

6 Modelling growth and carbon sequestration of agroforestry systems in Leyte

Plant growth at various sites was modelled using WaNuLCAS, a model for **Water, Nutrients, Light and Carbon in Agroforestry Systems** (v.NOORDWIJK, LUSIANA & KHASANAH 2004). The model runs in a STELLA® environment, which is combined with an Excel spreadsheet as front end. For this study, WaNuLCAS version 3.1 was used. Several steps need to be taken, before scenarios can be run in the model. In fig.84 the procedure is shown for crops, while for trees, a parametrisation software called WanFBA is used instead of WanHelp. Soil and weather data are directly entered into the spreadsheet or Stella file.

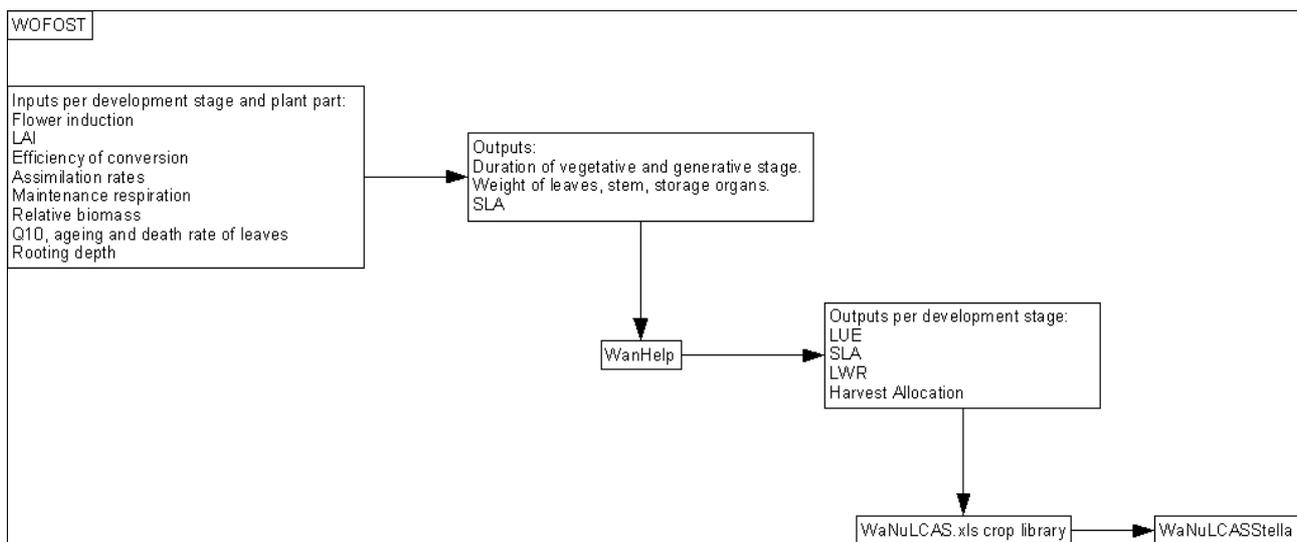


Figure 84: Flow chart crop parametrisation

Optional help modules such as WOFOST or WanHelp can be employed to derive input parameters, which are not at hand, from parameters, which are easier to measure. For tree parametrisation, a tree survey including semi-quantitative questions to farmers is part of the WanFBA and Tree Parametrisation modules. Entering field or literature data into the system (parametrisation) and calibrating, i.e. fine-tuning the model using field data, precede validation, i.e. running the calibrated model on additional measured datasets. Finally, hypothetical scenarios can be run on the calibrated and validated model.

Mature plants were used for parametrisation of the model, which was then calibrated and validated at the Cienda subplots 6, 7, 8 and 10 on young plants as well as at the Cienda demo site and LSU on >10year-old trees. On this basis, different land use systems were compared as regards to their carbon sequestration potential over a period of up to 20 years. These land use systems are grassland, *Gmelina* pure stands and rainforestation as presented in chapter 4. For rainforestation, different options were explored to optimise the system.

6.1 Parametrisation

Practically, entering data into WaNuLCAS consists of three steps (s. fig. 84): Optional help programmes like WanFBA for tree parametrisation or WOFOST and WanHelp for crop parametrisation are fed with measured biomass values and produce plant physiological data, which are then entered into a spreadsheet denominated Wanulcas.xls. Direct inputs

on soil, weather, profitability and management activities – planting, weeding, harvesting etc. at certain times – are also specified in this file. All soil, weather, plant and economic data fit into the spreadsheet are internally processed and transferred into an .stm (Stella) file, the actual model. The stella file allows for extensive fine tuning of nutrient, SOM and litter pools, soil physical properties, erosion, management, pests or maintenance respiration, among others.

6.1.1 Crop parametrisation

Technically, the parametrisation procedure has been outlined in section 2.7 for crops and trees. There was only one crop, abaca, to be parametrised. Instead of WOFOST, data obtained as interpolations of biomass inventories were directly entered into WanHelp. These were dry weight of leaf, stem and storage organs as well as SLA at different phenological stages.

Growth stages in WOFOST and WanHelp range from 0, germination, to 2, maturity, where 1, flower, is defined as the point of transition from the vegetative into the generative phase. Abaca is harvested before flowering, so that the generative phase is never reached. Another characteristic is, that the first vegetative phase until fibre harvest lasts 21 months, while subsequent harvests take place every six months. Due to the existing rootstock, growth is faster than during the initial phase. To account for this, it was assumed, that after harvesting the two tallest stems (of 3m), another two, of 2m and 1.5m height, are left while all other suckers are cut. For parametrisation this meant, that growth of the second and following suckers was defined as generative phases and that the plant would return to stage 1 after ratooning. N and P concentrations in tissues of both stages were maintained at the same level. Specific leaf area (SLA) was measured after >1 year on grown-up plants. For the initial stage, half leaf thickness was assumed and decreased linearly. Thus SLA decreased from 200 to 100% of the final value in phase 0-1, and during phase 1-2 a decrease from 150 to 100% was assumed. For leaf weight ratio (LWR), the relative weight of different plant organs, changing proportions during development were interpolated from own measurements as leaf:stem ratio = $-0.0122+0.0011\text{dap}$ ($r^2=0.98$). The cycle from phase 0-1 was then also applied for 1-2. For harvest allocation, two approaches were compared: In one case it was set zero, as fruits or storage organs are not developed; in the other values derived from WanHelp were adopted; after extensive testing over various environment, the second option was preferred. For root allocation, standard values from other species parametrised for WaNuLCAS were used as these are very similar across crops; in contrast to those species, root allocation was maintained at a constant level throughout the entire life cycle as is for the other crops during phase 0-1. Light use efficiency (LUE) was calculated through WanHelp as growth during the respective phase divided by maximum growth at the given relative light capture. Literature regarding light use efficiency (LUE) of different Musaceae was taken into account for the calculations (RODRIGO ET AL. 1997 for banana; TSEGAYE ET AL. (2003) for *Ensete ventricosum* and TURNER (1972a) and STOVER (1982), cited by TSEGAYE ET AL., for banana).

RODRIGO ET AL. (1997) found average LAI of 1.33 from 8 to 28 months after planting in a comparable banana system⁸⁴ in Sri Lanka, compared to 1.79 calculated by WanHelp for abaca after 24 months for Cienda under optimum conditions. Observations by TSEGAYE ET AL. (2003) on maximum LAI of enset were between 3.2 and 4.6, compared to 4.8 reported by TURNER (1972b) and 3.2-4.3 by STOVER (1982) for banana. For crop parametrisation in WaNuLCAS an intermediate value of 3 was chosen.

The light extinction coefficient k , in WaNuLCAS $Cq_k\text{light}$, was estimated 0.58, after

⁸⁴ wet lowlands, soil pH 4.84; 1500 plants ha⁻¹, interplanted with rubber.

measurements carried out on onset by TSEGAYE ET AL. (2003), namely 0.56- 0.62, and a range of 0.46-0.75 reported by TURNER (1990, as cited by TSEGAYE ET AL.) for banana.

For parametrisation of abaca roots, own measurements of banana root length density (Cienda subplot 8) were used (WaNulcas parameter Rt_ACType = 0). A root system extending to 40cm depth and 125cm in radius as reported by MURTHY & IYENGAR (1997) for several banana varieties may develop during several years of growth; for the two-year old abaca at Cienda, only few individual roots would extend beyond 1m of lateral distance from the stem.

Abaca polyphenol contents were analysed in Hohenheim and are used in table 24. Regarding lignin, literature values were adopted: Abaca fibres examined by MORENO ET AL. (2005) contained 6.43-9.54% for the most preferred varieties (selected for low contents), while DEL RIO & GUTIERREZ (2006) found 13.2%.

6.1.2 Tree parametrisation

Among the ten planted tree species, *Shorea contorta*, *Dipterocarpus validus*, *Durio zibethinus* and *Artocarpus heterophyllus* were selected for modelling due to economic potential, solidity of datasets and performance in the field. For the reference land use *Gmelina arborea* was also parametrised.

6.1.2.1 Aboveground architecture

General data on habitus and phenology were gathered through expert interviews and literature studies. FBA procedure as specified under 2.7 was conducted for mature individuals as suggested by the model developers (MULIA ET AL. 2001; MULIA 2001). The advanced stage of seedlings at planting is considered as initial stage in the spreadsheet and in the tree planting section of the stm-file, where field data for initial stem height and biomass are entered. All inputs entered into the tree parametrisation spreadsheet are listed in the Annex.

6.1.2.2 Belowground

Roots of *D. validus*, *S. contorta*, *G. arborea* and *A. heterophyllus* were studied by a modified FBA procedure (MULIA 2001), but measurements did not match the criteria set for WaNuLCAS in any case. Usually, a thin turn-off from a proximal root would blast the required proportionality factors p and q . In this respect, setting a minimum diameter for measurements might have been appropriate, but in turn would have led to more extensive excavations and damages in the dense plantations.

Instead, potential root length density was estimated for each planting zone (in Stella: Rt_TType=0) departing from the measurements described in chapter 5. Root length density was assumed to decrease exponentially from initially 3cm cm^{-3} , the measured average RLD at Cienda demo site (2.93cm cm^{-3} at a maximum distance of 1.1m from the trees⁸⁵). A species-specific decrease could then be estimated assuming an elliptically skewed gradient as for WaNuLCAS root type 1. As observed by MASRI (1991) for durian, root biomass would decrease to 15% of its initial value towards the canopy edge. Depth distribution of roots was estimated from knowledge of effective rooting space (chapter 3) and experiences gained during root excavations.

