8 m s-1			Soil Moisture Corporation
		Double ring infiltrometer: range 10-4 to 10-9 m s-1			
		Minidisc infiltrometer			Decagon Devices
Water quality	Multiparameter probe	T, Conduct, O2d, pH, ORP, salt, depth, turbid., NH4+, NO3-, NaCl, Chlorophylls			YSI 6000, Cambpell

ANNEX 1: METHODS FOR MEASURING SOIL WATER

Parameters	Method	Principle	Pros	Cons	E.g. Models and Brands
Plant Hydraulic potential	Pressure chamber (Scholander)	Plant organ(leaf or axis) trapped in pressure chamber. Pressure at equilibrium of menisc=tension of water in the organ. Measurement of predawn and daily water potentials Range 0-70 bars	Large range of potentials allowed. Gives an indrect estimation of the soil water potential sensed by the plant		PMS Soil Moisture Corporation
	Temperature corrected stem hygrometer				Plant Water Status Instruments
Sapflow	Thermal Dissipative Probe	Granier (1985): Delta T between one heated and one unheated probe	Ideal for big stems. Calibration recommended.	Calibration, azimuthal and radial effects. Not if radius	TDP Dynamax. Home made probes
	Heat Balance	range stem diameter 2-125 mm	No calibration required	Expensive. Fragile	Valancogne system Dynagage (Dynamax).
	Heat Pulse				
Leaf evaporation	Porometry	range stomatal conductance 5-1200 mmol m-2 s-1 or 0.25-30 mm s-1.			AP4 Porometer Delta-T. SC1 Decagon Devices Li 1600 LiCor
	Open Systems	IRGA			Li-6400, LiCOR ADC, Walz
	Closed Systems	IRGA			Li-6200, LiCOR

ANNEX 2: METHODS FOR MEASURING PLANT WATER AND FLOW

Parameters	Method	Principle	Pros	Cons	E.g. Models and Brands
Climate		Temp, Humidity, windspeed, winddir, radiation, rainfall			Campbell Davis Delta T LiCor
Air humidity	Psychrometer	Tdry and Twet	accurate, cheap	not for very dry air	
	Hair hygrometer			to calibrate	
	Capacitive probe	condensator sensitive in frequency to RH	accurate	to calibrate	Campbell
Stand evapo-transpiration	Bowen ratio				
	Eddy-Covariance				SONICS: Gill, CSAT3, Young. IRGA: LiCor (6262, 7000, 7500), ADC, Krypton hygometer
Canopy analysis, gap-fractions, LAI	Gap fractions by PAR Rings				LAI 2000 LiCOR.
	Gap fractions by Hemispherical Photography				Hemiview Delta T
	Gap fractions densitometry				
	PAR bar				PAR analyser Decagon Devices Sunscan Delta T

ANNEX 3: METHODS FOR MEASURING CLIMATE AND STAND WATER FLOW

	Energy balance	Turc	Priestley-Taylor	Penman	ET0_ref humid grass	ETc Penman Monteith (Big-leaf)	Crop coefficient	Shuttleworth & Wallace (sparse crop)	Sun-shade	Multi-layer (Canoak)	3D-architectural	BILJOU (Granier et al., 1999)	BGC-Running	HYDRUS 1-D	PASTIS	CASTANEA	MAPPS	ORCHIDEE
Main compartment(s) modelled	Climate +plant	Climate	Climate	Climate	Climate +ref grass	Climate +plant	Balanced climate +plant+ soil	Climate +plant	Climate +plant	Climate +plant	Climate +plant	Balanced climate +plant+ soil	Balanced climate +plant+ soil	Climate +soil	Climate +soil	Balanced climate +plant+ soil	Balanced climate +plant+ soil	Balanced climate +plant+ soil
Compatible with complement H2O compartment ?	+++	+	+	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	++	+++	+++	+++
Spatializable ?	+++	+++	+++	+++	+++	++	++	++	+	+	-	++	++	-	-	+	+	+
Compliant with photosynthesis module ?	+	no	no	no	no	+	+	+	+++	+++	+++	+	+++	+	+	+++	+++	+++
Compliant with C4 photosynthesis ?[1]	-	no	no	no	no	-	-	-	-	-	-	-	-	-	-	-	-	-
Compliant with nutrient module ?	+	no	no	no	no	+	+	+	+	+	+	+	+	+++	+++	+++	+	+
Possible compar. baseline and afforestation ?	+	no	no	no	no	+	+	+	+	-	-	+	+	+	+	+	+	+