Root length density and distribution of *Gmelina* roots were estimated based on data of MERCADO ET AL. (2005) and RUHIGWA ET AL. (1992). Both data sets are based on fine roots <2mm diameter. This diameter class accounted for 89.3% of all roots at 0-15cm depth and 86.3% at 15-30cm across subplots 1-13 at Cienda (coefficients of variation 5% and

⁸⁵ Planting distance of 2x1m

11%, respectively)⁸⁶. Lateral extension of *Gmelina* roots at Marcos site clearly exceeded 200cm from the stem and was not homogeneous as reported by RUHIGWA ET AL. (1992). This can be ascribed to the physiologically shallow soil (lateral water flow on a clay horizon).

6.1.2.3 Polyphenolics contents of plant tissues

Polyphenolics and lignin are classes of substances, that retard litter decomposition and thus influence turnover rates and nutrient cycling. Certain polyphenols reduce growth and activity of decomposers, while lignin as a major component of leaves is hard to metabolise if compared to other structural molecules such as cellulose (ISAAC & NAIR 2005). GAISER (1993) found humification rates of mulch to be correlated to polyphenol but not lignin contents. Data are required for both above and belowground parametrisation and polyphenols were analysed for leaves and fine roots (table 24).

Table 24: Total extractable polyphenolics (TEP) contents of fresh leaves and fine roots

	TEP [%]	
	Leaves	Fine roots
<i>D. validus</i>	6.65	8.46
<i>S. contorta</i>	9.75	13.1
<i>S. palosapis</i>	6.33	n.d.
<i>T. calantas</i>	9.24	n.d.
<i>G. arborea</i>	1.56	2.14
<i>N. lappaceum</i>	9.80	9.17
<i>G. mangostana</i>	5.07	n.d.
<i>D. zibethinus</i>	1.36	7.31
<i>A. heterophyllus</i>	3.70	n.d.
<i>A. odoratissima</i>	6.48	5.74
<i>L. domesticum</i>	3.20	4.14
<i>M. textilis</i>	1.09	2.51
<i>C. nucifera</i>	9.26	2.56

Values for leaves and fine roots of the same species were similar with exception to durian and coconut. *Gmelina* contained clearly less TEP compared to the native timber species and was similar to abaca tissues. Ranges were comparable to those stated by various literature sources: ISAAC & NAIR (2005) found 2% of polyphenols in leaves of *A. heterophyllus* and PALM ET AL. (2000) report median values for polyphenols in fresh leaves of 3%, though at considerable dispersion with many species >6%; fine roots were generally lower in polyphenols with a median of <2% TEP.

For lignin contents, default values provided by the model were used. Where literature data or own observations justified this, modifications were made. As an example, ISAAC & NAIR (2005) measured 15.2% and JAMALUDHEEN & MOHAN KUMAR (1999) 17.9% lignin for leaves of *A. heterophyllus*.

6.1.3 Site data

6.1.3.1 Weather

WaNuLCAS uses an elegant approach to simulate climate, based on the three

⁸⁶ From the relative decrease of roots with depth, a factor denominated $Rt_TDecDepth$ in Stella of 2 and 2.89 was calculated. This factor could have been employed alternatively to $Rt_TType=1$ or 2, in contrast to type 0, which was used here.

parameters rainfall, soil temperature and potential evapotranspiration. These can be randomly generated or read from monthly or daily observations. For this study, daily rainfall and potential (pan) evaporation recorded by PAGASA at LSU served as direct meteorological input data. Measured pan evaporation was significantly correlated to calculated FAO Penman-Monteith ETP⁸⁷ (Pearson correlation $r^2 = 0.705$ at $\alpha = 0.01$), derived from general geographical data, so that few missing values caused by pan overflow could be substituted by theoretical ones. Soil temperatures were calculated from a quadratic regression of mean air temperature at PAGASA-LSU on measured soil temperatures at Cienda site between 2004-6; minima of 9 outliers (of 4380) were set 19.0°C. Four years (Jan 1st, 2003 – Dec 31st, 2006) of calculated soil temperatures, measured rainfall and ETP were used as a loop in Stella, coinciding with real time weather and extended back- and forwards for the simulations.

6.1.3.2 Soils

Analytical data as presented in the previous chapters were entered for parametrisation of the following parameters: C_{org} , texture, bulk density, estimates for field capacity and rough estimates of saturated hydraulic conductivity (K_{sat}) were used to derive pedotransfer functions and P_{Bray} values inside the WaNuLCAS spreadsheet file. Further, stone contents and horizon thickness, pH KCl, C, N_T , C:N and N:P ratios of different soil organic matter pools were fed directly into the respective Stella files.

6.1.4 Management and profitability

Management was reduced to a minimum and no external inputs, burning, grazing or other special treatments were applied except pruning (for one later scenario). Model input data concerning labour costs and demand as well as commodity prices were obtained from the planting experience at Cienda, interviews with farmers, negotiations with tree nursery owners and a cost-benefit analysis evaluating rainforestation in comparison to coconut + abaca and *Acacia mangium* + abaca land uses in Leyte (AHRENS ET AL. 2004). Rentability data resulting from this module are seen only as a first approximation since detailed data, e.g. on transport costs, were not collected or updated. Results will not be discussed in the context of this study.

6.2 Model calibration

Having entered all soil, weather and plant data as well as management and others in the .stm model, additional adjustments were needed to adapt the simulation results to biomass data measured in the field. This is an iterative procedure based on test simulations. Key input parameters, which influence the respective outputs have to be identified and modifications effected must not deviate too much from measured physiological and architectural characteristics of the species. Calibration was carried out for subplots 6 and 7 including as few modifications as possible to the parametrisation data.

Goodness of fit was evaluated by various statistical terms: Coefficient of determination (R^2) expresses explained variance, the sum of squared deviations of observed data from their mean, as ratio of total variance, the sum of squared deviations between predictions and observations. However, this parameter is sensitive to trends but not orders of magnitude, so that constant over- or underestimation would not necessarily be indicated

⁸⁷ Potential evapotranspiration for a standardised surface at PAGASA-LSU at 7m asl, $P = 101.2\text{kPa}$. $N10^\circ44' = 0.1873\text{rad}$.

by low R^2 . This is detected by modelling efficiency (EF), the squared difference of explained and total variance divided by explained variance. For both R^2 and EF, a value of one stands for best fit of prediction and measurement; EF can become a negative value. The root mean square error (RMSE) gives a percental error of the predictions from the mean of observations. Best fit would be associated with an RMSE value of 0. Formulae for all model fit statistics can be found under 2.8.

For abaca, the reference unit to measured AGB was C_CanBiom, the sum of stem, leaves, storage organs and, theoretically, fruits. Modelled values were compared to the average of all surviving plants at the respective inventory, not the totality including dead plants. As measured soil parameters were available at sufficient detail, only adjustments affecting plant physiology were made during calibration: In a first instance, *relative light intensity at which shading affects growth rates* ($T_RelLightMaxGr$) was adjusted; this is the 'light switch' in WaNuLCAS, a threshold at which plants can still achieve maximum growth. Daily maximum dry matter production was also modified, as it limited biomass production below levels observed on site (fig. 85). For tree calibration, basically the same procedure was applied with light and maximum growth as adjusting screws. The model was calibrated for *S. contorta*, *D. validus*, *A. heterophyllus* and *D. zibethinus* (fig.86-89).

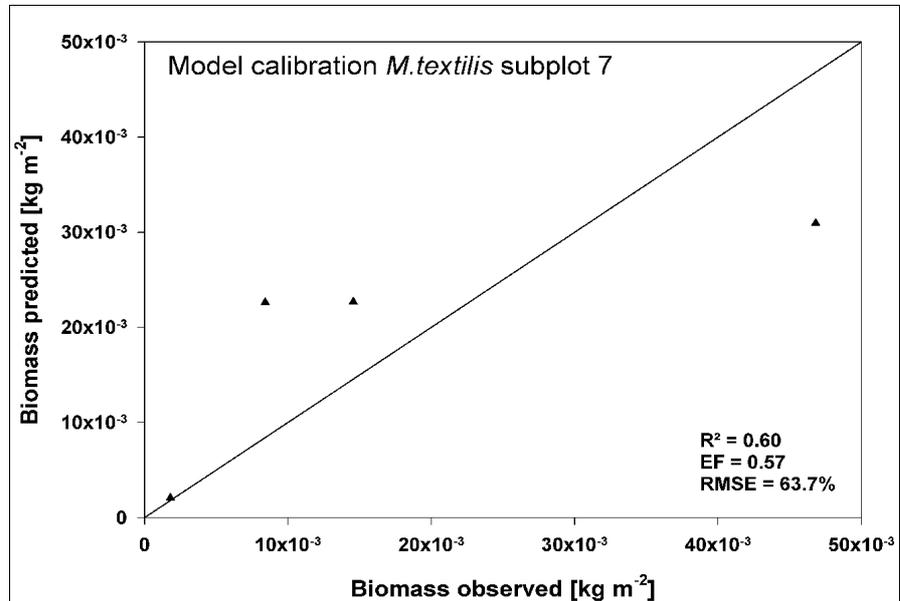


Figure 85: Model calibration for *M. textilis* on subplot 7, Cienda (open area)

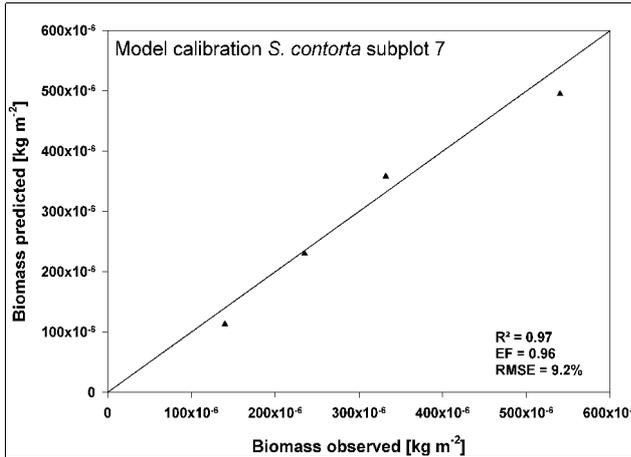


Figure 86: Model calibration for *S. contorta* on subplot 7, Cienda (open area)

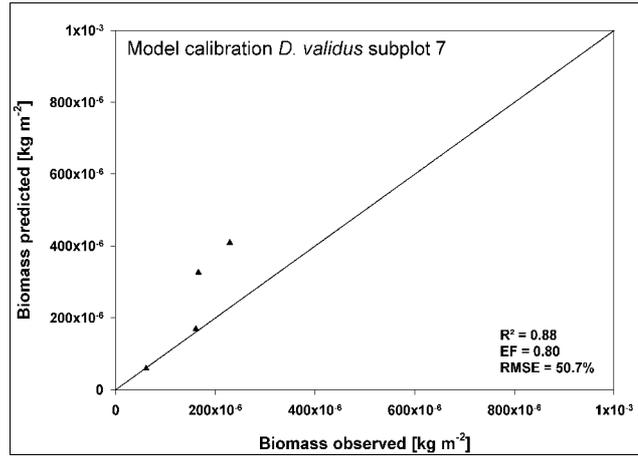


Figure 87: Model calibration for *D. validus* on subplot 7, Cienda (open area)

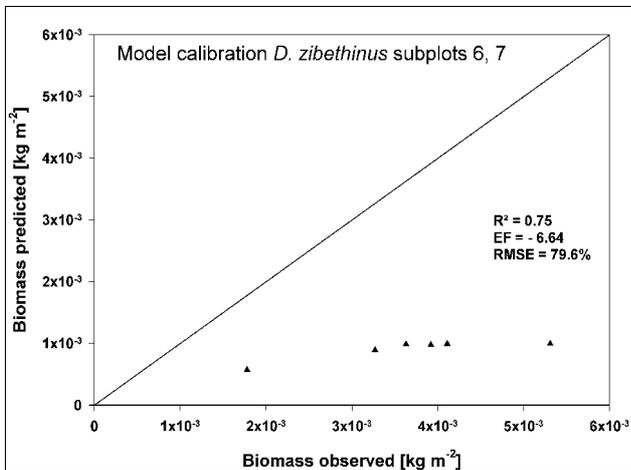


Figure 88: Model calibration for *D. zibethinus* on subplots 6&7 (average, open area)

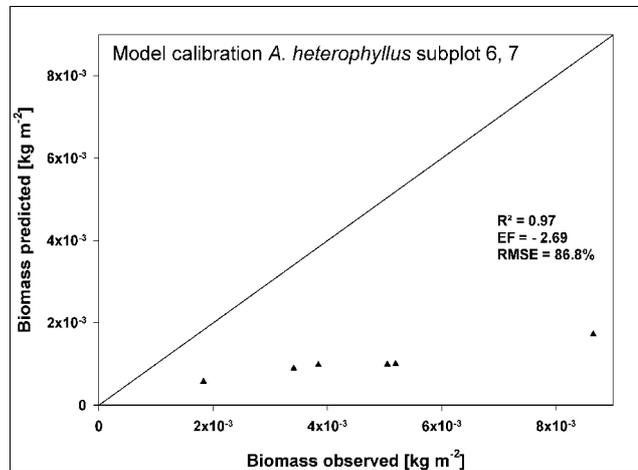


Figure 89: Model calibration for *A. heterophyllus* on subplots 6&7 (average, open area)

The slow overall growth in abaca biomass was represented well – plant growth stagnated after a small initial increase – but the high mortality under field conditions was not sufficiently reflected as negative growth in the simulation. Still, coefficient of determination (R^2) remained below values obtained for timber tree calibration. Root mean squared error (RMSE) was satisfactory for *S. contorta*, less for *D. validus* and *M. textilis*. For durian and jackfruit, good fit with respect to correlation coefficient and R^2 does not reflect the constant underestimation revealed by modelling efficiency and RMSE. A calibration for *Gmelina* was not carried out, because the species had not been planted in Cienda in 2004 and not included in inventories. Anyway, heights of ten year old trees at Marcos were known from FBA and could be used to estimate plausibility of modelling.

Generally, the numerous parameters in WaNuLCAS would allow for a very precise calibration; on the other hand, it cannot be the intention to deviate too much from measured values and create artefacts. In addition, these would be very site-specific and most likely not match data during validation. In small datasets, the used statistical terms are sensitive to outliers (LOAGUE & GREEN 1991). Especially for young plants, which are strongly susceptible to environmental factors (here: water stress), these environment-related outliers can occur even across means of many plants.

6.3 Validation

All validation was carried out on aboveground basis⁸⁸, which can be displayed separately by the model. This was considered more accurate than total biomass as available aboveground field data were more precise than root biomass data. Four different data sets on biomass were used to evaluate the fit of simulations.

- Growth of abaca under canopy on subplots 8 and 10 in Cienda, varying mainly in light conditions and to some extent in SOM and water. These subplots represent optimum growth.
- Growth of the trees planted under canopy at Cienda in 2004 (also subplots 8 and 10).
- Height of trees planted in 1997 at the Cienda demo site and
- at the LSU rainforestation plot installed from 1992 onwards.

Tree inventories by KOLB (carried out in 2003) served as a basis for the two latter datasets. For LSU, soil data by ASIO (1996) were available to initialise the model; for Cienda these had to be estimated.

6.3.1 Abaca and tree seedlings in Cienda

Two different characteristic subplots at Cienda were tested for abaca and tree growth. These were the banana-dominated subplot 8 and subplot 10 under tree canopy, which had yielded the highest abaca growth rates. For both areas soil data were available from measurements presented in chapter 5. Profile data from PN1 and 2 (see chapter 3) were used to complement these.

Both subplots were under canopy when the plantation was installed in 2004. Thus, the challenge was to simulate reduced light availability and competition with trees present before plot installation. Two options were tested:

- To grow trees well before 2004, which would reach the density, height and lower canopy boundary observed on site before planting. Following this approach and using plant physiological values as calibrated for the open area PN3, competition for light was extreme. Almost independently of planting dates, one tree species grew vigorously and shaded out the second species. A minimal change in light demand (T_RelLightMaxGr) could make *D. validus* overgrow *S. contorta*, although the latter had been planted 6 years in advance. Secondly, the present canopy was composed of different species, which the model had not been calibrated for. N and P were only minor limitations to the growth of either species, which led to the second approach:
- To plant all trees at one time, assuming the influence of the canopy to be restricted to reduced availability of sunlight and reduced transpiration leading to less water stress. In a simplified approach, this was done by setting Run_WaterLim? to 0.5, in other words to reduce water stress. Biomass was then calibrated setting a fixed shade tolerance (T_RelLightMaxGr) and initial amount of growth reserves (T_GroResInit, in stella) and successively varying species-specific potential growth T_MaxGro. This procedure can be justified as competition for N or P was not limiting at the given seedling stage and planting distances.

Simulation run time was 1460 days from Jan 1st, 2003, onwards with all species planted after 16 months on May 1st, 2004. 20% slope and one forested plot uphill were assumed for both subplots, extension of all agroforestry zones (AF_ZoneTot) was 10m, equally shared among *S. contorta*, *M. textilis*, *M. textilis* and *D. validus*. Planting density for the trees was 200 per hectare and species. Measured and predicted data of aboveground tree biomass were compared on inventory days 544 (58 days after planting), 678, 834, 910,

⁸⁸ T_BiomAG for trees and C_CanBiom as sum of leaf, stem, fruit and storage organ biomass, for crops.

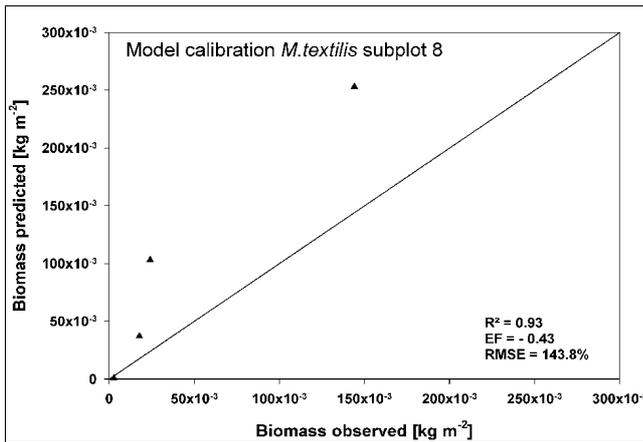


Figure 90: Model calibration for *M. textilis* on subplot 8, Cienda (area under canopy)

1065 and 1218 and on days 570, 855, 915 and 1215 for abaca. Plant physiological parameters as calibrated for the open area were used first. Even without water and nutrient competition through big trees, plant growth stagnated after small initial growth under these settings, so that a new plant calibration was necessary for the plots under canopy; this was realised for subplot 8. The adjusted physiological settings are listed in the Annex and the goodness of fit statistics are shown in fig. 90-94.

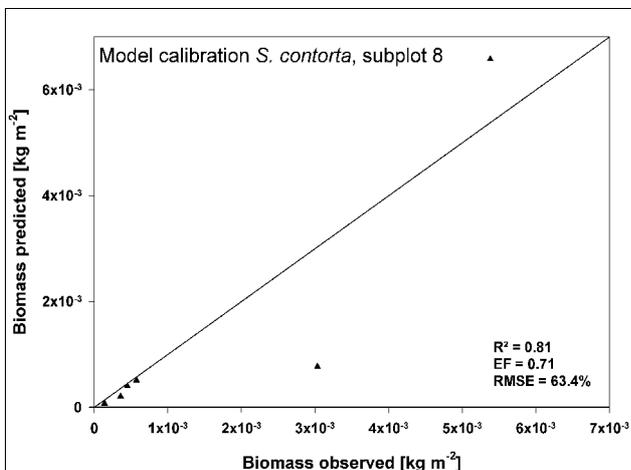


Figure 91: Model calibration for *S. contorta* on subplot 8, Cienda (area under canopy).

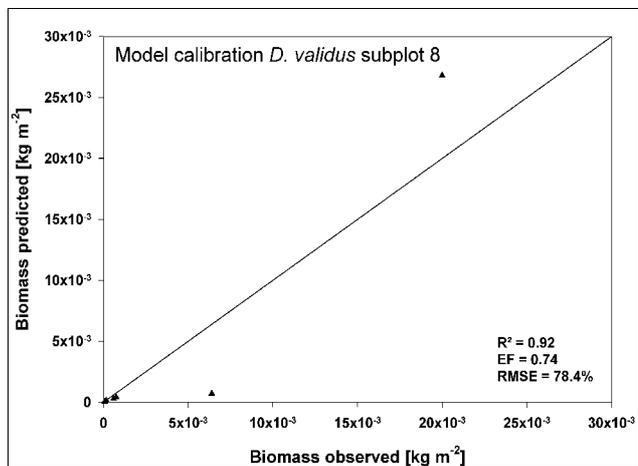


Figure 92: Model calibration for *D. validus* on subplot 8, Cienda (area under canopy).