[1]: see Collatz, G. J., M. Ribas-Carbo and J. A. Berry (1992). "Coupled photosynthesis - stomatal conductance model for leaves of C4

ANNEX 4: SUMMARY OF THE CHARACTERISTICS OF THE DIFFERENT SELECTED MODELS

Identification	Name of model	Hydrus 1D
	Author	Šimůnek J., van Genuchten M. Th., Šejna M., 2005
	Reference	Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. Version 3.0. Department of environmental sciences, University of California, Riverside, California, 240 pp.
Type of model	Process based	estimated from other models)
	Model configurations	
	Physiologically based	no
	Time resolution	defined by the user (day for example)
	Spatial configurations	not spatialised
	Spatial resolution	not spatialised
	Spatial coverage	soil profile
	Soil compartments	1 to n
	Plant compartments	1
	Modular	yes
Programming	Langage	unknown
	Open source	yes
Applications	Climate change mitigation compliant	no
	Climate change adaptation compliant	no
	Compliancy with GCM	no
	Feed back between cover and climate	no
	Effects of alternative land-use and management	no
Variables	Input variables	curves and Ks for each soil layer), fine root profiles, Initial conditions of soil water content
	Intermediate variables	Infiltration
	Output variables	D, soil water content, Heat transport, carbon dioxide and major ion solute movement
Assumptions	Major assumption 1	Basic hydraulic soil parameters are constant at the spatial scale considered (soil profile, plot,...).
and limitations	Limitation 1	The spatial variability of Ks and retention curves is likely to be high. Values are proposed according to soil texture but they should be calibrated for specific soil types.
	Major assumption 2	Superficial infiltration at the time step considered is uniform at the spatial scale considered.
	Limitation 2	Throughfall+Stemflow-Runoff can be estimated from other models and are constant at the spatial scale consi
	Major assumption 3	index (Jarvis, 1989)
	Limitation 3	The root depth, can be either constant or variable during the simulation. For annual vegetation a growth model is required to simulate the change in rooting depth with time.
Details on variables	Rainfall	
	Interception/throughfall	computed from empirical equations that need to be calibrated per specie
	Snowmelt	
	Runoff	age, etc...
	Infiltration	
	Actual ET	
	stomatal conductance	
	PET	Provided at the time step considered by another model.
	Number of vegetation types	
Calibrations	Calibration 1	Classically used in the literature.
	limitations for calibration 1	
	Calibration 2	
	limitations for calibration 2	
Validations	Validations	
Future	Future developments	Hydrus 2D and 3D available but not free.