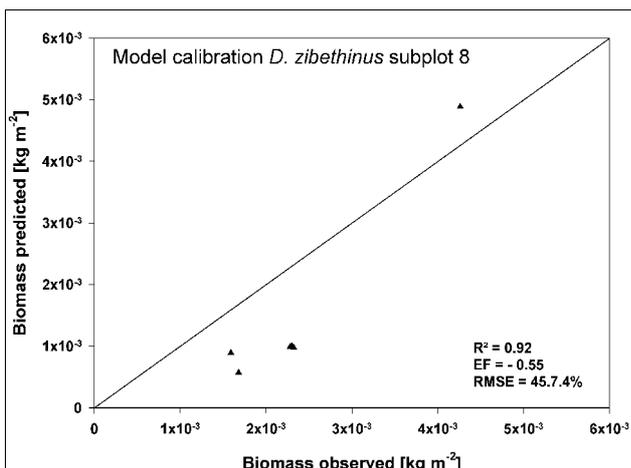


Figure 93: Model calibration for *D. zibethinus* on subplot 8, Cienda (area under canopy)

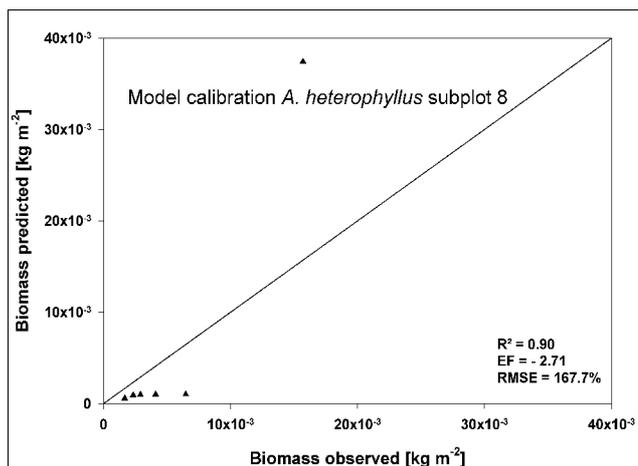


Figure 94: Model calibration for *A. heterophyllus* on subplot 8, Cienda (area under canopy)

In most cases for subplots 8 and 10, maximum biomass, corresponding to the last inventory date, was much higher than values of the previous dates. This can be explained by the relatively high growth rates on these subplots once plants were well established; on

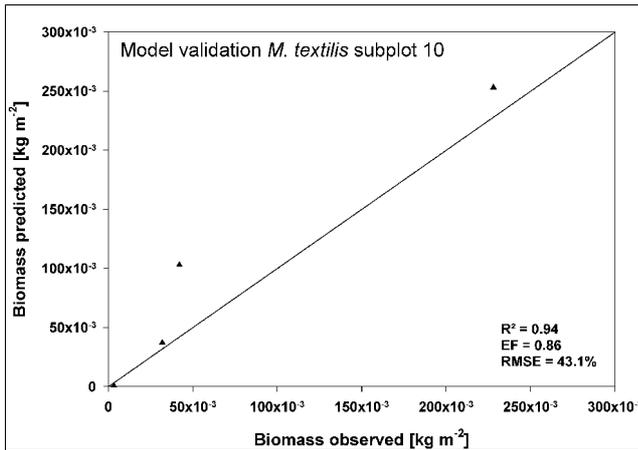


Figure 95: Model validation for *M. textilis* on subplot 10, Cienda (area under canopy).

subplots 6 and 7, in contrast, biomass remained low even at later development stages. Despite very good R^2 , calibration for abaca and jackfruit were not satisfactory with respect to modelling efficiency and RMSE. For durian, EF was also not satisfactory, while R^2 was very good and RMSE was still acceptable. Biomass of both timber species was underestimated when simulating the last but one inventory date, but still rendered very satisfactory modelling efficiency and R^2 . Data obtained for subplot 8 were then used to test the validity of the calibrated model to predict the dataset of subplot 10 (fig.95-99).

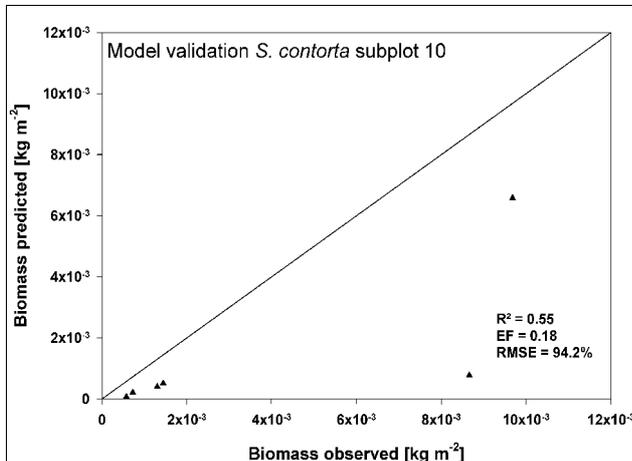


Figure 96: Model validation for *S. contorta* on subplot 10, Cienda (area under canopy).

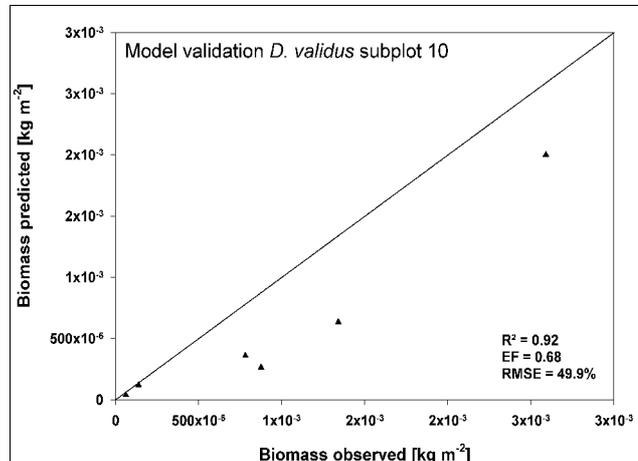


Figure 98: Model validation for *D. validus* on subplot 10, Cienda (area under canopy).

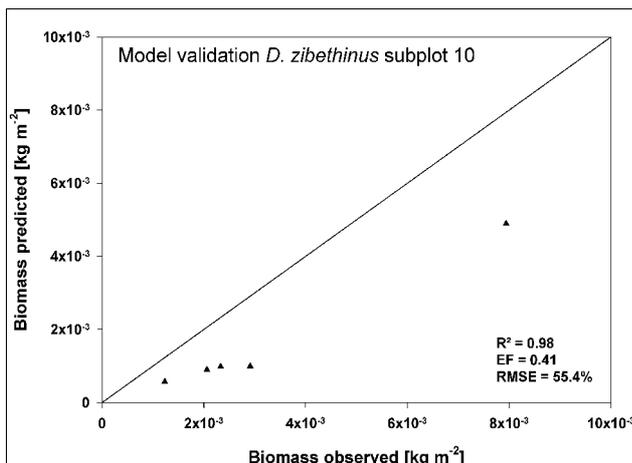


Figure 97: Model validation for *D. zibethinus* on subplot 10, Cienda (area under canopy)

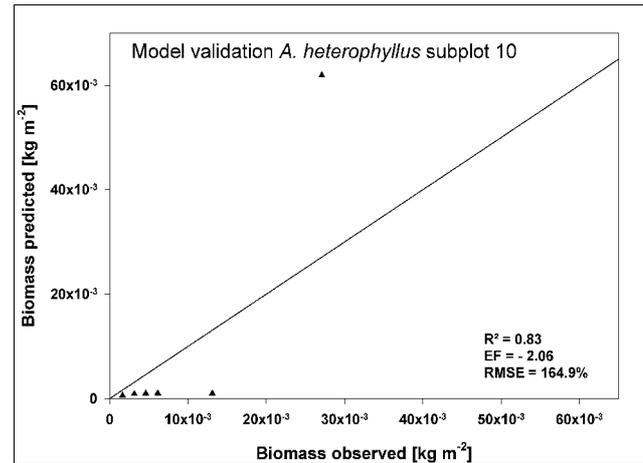


Figure 99: Model validation for *A. heterophyllum* on subplot 10, Cienda (area under canopy)

This time, abaca and *D. validus* were predicted well and so was durian, while the linear regression for *S. contorta* was constantly below the 45° line and thus biomass was underestimated. Jackfruit was massively overestimated when predicting the last measurement, but underestimated for the previous measurements. This points to a general tendency, which can be also observed for *S. contorta* (fig. 96): The last but one inventory was carried out without supervision and several, especially smaller, plants were overlooked; this impression was verified during the last inventory, when supposedly dead plants appeared again. So to speak, growth was not underpredicted, but measurement averages were inflated. Effects of the exceptionally dry period in 2005 were best visible as limiting factor for abaca growth. Nutrients were not limiting for plant growth, if a short but steep drop-down in P-supply is neglected. This sudden descent always occurred directly after planting and lasted only 1-2 days before returning to 100% or optimum supply. This seemed to be an artefact rather than a physiological effect.

6.3.2 Trees planted 1996 at Cienda site

This validation builds on data collected by KOLB (2003) from May - Jul 2001, five years after installation of the demo plot at Cienda had started. KOLB's soil data for pH KCl, C:N ratio and clay contents were almost identical to those obtained during this study, but C_{org} was higher (3.6 vs. 2.77%) in 2001 compared to 2004. CEC in 2001 doubled and BS tripled that found in 2004, while Al saturation was also remarkably higher in 2001. This is likely to be due to different sampling points rather than to changes in time. Simulating weather data, open area temperatures were used as the plot had been planted to annuals before the tree plantation was installed. A four-year loop was used for rainfall, temperature and soil evaporation. Run time was 2005 days, from Jan 1st, 1996 until Jun 30th, 2001, planting time being on day 90 in year 1996. Planting scheme was dense, 2x2m as initially planted (in reality this was intensified to 2x1m later, but at high mortality), resulting in 2500 trees per ha and species. Plant parameters as obtained from the calibration of PN3 were employed as the plantation was set up under open sky. Comparison of observations and predictions were based on tree height; when this was not indicated in the reference data, formulae provided by Kolb to convert diameter into height data were applied. These are

$$H = 1.3 + \left[\frac{d}{0.8719 + 0.39239d} \right]^3 \quad \text{for } D. \textit{validus}$$

$$\ln H = 0.72364 + 0.79444 \ln d - 0.03803 (\ln d)^2 \quad \text{for } S. \textit{contorta}$$

with H = height and d = diameter at breast height.

For simulation of understorey trees, it was assumed, that these had been planted later. Thus, one species was given an advance of 2 years before the second species was planted. This corresponds to the extended planting period mentioned by Kolb and obtained during interviews with resource persons.