Annex 4a: Detailed description of Hydrus 1 D Model

Identification	Name of model	CASTANEA
	Author	Dufrêne at al (2005), Davi et al. (2005)
	Reference	Dufrene, E., Davi, H., Francois, C., Maire, G. l., Dantec, V. L., and Granier, A. (2005). Modelling carbon and water cycles in a beech forest: Part I: Model description and uncertainty analysis on modelled NEE. Ecological Modelling 185, 407-436.
Type of model	Process based	Yes for the soil (bucket model) and yes for vegetation (Ball et al. 1987)
	Model configurations	Radiation Interception (Multilayer for PAR, NIR, thermal), SVAT (H2O, C, N) +C allocation (NPP, growth, litter production) +soil model (bucket + SOC CENTURY)
	Physiologically based	Yes (Ball et 1987 al for photosynthesis;)
	Time resolution	half-hourly or day
	Spatial configurations	can be spatialised
	Spatial resolution	can be spatialised
	Spatial coverage	plot to landscape
	Soil compartments	3 comparments: litter + 2 soil
	Plant compartments	6 + reserves
	Modular	yes: SVAT+C allocation +soil model
Programming	Langage	unknown
	Open source	no
Applications	Climate change mitigation compliant	yes
	Climate change adaptation compliant	no
	Compliancy with GCM	no
	Feed back between cover and climate	no
	Effects of alternative land-use and management	no
Variables	Input variables	Climate; vegetation (compartments, LAI, L angle, phenology, roots); soils (physics), litter
	Intermediate variables	EW, REW, C stocks, water stocks, N stocks, gs, gc, Rn, Rnu, gsoil, glitter, ra
	Output variables	T, D, Eu, E, stress index and water stress duration, NEE, GPP, NEP, NPP, Ra, Rsoil, Rh, Re
Assumptions and limitations	Major assumption 1	Canopy is horizonthally homgeneous, with one single average tree simulated
	Limitation 1	non-closed (sparse) canopies or multi-layer canopies
	Major assumption 2	Phenology depends on degree-day and day duration; LAImax is forced according to year and site
	Limitation 2	problem to adjust in tropical situations. Include a REW dependent submodel ?
	Major assumption 3	of priorities varying along the year according to the phenological stage. The use of assimilates for maintenance respiration has priority over growth and storage allocation all over the year. Vegetative growth of forests may be temperature limited in temperate environment (Cannell et al., 1988). However, except for leaves (see above), no direct effect of temperature on growth has been incorporated in the model. The water stress effect operates only indirectly by reducing gross photosynthesis. Moreover, there are no age-related effects on carbon allocation besides the indirect
Details on variables	Rainfall	
	Interception/throughfall	During the leafy period, leaves intercept a fraction of rainfall, depending on both leaf area index and gap fraction. Evaporation rate occurs according to the Penman–Monteith equation (Monteith, 1965) assuming a zero stomatal resistance.
	Snowmelt	not considered ?
	Runoff	not considered ?
	Soil water balance and infiltration	Bucket with 3 compartments, litter, topsoil, total soil root zone
	Actual ET	P-M, with retroactive loop on gs from soil REW
	stomatal conductance	Ball et al. (1987)
	PET	not used
	soil evaporation	P-M, using Rnsoil, rasoil and gsoil
	Number of vegetation types	1
Calibrations	Calibration 1	Fagus silvatica (Granier et al, Hesse, France) + detailed sensitivity analysis
	limitations for calibration 1	
	Calibration 2	
	limitations for calibration 2	
Validations	Validations	with Eddy-cor Fagus silvatica (Granier et al, Hesse, France)
Future	Future developments	