Table 25: Measured and predicted tree height for various species at the Cienda demo plot

Species (all planted 1996)	Average height [m] observed	Height [m] predicted
Overstorey		
<i>S. contorta</i>	12.62	12.52
Understorey		
<i>S. contorta</i>	3.41	10.56
<i>D. validus</i>	3.78	6.17

Height of *S. contorta* was predicted very well for the main stand (see tab. 25), which may be attributed to the use of original weather data. On the other hand height of understorey trees was subject to the difficulties mentioned before and thus over- or underestimated. Realistically, simulated height increase of seedlings planted under tutor trees was accelerated if compared to plants of the same species growing under full sunlight. Further, understorey plants stretched out towards the sunlight as can be observed in dense stands. On the other hand, denser spacing of even-aged stands led to less height increase, which is contrary to observations in plantations, unless other factors than light are more limiting to plant growth.

6.3.3 Trees planted at LSU in 1991-3

Reference measurements for validation were again obtained from Kolb's inventory in 2001 as given in table 27. Observations by QUIMIO ET AL. (1998) 5 years after planting are shown for comparison in table 26. Kolb based his inventories on a calculated original planting density of about 10,000 trees per hectare and subsequent mortality of 50%. For the part of the area under study, density was clearly lower in 2004, so that 2500 trees ha⁻¹, shared among two species, were assumed for simulations. For weather data, a 4-year loop was run on soil temperatures starting under open sky. Simulation run time was 3500 days. Profile data from ASIO (1996) were evaluated to obtain an estimate of the original state of the soil. Horizonation was almost identical, if ASIO's Bt1 and 2 are merged into one horizon and roughly 5cm deviation in topsoil thickness are considered due to different profile positions and soil erosion. Texture, pH and even organic matter contents mentioned by ASIO (approximately 4% OM, corresponding to 2.3%C) were found unchanged⁸⁹ compared to those found in 2005.

Table 26: Observed (QUIMIO ET AL. 1998) tree heights at LSU site 1998

Species	Number of observations	Average height [m] observed
QUIMIO ET AL. (1998)		
Plot # 1		
<i>S. contorta</i>	18	5.17
<i>D. validus</i>	19	5.05
<i>A. heterophyllus</i>	3	5.33
Plot # 2		
<i>S. contorta</i>	9	3.75
<i>D. zibethinus</i>	8	3.48
Plot # 3		
<i>S. contorta</i>	8	5.26
<i>D. validus</i>	16	5.88
<i>D. zibethinus</i>	5	5.20
<i>A. heterophyllus</i>	1	7.30

As for Cienda, measurements were differentiated into two groups, main stand and understorey. While simulation of the main stand was straight forward, conditions were simulated for the understorey by letting one set of trees grow from year 0 onward and plant the second set in year 5 (as sequential planting at LSU took from 1991-1996; KOLB 2003). For this case, planting density was assumed to be 1650 trees per species and hectare. A spacing of 2m between and 1.5m in lines was implied for undergrowth simulation. Especially planting distances of *D. validus* as overstorey species were crucial for the development of *S. contorta*.

89 or recovered

Under these circumstances and with no adjustments effectuated in the spreadsheet or stella file, growth of *S. contorta* was overestimated, while *D. validus* was predicted well for both strata (tab. 27). Modelling jackfruit also gave a realistic picture, but understorey durian was overpredicted.

Table 27: Observed (K_{OLB} 2003) and predicted tree heights at LSU site 2003

Species	N of observations K _{OLB} (2003)	Average height [m] observed	Height [m] predicted
Overstorey			
<i>S. contorta</i>	17	12.1	18.12
<i>D. validus</i>	46	10.1	12.82
<i>A. heterophyllus</i>	8	11.9	10.46
Understorey			
<i>S. contorta</i>	31	5.5	11.27
<i>D. validus</i>	38	6.3	5.24
<i>D. zibethinus</i>	9	4.6	12.98

D. validus was more susceptible to water stress than *S. contorta*, but turned into the stronger competitor once P limitations were switched off. Shifting the planting date from dry into wet season did not significantly affect biomass development, while a dry spell during any later year could still have drastic effects. This has been documented by K_{OLB} (2003) for the Cienda plot in 2000, when drought supposedly killed the majority of a pioneer species (*Melia dubia*) more than four years after planting. This needs to be considered since original weather data were only used for the last years of the model run and copied backwards in time.

Causes of overestimation of *S. contorta* were assessed through different approaches. Running a sensitivity analysis across a wide range of C_{org} contents (more precisely, of Mc_CNRatNitMetab, i.e. different C:N ratios at stable N contents), did not lead to any response in aboveground biomass of *S. contorta*. Water, N and P limitations affected potential growth of *D. validus*, but for *S. contorta* limitations were probably caused by other factors or intrinsic to plant parametrisation.

Gmelina as parametrised on ten year old trees in Marcos was tested for LSU site and gave plausible heights of 11.64m after 3500 days. The dry season from approximately day 2600 onwards delivered very realistic biomass loss due to leaf shedding. At the same time, N and P availability dropped suddenly as would be assumed as an effect of drought. In summary, validation showed, that biomass and height could principally be predicted for small as well as taller trees on the basis of the same calibration set-up. Calibrations could be used across different sites, but not transferred from plots under full sun to such under canopy. These experiences are true for simulations of even-aged plantations, while predicting growth of understorey trees was not possible to the desired accuracy under the given circumstances. Simultaneously growing *S. contorta* and *D. validus* complicated simulations of undergrowth species and did not always deliver plausible results. Kolb's documentation does not inform, whether understorey trees had been planted later than others, e.g. as replacement, or overtaken in growth and shaded by others. Apart from this, planting density at LSU could not be exactly reconstructed, because seedlings had been planted randomly with respect to species and position. Growth rates often oscillated between two extremes, which were caused by competition and could be inverted by small changes in planting density.

6.4 Modelling land use scenarios

The main goal of modelling was a comparison of various land uses under the aspect of carbon sequestration in context with potentials for CDM projects. In this context, the following hypotheses were formulated:

- Within 20 years after planting, an agroforestry system as planted in 2004 at Cienda will:
 - a.) act as a sink for CO₂ and
 - b.) sequester more carbon than the traditional grasslands but less than a dense *Gmelina* pure stand.
 - c.) This is also true for the soil carbon balance of the systems.
- In addition to its marketable yield, which is not evaluated here, the abaca component will – due to the rapid biomass build-up – contribute significantly to carbon sequestration in the system.

With respect to phosphorus as most limiting nutrient, another hypothesis was tested with WaNuLCAS :

- Limiting P resources can be mobilised from the subsoil by trees and via litterfall made available to plants with a superficial rooting system.

6.4.1 Scenarios

To test the hypotheses, the following scenarios were based on some common assumptions: Soil pedotransfer functions and nutrient contents for all scenarios were those of subplot 10, combined with profile data for PN1. This plot is representative for slope lands under extensive use. It was assumed that the plots had been cleared for the plantations, which were installed under full sunlight using the respective weather data in a 4-year loop from 2003-6. On the basis of the available calibration, scenarios focused on the time frame covered by the reforestation projects, roughly ten years.

- Scenario 0 (CO₂ baseline):

Grassland as a widespread land use in Leyte was chosen as the baseline scenario for carbon sequestration of improved systems. Grassland plots often contain scattered coconut trees, which were not taken into account for any scenario. It was assumed, that they would be maintained under agroforestry use, so that costs, benefits and carbon sequestration concerning this component would generally not differ between the systems. On the other hand, cultivation of cocos palms is usually a pre-requisite for grassland as it implies the necessity to brush the land before every coconut harvest, which prevents significant biomass to build up in the form of natural forest regeneration. For the dominating *Imperata cylindrica*, default values provided in the model were used. The reference scenario does not include burning, overestimating the average carbon balance of all grasslands in Leyte.

- Scenario 1a: *S. contorta* + *D. zibethinus* + *M. textilis*, 20% slope, no pruning:

This basically represents the system installed in 2004 at Cienda site. Planting distances are 10x10m for timber trees, 5x5m for fruit trees and 2.5x2.5m for abaca (lay-out see chapter 2), resulting in 100 timber and 300 fruit trees and 1200 abaca plants per hectare. The lines were arranged as timber-abaca-abaca-fruit, zones being distributed equidistantly over 10m. No external inputs were imported and maintenance was reduced to a minimum as is the case for many upland plots in Leyte, which are located distant from their owners' homes. Weeds were included in the scenario (at 0.5 level); their contribution to the carbon balance can be distinguished and listed separately in WaNuLCAS. Anyway, undergrowth vegetation is shaded out in the model once maintenance respiration leads to a negative

CO₂-balance for a plant. Besides weeding, pruning was also not included in this scenario. This was later contrasted with a pruning scenario to assess effects on abaca growth.

Tree and abaca parameters were based on the calibrations for subplot 10, but slightly modified due to the presence of weeds and absence of canopy. In the case of *S. contorta* this meant, that T_RelLightMaxGr was increased from 0.15 (under canopy) to 0.35, and that T_MaxGro was slightly reduced from 0.0409 to 0.049. Inputs for plant growth are documented in the attached CD. For abaca, seed weight was increased as is the case for corms compared to tissue culture; in addition, planting was shifted to September (Julian day 244), the onset of the rainy season.

Plant biomass and carbon as well as soil carbon were then evaluated against those of the baseline.

- Scenario 1b: *S. contorta* + *D. zibethinus* + *M. textilis*, 20% slope, pruning

An option of automatic pruning as soon as the trees surpassed an LAI of 2.5 was chosen to increase available light for the understorey abaca. An additional effect of this management on SOM was expected as the pruned biomass was left on the field. Parameters evaluated were abaca biomass and SOM carbon as compared to 1a.

- Scenario 1c: *S. contorta* + *D. zibethinus* + *M. textilis*, no slope, no pruning

This scenario was chosen to assess the influence of soil erosion on soil carbon stocks. Settings were the same as for 1a except slope, which was set from 20% to 0%. Soil carbon as influenced by erosion was compared to contents of scenarios 0 and 1a. In the same context, systems with different litter and mulch inputs were evaluated.

- Scenario 2: *S. contorta* + *D. zibethinus*.

This scenario was chosen to quantify the contribution of abaca to the system in terms of carbon sequestration. In WaNuLCAS, biomass is listed separately for each component or planting zone of the system. However, a simple subtraction of the abaca biomass calculated in scenario 1a may not have accounted for interactions between crop and trees. For this reason, an extra scenario was run. Planting distances are the same as for the previous scenarios, as otherwise trees would strongly interfere during later years. Biomass and soil carbon were compared to those of scenario 1a.