Annex 4b: Detailed description of CASTANEA Model

Identification	Name of model	BILJOU: Bilan Jour
	Author	Granier at al (1999)
	Reference	Granier A, Breda N, Biron P and Villette C 1999 A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands. Ecol. Model. 116, 269-283.
Type of model	Process based	No for the soil (bucket model) and no for vegetation (empirical relationships between T and ETP)
	Model configurations	
	Physiologically based	no
	Time resolution	day or infra-day
	Spatial configurations	not spatialised
	Spatial resolution	not spatialised
	Spatial coverage	plot to landscape
	Soil compartments	1 to n
	Plant compartments	1
	Modular	yes
Programming	Langage	unknown
	Open source	no but rewritable from paper
Applications	Climate change mitigation complia	no
	Climate change adaptation complia	no
	Compliancy with GCM	no
	Feed back between cover and clim	no
	Effects of alternative land-use and	no
Variables	Input variables	pressure-volume for calulating EW), fine root profiles, REWc
	Intermediate variables	EW, REW
	Output variables	T, D, Eu, E, stress index and water stress duration
Assumptions and limitations	Major assumption 1	rmax = Tmax/ETP in absence of water stress is a power function of LAI
	Limitation 1	VPD on canopy conductance
	Major assumption 2	r = T/ETP in occurrence of water stress is a linear function of REW
	Limitation 2	VPD on canopy conductance
	Major assumption 3	REWc = critical REW value below which r < rmax = 0.4
	Major assumption 4	universaility of this value according to soil types and cover
	Major assumption 5	Runoff is neglected
Details on variables	Rainfall	
	Interception/throughfall	computed from empirical equations that need to be calibtared per specie
	Snowmelt	
	Runoff	not considered in initial version
	Infiltration	
	Actual ET	
	stomatal conductance	not used
	PET	
	Number of vegetation types	
Calibrations	Calibration 1	Quercus petraea (30 yr old);
	limitations for calibration 1	
	Calibration 2	Douglas-fir;
	limitations for calibration 2	
Validations	Validations	Quercus petraea (30 yr old); Douglas-fir;
Future	Future developments	

Annex 4c: Detailed description of BILJOU Model

Identification	Name of model	MAPSS: Mapped Atmosphere-Plant-Soil System
	Author	Nielson
	Reference	balance. Ecol. Appl. 5: 362-385.
Type of model	Process based	yes
	Physiologically based	yes
	Time resolution	month
	Spatial resolution	10 km for regional; 0.5° for global
	Spatial coverage	landscape, region, country, continent, global
	Soil compartments	L1=(0-50 cm), L2=50-150 ; L3 = drainage
	Plant compartments	3 possible storeys: tree, shrub and grass
Programming	Langage	
	Open source	no
Applications	Climate change mitigation compliant	yes
	Climate change adaptation compliant	yes
	Compliancy with GCM	yes (for documenting AET)
	Feed back between cover and climate	yes
	Effects of alternative land-use and manage	yes in future versions
Variables	Input variables	Climate, PET, fires, soils physics
	Intermediate variables	WUE, stomatal cond., stomatal or canopy conductance, Actual ET,
	Output variables	Potential vegetation type; LAI (tree+shrub+grass); complete site water balance and partitioning;
Assumptions and limitations	Major assumption 1	Site water balance is the primary determinant of terrestrial vegetation
	Limitation 1	by successive vegetation
	Major assumption 2	N is only limiting on the how rapidly vegetation attains its "carrying capacity"
	Limitation 2	N limitations, P limitations
	Major assumption 3	Physiological limits and thresholds
	Major assumption 4	Higher leaf areas produce higher rates of transpiration and \vould deplete the soil moisture before the end of the growing season, in turn causing a drought-induced reduction of leaf area (Woodward 1987). Lower leaf areas will result in moisture surpluses and in subsequent years continued growth will increase leaf area.
	Major assumption 5	Biotic interactions, such as grass-tree competition, can alter the state of the ecosjstem and have also been incorporated in the model.
	Major assumption 6	under-storey. Beer law optional
	Major assumption 7	Competition for light watern tree-shrub-grass; soil moisture layer 1 (0-50 cm) accessible for grass roots ; and level 0-50+50-150 for trees
		whole year.
	Major assumption 8	LAI Grass adjusted iteratively in order to consume the monthly available water, but constrained by
	Major assumption 9	WUE =GPP/AET. A good surrogate for GPP is LAD (leaf area duration) = LAI.time
	Major assumption 10	Leaf forms (evergreen, broad, needles, microphyllous) controlled by rules
	Major assumption 11	Deep recharge is supposed to be nil
Details on variables	Rainfall	Input
	Interception/throughfall	Rutter et al. 1975, Benecke 1976, Miller 1977. McNaughton and Jarvis 1983
	Snowmelt	yes
	Runoff	fast runoff (surface runoff + macropore flow)
	Infiltration	time step
	Actual ET	function of PET, LAI (exponential), gs
	stomatal conductance	function of soil water potential and PET
	PET	aerodynamic turbulent transfer model (Marks 1990); surface roughness length
	Number of vegetation types	35: Major groups: Ice, toundra, taiga, forest, tree savanna, shrub savanna, grassland, desert
Calibrations	Calibration 1	soil, climate, hydrologic and water balance variables
	limitations for calibration 1	weather station net
	Calibration 2	vegetation variables (distribution, life forms, stomatal conductance patterns and leaf areas)
	limitations for calibration 2	stomatal conductance; parameters to be found (more sparse) for tropical regions
Validations	Validations	Yes for Runoff, Runoff/Rainfall, vegetation distribution, LAI,
Future	Future developments	Stomatal conductance; CO2 and N; rules for dispersal;