- Scenario 3: Subsoil P acquired through tree roots

Subsoil phosphorus contents were one important reason to choose PN1 for modelling. P is a limiting factor for plant growth in many volcanic soils in Leyte (ZIKELI 1998, ZÖFEL 2004), but was found in higher concentrations in the PN1 subsoil. It was of interest, if trees would be able to tap this pool and make P available to the system, including shallow-rooting abaca (CANNELL ET AL. 1996). *Gmelina* as a fast-growing competitive plant was used for this test. In a first simulation run, a.), *Gmelina* was grown under the conditions found at PN1, i.e. at 25mgP kg⁻¹ in the subsoil. For the comparative run b.), subsoil P was reduced to 1mgP kg⁻¹, a typical concentration found in other Leyte soils. c.) Doubled root length density in the deepest soil layer. All other parameters were left unchanged and both scenarios were evaluated with respect to P contents in tree tissues and litterfall. Apart, carbon balances of 3a were included in the systems comparison.

Run time for scenarios 1-3 was 3500 days, less than one rotation of a timber-oriented system, but long enough for the fruit trees to enter in production.

- Scenario 4: Comparing long-term carbon balances

An exploratory scenario over 7300 days was added to estimate long-term total carbon balances of a.) the grassland, b.) rainforestation and c.) the *Gmelina* system. Environmental conditions were left unchanged to those of scenarios 0, 1a and 3a.

6.5 Modelling outputs

6.5.1 Total carbon balance compared across land uses

In a comparison of the grassland baseline (0), the rainforestation system and the dense and fast-growing *Gmelina* pure stand (3a), balances of total carbon during 7300 days were not as presumed for hypothesis 1b (fig.100): Although both captured more carbon than the *Imperata*-grassland, the expected ranking between tree-based systems was inverted. *Gmelina* as a pioneer species grew ahead of the mixed system during the first years, but was soon overtaken. This was due to the surprisingly fast growth of *S. contorta*, which overestimated observed growth at Cienda demo site (after 5 years) and LSU (after 10 years). At the same time, modelled height increased faster than cross-checking at LSU or Marcos would have suggested. Tendencies of the simulation are valid even though the absolute magnitude of *S. contorta* was not predicted correctly. Magnitudes of C stocks and rates will be discussed in depth under 6.6.2. Comparing predictions to literature data will show, that the simulation is not too far from real conditions.

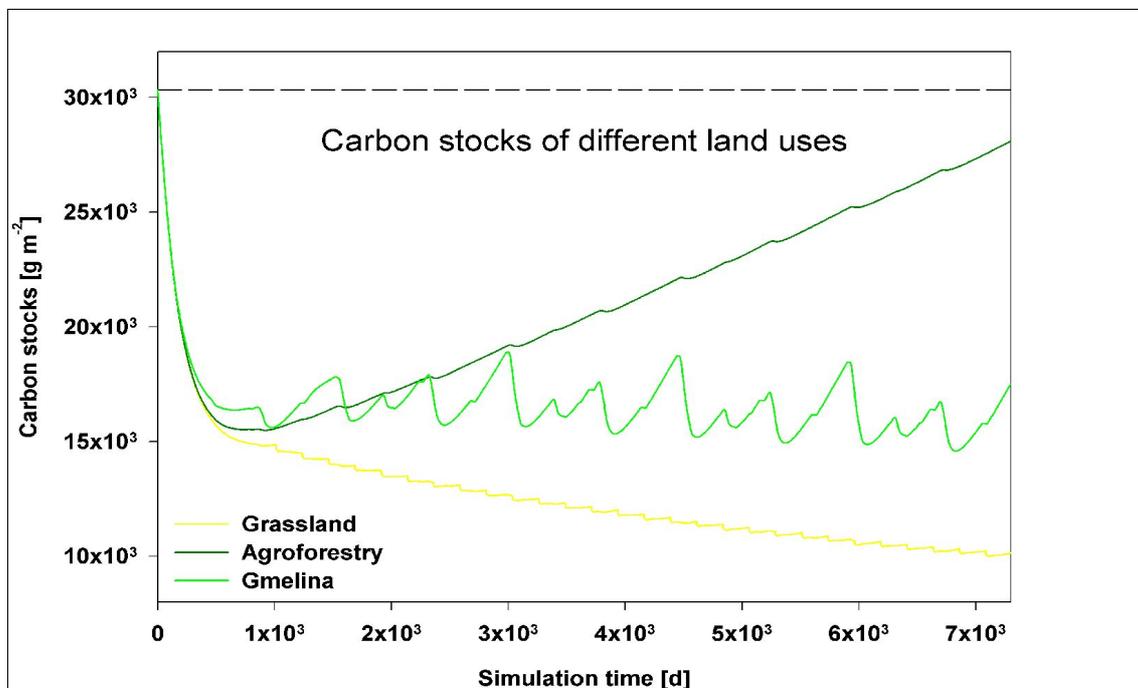


Figure 100: Carbon stocks under different land uses during 7300 days of simulation

An intrinsic limitation in the plant parametrisation file was not the reason for the slightly decreasing tendency in *Gmelina* biomass; this is fully attributable to environmental conditions. Oscillations in *Gmelina* biomass can be explained by leaf shedding due to water stress: A factor governing the degree of leaf shedding as a reaction to water stress ($T_LifallThreshWstr$) is defined for each species. This value was estimated to be 0.5 for *Gmelina*, 0.7 for durian and 0.9 for *S. contorta*, which explains the more constant progression of the latter. In conclusion, while slow-growing durian was well-predicted, *S. contorta* is likely to be overestimated as had been the case for the LSU validation. The common sense impression of *Gmelina* as a fast-growing species is true with respect to tree height; looking at biomass, this is partly rectified through the low wood density and losses in leaf litter.

Hypothesis 1a, too, could be discarded. A break-even for carbon stocks (intersection with the dashed line in fig. 100) to the state before planting was not reached within the simulated time of 7300 days. Under a more realistic growth of *S. contorta* the break-even point would be postponed even further. Still, carbon balances are calculated against a business-as-usual baseline, not against previous levels, so that for CDM purposes the scenario would be considered as a relative sink. In the scenario, carbon stocks departed from a relatively high level characteristic for recently cleared fallows, but not degraded lands. A more typical land use history would be fallow → clearing → annual crops → land rehabilitation through agroforestry. In that case, soil carbon stocks at planting time of the agroforestry system would have started from a lower level and a positive balance been reached earlier. The warming potential – expressed as CO₂ set free from the plot and inverse to carbon sequestration (both in gCO₂ equivalent m⁻²) – would then be lower. Total carbon balance during the first years was almost entirely determined by changes in soil carbon stocks as plants still did not contribute substantial amounts of C to the system. Absolute magnitudes of soil carbon depletion during the first years appear extreme, especially as no tillage was involved.

6.5.2 Biomass distribution between plants and agroforestry zones

Fig. 101 gives an impression of the different components' contributions to total biomass. It shows the dominant influence of *S. contorta*, which is realistic if compared to older plots as in Marcos or (s. KOLB 2003) at LSU, even though the absolute magnitude was overestimated (see previous section). This did not change, if the plant settings from Cienda DS validation – which had given an excellent fit – were used instead of the slightly modified version used here. These validated settings differed from the ones used here with respect to maximum growth rate (which was actually even higher for the validated settings) and extinction light coefficient (which was reduced from 0.78 to 0.5). When the maximum growth rate was maintained and extinction light coefficient reduced, *S. contorta* did not grow beyond its planting stage.

Durian reached a relatively stable level after approximately 5 years, which is not due to the transition from the vegetative into the generative phase, which *per definitionem* did not start before day 2920. It is rather owed to an intrinsic limit set in the spreadsheet for canopy height above stem (assuming an improved variety with limited growth). Oscillations from this stable tendency are due to leaf shedding as a consequence of drought. Phases of decreasing biomass coincide with water stress (limiting factors for durian will be discussed later).

As measurements confirmed, abaca contributed a significant C input during the first years in relation to the tree component, but not if sequestration during the entire cycle is considered. Hypothesis 2 needs to be answered with some differentiation; it can be accepted, if the first two years are considered but is not valid over a longer period.

As a consequence of light competition, abaca biomass in zone 2, next to *S. contorta*, constantly remained below that in zone 3, next to the less competitive *D. zibethinus*. Abaca in zone 2 was shaded out around day 900 (i.e. biomass decreased to values near zero), more than two years before abaca in zone 3. WaNuLCAS allows to display factors limiting plant growth: Departing from potential plant growth under optimum conditions, limiting factors water, light, N and P can be quantified as a percentage of amounts/concentrations required for maximum growth. Using this option, light already became a limiting factor before a dry spell hit the plot around day 900. Abaca growth in zone 3 was constrained to a lesser extent by lack of nitrogen from day 900-1700.

At this point, abaca in zone 2 had already been phased out. In context with competition, an advance in planting of 154 days for the trees has to be taken into account. As abaca grows fast under favourable conditions, simultaneous planting could have retarded the take-over of trees for several months or in some places protected trees from too much sunlight.

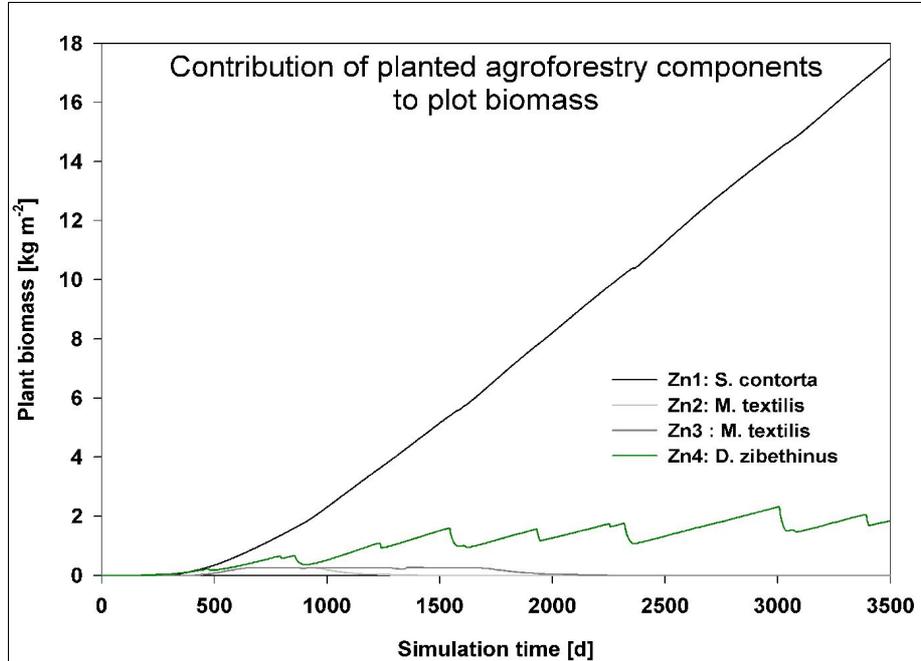


Figure 102: Contribution of pools to the agroforestry C balance

When the abaca component was omitted, but planting pattern and density for trees were maintained, the total carbon balance was lower than in the scenario that included abaca (fig. 102).

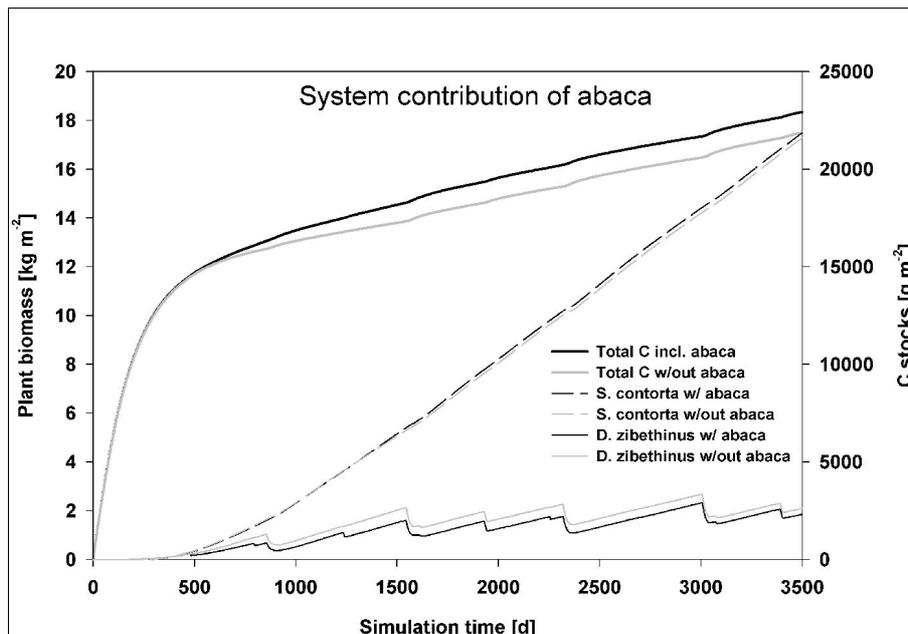


Figure 101: Contribution of *M. textilis* to the system C balance

This is not obvious as trees partly made use of the freed resources and could have (over)compensated for the missing element. A relatively higher biomass production of durian indeed compensated for some of the resources desoccupied (grey hairline in fig. 102).

S. contorta biomass remained the same between scenarios during the first years, but was slightly lower in the system without abaca. This cannot be explained as a direct effect of abaca, but as competition with a fortified durian, which during the first years benefited from more light in the middle stratum and less belowground competition.

Apart from initial carbon sequestration, increasing demand of abaca fibre could be a justification to patronise this element. The importance of abaca as of any annual crop in agroforestry lies in the timely return of investments, which otherwise confines acceptance of tree-based systems among farmers with limited capital. In scenario 1b, the effects of tree pruning on abaca biomass were assessed. WaNuLCAS offers an automatic pruning option, which allows to determine a percentage of biomass reduction as soon as the leaf area index of a tree surpasses a defined threshold. In the case of scenario 1b, this was set to LAI 2.5 which induced pruning.

Fig. 103 illustrates the effect of such pruning on abaca biomass. For zone 2, pruning was minimal as WanFBA determined a maximum LAI of 2.66 for *S. contorta*.

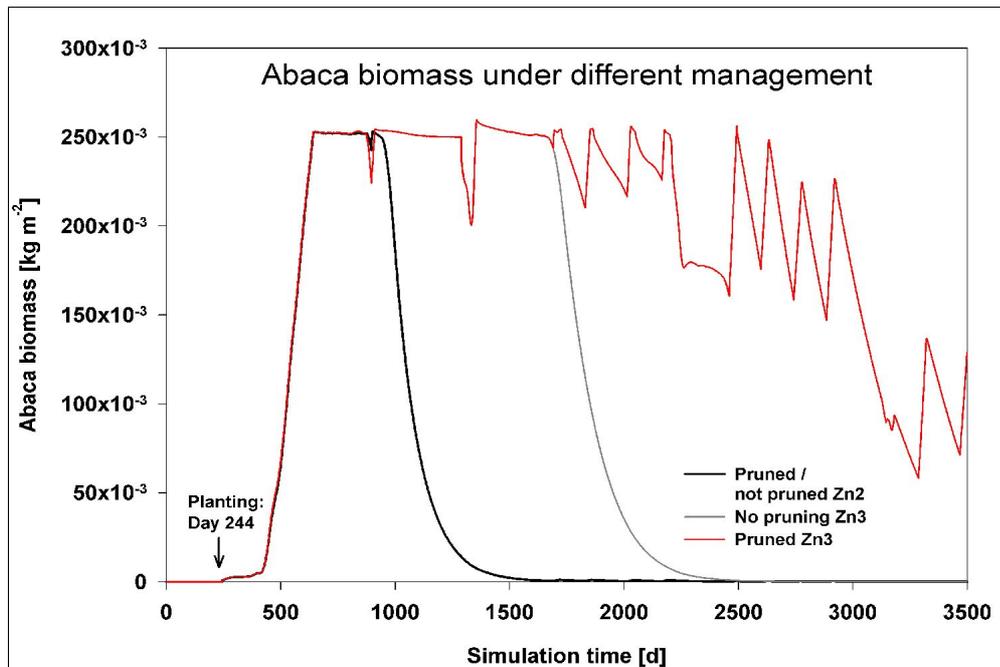
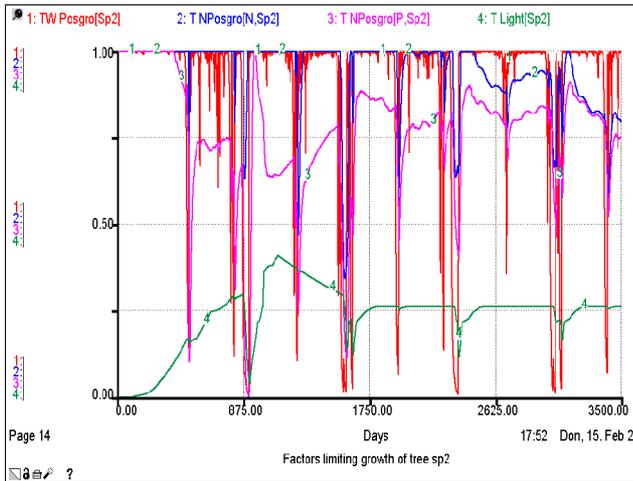
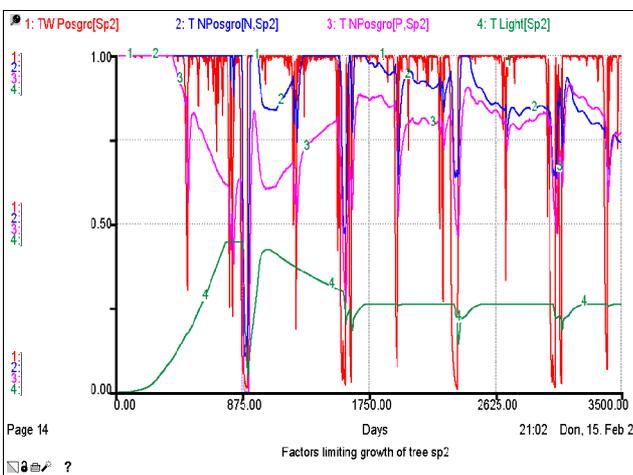


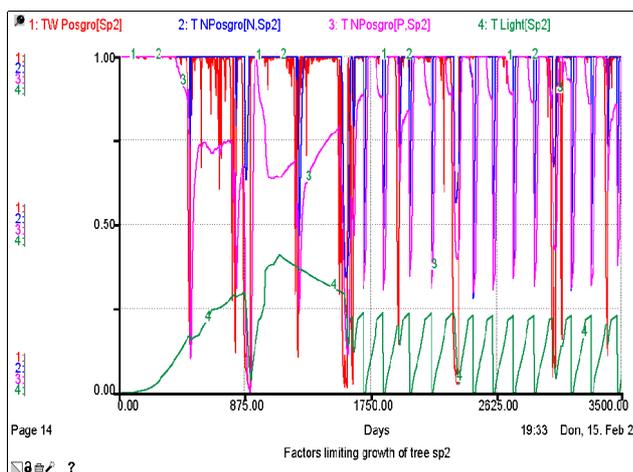
Figure 103: Effect of tree pruning on abaca growth



System with abaca



System without abaca



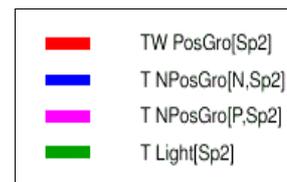
System with abaca; durian pruned

Figure 104: Durian biomass as limited by water, N, P and light as a consequence of planting system and management

Consequently, abaca growth was equal with and without pruning. In zone 3, the reduced canopy of durian led to longer permanence of abaca in the system, even though at decreasing biomass levels. The same effect could be obtained in zone 2 without pruning, when the original Cienda demo validation settings were used for *S. contorta*. These include a lower extinction light coefficient (0.5 instead of 0.78), which allowed more light to reach the abaca canopy.

Limitations for durian growth were also explored under different management options. While pruning of timber branches is beneficial to obtain a straight bole and self-pruning species may be preferred, yields of fruit trees may decrease under heavy pruning, depending on planting distances and variety. On the other hand, pruning will increase yields and facilitate harvest, if carried out correctly. Generally, if space is limited, it will be ceded to the more profitable crop, which is in most cases the fruit tree. The scenario assumes improved varieties of durian with limited canopy volume, for which mild pruning is sufficient even at dense planting. In practice, this corresponds to the grafted early-yielding varieties planted at Cienda.

Fig. 104 shows the modelled response of durian potential growth to different species composition and pruning. As mentioned before, depressions in durian growth around days 900, 1600, 2400 and 3100 were related to water stress additionally causing shortages in P supply.



The main difference between the systems with and without abaca consists in increased light availability for durian in the mixed system until approx. day 875. Competition for water occurs mainly during the initial 1.5 years, but also during single events as from days 2240-60. Effects of P competition are observable during >5 years. Looking at the pruned system (which includes abaca), reduced light use efficiency of durian after each pruning event is the most obvious reaction. This is always accompanied by limitations in P availability. A beneficial effect of pruning on durian water supply is best visible around days 2000, 2250 or 2700. This may be an effect of reduced transpiration due to cut leaves or reduced soil evaporation as a consequence of mulching.