Annex 4d: Detailed description of MAPPS Model

Identification	Name of model	ORCHIDEE: Organizing Carbon and Hydrology In Dynamic Ecosystems Environmentoil System
	Author	Krinner at al (2005)
	Reference	Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice. 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19.
Type of model	Process based	yes; Sechiba=hydrological module; Stomate=C module; LPJ=vegetation module
	Model configurations	Hydrology only (Sechiba); hydrology and photosynthesis; Hydrology and C cycle with static vegetation (no LPJ);
	Physiologically based	yes
	Time resolution	Sechiba (min, 30 min); LPJ-DVGM (1 year); Stomate (1 day)
	Spatial configurations	Stand; local; global; coupled with an AGCM
	Spatial resolution	Several PFT simulated per grid element possible
	Spatial coverage	plot to global
	Soil compartments	
	Plant compartments	PFTs
	Modular	yes
Programming	Langage	
	Open source	no
Applications	Climate change mitigation com	yes
	Climate change adaptation compliant	
	Compliancy with GCM	yes
	Feed back between cover and	yes
	Effects of alternative land-use and management	
Variables	Input variables	Climate; vegetation, soils, weather generator
	Intermediate variables	mortality, tree age, gaps
	Output variables	Fluxes and stocks of H2O, C, energy; NPP, GPP, NEE, impact of fires
Assumptions and limitations	Major assumption 1	12 Plant Functional Types (PFT) like in LPJ; grass cannot grow below trees
	Limitation 1	agroforests no represented; syst sylvo-pastoral color
	Major assumption 2	stomatal functioning included
	Limitation 2	
	Major assumption 3	Leaf onset and senescence has to be set
	Major assumption 4	how to parameterize in tropical wet areas ?
	Major assumption 5	No limitation by N
	Major assumption 6	
	Major assumption 7	no detailed soil hydrology
	Major assumption 8	
	Major assumption 9	no distinctinction between direct and diffuse solar radiation
	Major assumption 10	
	Major assumption 11	
Details on variables	Rainfall	
	Interception/throughfall	
	Snowmelt	
	Runoff	
	Infiltration	
	Actual ET	
	stomatal conductance	
	PET	
	Number of vegetation types	
Calibrations	Calibration 1	Fluxnet
	limitations for calibration 1	
	Calibration 2	Global LAI
	limitations for calibration 2	
Validations	Validations	with Fluxnet data; Rn; H, LE; Fc / Globally in static and dynamic modes
Future	Future developments	N limitation; detailed soil hydrology; direct and diffuse

Annex 4e: Detailed description of ORCHIDEE Model

		Eucalypt (Kondi cycles experiment)	**Grassland (Kondi cycles experiment)**	**Eucalypt (Hinda experiment)**	**Eucalypt (Kissoko experiment)**	**Grassland (Tchizalamou experiment)**	**Eucalypt (Kondi cycles experiment)**	**Eucalypt (Kondi cycles experiment)**
Experiment	Name of experiment	Kondi cycles	Kondi cycles	Hinda Eddy-cor. eucalypt-PF1 variety	Kissoko Eddy corr eucalypt-Urograndis variety	Tchizalamou Eddy Corr. Grassland	Kondi cycles	Kondi cycles
	Type of ecosystem	Eucalyptus	Grassland	lonal eucalyptus plantatio	lonal eucalyptus plantation		Eucalyptus	Eucalyptus
	Species/clones_top layer	PF1-41	-	PF1-41	18-65	-	18-52	PF1-41
	Under-storey species	No	-	No	No	-	No	-
	Main goal of experiment	Biogeochemical cycles of nutrients	Biogeochemical cycles of nutrients	NEE, NPP, GPP, Reco, Rsoil, E, T, WUE	NEE, NPP, GPP, Reco, Rsoil, E, T, WUE	NEE, NPP, GPP, Reco, Rsoil, E, T, WUE	Biogeochemical cycles of nutrients	Biogeochemical cycles of nutrients
	Location	Kondi	Kondi	Hinda	Kissoko	Tchizalamou	Kondi	Kondi
	Name of P.I.	Laclau JP; Deleporte P	Laclau JP; Nouvellon Y.	Nouvellon Y	Nouvellon Y.	de Grandcourt A.	Deleporte P.; Levillain J	eleporte P.; Levillain
	Report or publication	Laclau et al.	Laclau et al.	Nouvellon et al.; Epron et al.; Saint-André et al.; Jourdan et al.	Marsden et al. (in press)			
	Availability for Carboafrica ?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Date of planting	1992		1998	2002		2001	2001
	Period of experiments	01/01/1998 to dec 2000		october 2000 to december 2002	April 2004 to April 2006	June 2006 to	2001 to	2001 to
	Latitude			4°40'52"S	4°47'29" S			
	Longitude			12°00'13" E	11°58'56" E			
	Elevation			136	108			
	Slope	< 3%	< 3%	< 3%	< 2%	0	< 3%	< 3%
	Runoff important ?	No	No	No	No	No	No	No
	Type of Management	Classical with herbicide	None but annual fires	Classical with herbicide	Classical with herbicide	None but fires	Classical with herbicide	lassical with herbicid
	Range of basal area during period of measurements	01/01/1998 to dec 2000	-			-	2001 to	2001 to
	Density	530 trees/ha		700 trees / ha	750 trees/ha	-	800 trees/ha	530 trees/ha
	Minimum and maximum LAI during period of measurements		0 to	~0.8 to 1.7	~1.8 to 2.5	0 to		
Ancillary Climate	Climate (PNR airport)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Climate (automatic weather station)	No	No	Yes	Yes	Yes	No	No
	PAR	No	No	Yes	Yes	Yes	No	No
	% diffuse	No	No	Yes	Yes	Yes	No	No
	Rg	No	No	Yes	Yes	Yes	No	No
	Rn	No	No	Yes	Yes	Yes	No	No
	Rh	No	No	Yes	Yes	Yes	No	No
	Ta	No	No	Yes	Yes	Yes	No	No
	Windspeed	No	No	Yes	Yes	Yes	No	No
	Rainfall	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Class-A	No	No	No	No	No	No	No
	Piche	No	No	No	No	No	No	No
Ancillary Soil and Water	Tsoil surface	No		Yes	Yes	Yes	No	No
	Tsoil profile (give depths)	No		Yes	Yes	Yes	No	No
	Stone content	Yes		Yes	Yes	Yes	Yes	Yes
	Humsoil surface	No		Yes	Yes	Yes	No	No
	Humsoil profile (give depths)	Yes, down to 5m	Yes, down to 3m	Yes	Yes	Yes	Yes, down to 5m	Yes, down to 3m
	Soil dry bulk density profile	Yes		Yes	Yes	Yes	Yes	Yes
	Soil texture profile	Yes		Yes	Yes	Yes	Yes	Yes
	Soil organic matter profile	Yes		Yes	Yes	Yes	Yes	Yes
	Pressure-volume curves profile	Yes		No	No	No	Yes	Yes
	Predawn leaf water potential	No		No	No	No	No	No
	Daily leaf water potential	No		No	No	No	No	No
	Soil water potential (potentiometry)	Yes		No	No	No	Yes	Yes
	Soil porosity	Yes		No	No	No	Yes	Yes
	Soil hydraulic conductance	Yes		No	No	No	Yes	Yes
	Lysimetry	Yes		No	No	No	Yes	Yes
Ancillary Plant	Rooting depth	9 m	2.5 m	Yes	Yes	Yes	9 m	9 m
	Fine root biomass	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Fine root biomass profile	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	LAI	No but leaf biomass	No but leaf biomass	Yes	Yes	Yes	No but leaf biomass	No but leaf biomass
	Gap-fractions	No but clone 1-41		Yes	Yes	Yes		No but clone 1-41
	Leaf angle distribution function	No but clone 1-41		Yes	Yes	Yes		No but clone 1-41
	Clumping	No but clone 1-41		Yes	Yes	Yes		No but clone 1-41
	IPAR	No but clone 1-41		Yes	Yes	Yes		No but clone 1-41
	APAR	No but clone 1-41		Yes	Yes	Yes		No but clone 1-41
Ancillary evapo-transpiration	Sapflow	Yes (1 year)		Yes (1 year)	No	-	No	No
	Eddy-cov.	No		Yes	Yes	Yes	No	No
	Soil water balance	Yes		Yes	Yes	Yes	Yes	Yes
	Throughfall	Yes		No	No	No	Yes	Yes
	Stemflow	Yes		No	No	No	Yes	Yes
	Stomatal conductance	No		Yes	Yes	Yes	No	No
Models possible to develop	ET0_ref humid grass	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Penman	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Priestley-Taylor	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	AET Penman-Monteith (Big-leaf)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Crop coefficient	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Sun-shade	No	No	Yes	Yes	No	No	No
	Multi-layer (Canoak)	No	No	Yes	Yes	No	No	No
	Shuttleworth & Wallace (sparse crop	No	No	No	No	No	No	No
	BGC-Running	No	No	No	No	No	No	No
	3D-architectural	No	No	No	No	No	No	No
	HYDRUS 1-D	Yes	Yes	No	No	No	Yes	Yes
	BILJOU (Granier et al., 1999)	Yes	Yes	No	No	No	Yes	Yes
	CASTANEA	Yes	Yes	No	No	No	Yes	Yes
	MAPPS	Yes	Yes	No	No	No	Yes	Yes
	ORCHIDEE	Yes	Yes	No	No	No	Yes	Yes

ANNEX 5: SUMMARY OF THE MAIN EXPERIMENTS CONDUCTED IN THE EUCALYPT PLANTATION OVER GRASSLAND OR SAVANNA (AROUND 40 000 HA NEAR POINTE-NOIRE, CONGO)

	Turc		Priestley-Taylor		Penman		ET0_ref humid grass		ETc Penman-Monteith (Big-leaf)		Crop coefficient		Shuttleworth & Wallace (sparse crop)		Sun-shade		Multi-layer (Canoak)		3D-architectural		BILJOU (Granier et al., 1999)		BGC-Running		HYDRUS 1-D		PASTIS		CASTANEA		MAPPS		ORCHIDEE (hydrology-only mode)	
Model characteristics and INPUT PARAMETERS	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available	Required	Available
Time resolution	10 days or month	10 days or month	daily	daily	daily	daily	daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	half-hourly to daily	daily	daily	daily	half-hourly to daily	daily
Sunshine hours	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1	1a	1			1a	1			1a	1	1a	1	1a	1
PAR or Rg	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C			1a	C			1a	C	1a	C	1a	C
% diffuse															1	C	1	C	1	C									1a	C				
Rn	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C	1a	C			1a	C			1a	C	1a	C	1a	C
RH					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1			1	1	1	1	1	1
Ta	1	1			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1			1	1	1	1	1	1
Windspeed					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1			1	1	1	1	1	1
Rainfall																													1	1				
G					1	E	1	E	1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E	1	E	1	E
albedo																													1	E			1	E
Stand density																			1	1									1	1				
Canopy height									1	1	1	1	1	1	1	1	1	1	1	1									1	E				
Aerodynamic resistance (ra)									1	C	1	C	1	C	1	C	1	C	1	C									1	E	1	C		
surface roughness																													1	E			1	E
Throughfall									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E	1	E	?	?
Stemflow									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E	1	E	?	?
Interception									1	C	1	C	1	C	1	C	1	C	1	C	1	C			1	C			1	C	1	C	?	?
Superficial run off																									1	E								
Stomatal conductance									1b	C	1b	C	1b	C	1b	C	1b	C	1b	C									1	C	1	E	1	E
Canopy Conductance									1b	C	1b	C	1b	C	1b	C	1b	C	1b	C									1	C				
T									1b	C	1b	C	1b	C	1b	C	1b	C	1b	C					1b	C			1	C				
ETc									1b	C	1b	C	1b	C	1b	C	1b	C	1b	C									1	C				
rm = Tmax /PET no water stress																					1	E												
r=T/ETP = f(REW) during water stress																					1	E												
REWc critical REW for affecting T/ETP																					1	E							1	C				
Canopy openness													1	1																				
LAI									1c	E	1c	E	1c	E	1c	E	1c	E	1	E	1c	E							1c	E	No	C	1c	E
LAI per layer																	1	E	1	E									1c	E				
LAD zenital															1	E	1	E	1	E									1c	E				
LAD azimutal																			1	E														
LAD zenital per layer																	1	E	1	E									1c	E				
LAD azimutal per layer																			1	E														
K extinction coefficient									1c	E	1c	E	1c	E	1c	E	1c	E			1c	E							1c	E	1c	E	1c	E
Gap-fractions									1c	E	1c	E	1c	E	1c	E	1c	E			1c	E							1c	E	1c	E	1c	E
SLA+stand leaf mass									1c	E	1c	E	1c	E	1c	E	1c	E			1c	E							1c	C	1c	E	1c	E
Clumping															1	E	1	E																
IPAR									1c	E	E	E	1c	E	1c	E	1c	E			1c	E							1c	E	1c	E	1c	E
APAR									1c	E	E	E	1c	E	1c	E	1c	E			1c	E							1c	E	1c	E	1c	E
																																	?	?
Rooting depth									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E			?	?
Fine root biomass									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E			?	?
Coarse root biomass																													1	E			?	?
Fine root biomass profile									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E			?	?
Coarse root biomass profile																																	?	?
Stone content									1	E	1	E	1	E	1	E	1	E	1	E	1	1			1	1			1	E	1	E	?	?
Soil porosity									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E	1	E	?	?
Distinction between micro and macro por.									1	E	1	E	1	E	1	E	1	E	1	E	1	E							1	E	1	E	?	?
Soil dry bulk density profile									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E	1	E	?	?
Soil texture profile									1	E	1	E	1	E	1	E	1	E	1	E	1	E							1	E	1	E	?	?
Soil organic matter profile									1	E	1	E	1	E	1	E	1	E	1	E	1	E							1	E	1	E	?	?
Pressure-volume curves profile									1	E	1	E	1	E	1	E	1	E	1	E	1	E			1	E			1	E				
Soil hydraulic conductance																									1	E								
Humsoil surface																																		
Humsoil profile																									1	E								
Soil water potential (potentiometry)																																		

ANNEX 6: SUMMARY OF ALL THE MODELS PRESENTED ABOVE, WITH THEIR REQUIRED INPUT PARAMETERS, AND AVAILABLE OR NOT AVAILABLE ALTERNATIVES FOR RUNNING THEM AT THE SCALE OF THE WHOLE EUCALYPT PLANTATION (AROUND 40 000 HA NEAR POINTE-NOIRE, CONGO)

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