6.5.3 Soil conservation

The importance of soil carbon stocks for the global carbon budget has often been highlighted, e.g. by POWLSON (2005). On plot level, litter and SOM, initially containing more than 300MgC ha⁻¹, represented by far the most important C pool (see fig. 105), which was drastically depleted after clearing the land and reached less than 120MgC ha⁻¹ after 3500 days (fig. 106). Consequently, apart from the carbon sequestered in plant biomass, a decisive role of trees to be planted would be their contribution to litter and SOM pools.

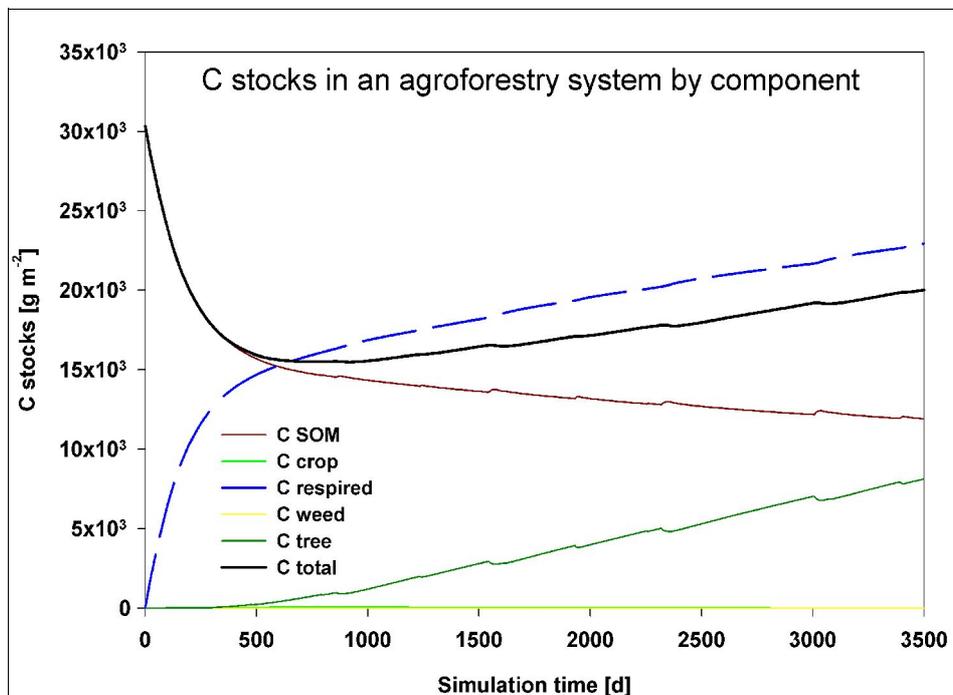


Figure 105: Contribution of pools to the agroforestry C balance

As hypothesised, soil carbon contents under *Gmelina* exceeded those under agroforestry. Regarding grasslands, the hypothesis was too optimistic in favour of the agroforestry system, which remained below the *Imperata* plot, although differences were decreasing during the simulated period. This could have been anticipated from sources as v. NOORDWIJK ET AL. (1997), who state, that soil carbon does not necessarily decrease through land use change from forest to well-managed (!) pasture and from results presented in chapter 4, where C_{org} contents under rainforestation were mostly below those under reference land uses. Due to the importance of soil carbon, different scenarios were tested in order to improve SOM under agroforestry. Apart from the previous scenarios with and without abaca and pruning, erosion control was included as an additional option. In an unrealistic but most effective theoretical approach, terrain was 'tilted' from 20 to 0% slope.

Again, the influence of abaca as additional system component on the carbon balance was minimal. Concerning erosion, carbon stocks of agroforestry with abaca on flat land were lower than in the same system on slopes. No effect would have been a plausible modelling output as water infiltration was excellent. Lower stocks would only be realistic for footslopes. Higher contents on slope lands can only be explained by run-on from upper slope positions; this option, however, had been deselected in the model. The effect of pruning significantly improved the soil carbon balance. A trend line in fig. 100 would give very similar magnitudes for agroforestry and *Gmelina*, even at a slightly steeper slope for the first option. The stronger oscillation of the *Gmelina* curve represents the lower frequency of naturally induced litterfall compared to pruning, but possibly also the better decomposability of *Gmelina* litter.

Similar tendencies for soil carbon have been reported by LASCO ET AL. (2005a): In a simulation over 100 years, SOM decreased by about the same amount at which forest biomass C was built up. Given the restrictions for *S. contorta*, the Cienda scenario, however, is more optimistic, marking a turning point from total C depletion to accumulation within the first 20 years.

6.5.4 Nutrient supply – acquisition of subsoil Phosphorus

Tree growth was, as assumed, influenced by P in the C horizon, meaning that roots were able to access reserves from the subsoil. In fig. 106, average P in plant tissues and in litterfall is shown for *Gmelina* grown on PN1 with medium P contents (25mgP kg^{-1}) and a virtual low-P (1mgP kg^{-1}) subsoil under a $2\times 2\text{m}$ *Gmelina* plantation. After 3500 days, *Gmelina* biomass (dry weight) on the plot with low P in the subsoil reached hardly 80% of the biomass at PN1 profile; on a plant P basis, the ratio was even lower.

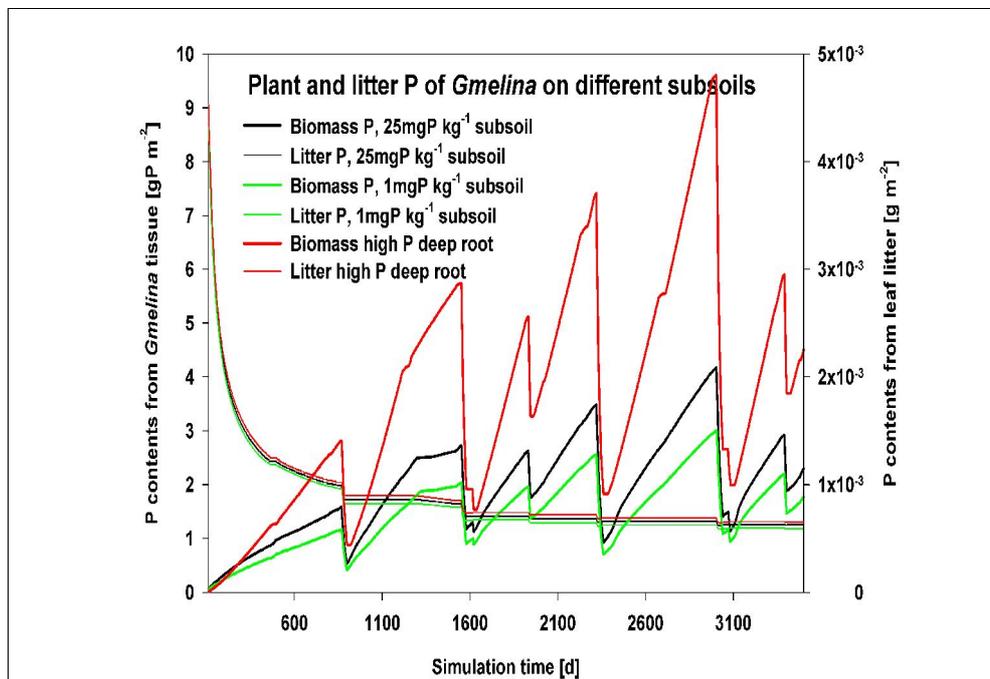


Figure 106: Phosphorus in *Gmelina* and in litterfall on sites with medium and low subsoil P contents

PN1 is still a moderate example compared to Marcos site with $>300\text{mgP kg}^{-1}$ where effects might have been even more significant; on the other hand it is clear, that plants at Marcos were not able to make full use of subsoil P reserves: Clay contents are moderate at PN1

and rootability is better than at Marcos with up to 72% clay and stagnic properties. This is supported by the modelled result, that P leaching (data not shown) was considerable at PN1, especially if compared to the low P version. V. NOORDWIJK ET AL. (2004) modelled a similar situation with respect to safety net functions of roots and nitrogen. They found, that safety net efficiency, expressed as the fraction of N uptake to leached N, varied seasonally depending on plant demand.

Looking at different P pools, the ratio between low and high P treatment after 3500 days was most distinct for plant P of the entire plant (T_Biom[P, SpX]; 75%), followed by P contents of leaves and twigs (T_LfTwigConcAct[P,SpX]; 94%) and consequently litterfall (T_LifallConcAct[P,Sp1]; 94%). It appears, that the tree, after covering its own needs, would still store some P in the stem and roots. Equal P contents in live leaves / twigs and in leaf litter indicate low relocation as may be the case for drought-induced leaf shedding. On site, this result was supported by elevated topsoil P_{Bray} contents in Marcos. Doubling root length density (red curve) led to significantly higher P uptake into the plant, while P in litter did not increase at the same ratio.

P mobilisation by mycorrhizae was neglected in the model, which most likely led to underestimation of P supply in the plants. Especially Dipterocarpaceae are known for their association with ectomycorrhizae (YOUNG 1997). In the standard agroforestry scenario including *S. contorta* and *D. zibethinus*, the first species was limited through P during most days.

6.6 General discussion

6.6.1 Evaluation of modelling assumptions

Generally, identifying key parameters and developing a feeling for their impact were crucial for the entire modelling process. Continuous work and experience with the model were needed for an efficient calibration as well as reference data and common sense for the evaluation of outputs. In the following sections, some assumptions taken for the different steps in modelling are evaluated.

For calibration and validation as well as in the tested scenarios at the new Cienda plot, differences in soil between subplots did not play a major role for plant growth. This became evident, when the respective parameters were varied and had been expected for soil chemical parameters, which were not yet limiting for young plants. On the older plots at Cienda demo site and LSU, P and N deficiencies affected growth. With respect to water availability, better supply at the footslope subplots 6 and 7 had been expected due to lateral flow and capillary rise in the clayey profile. However, plants did not benefit from supposedly higher soil water contents, probably due to a larger portion of unavailable water in fine pores or due to their still shallow root systems. In this context, it would be of interest, how plants on the very well to excessively drained and clayey calcareous soils, e.g. at Punta, cope with drought.

Erosion is an important factor on forest lands in Leyte, but this was not reflected in the soil carbon balance when slope was varied. This may be due to the high infiltration rates mentioned in chapter 3 and would then change for clayey soils like Punta or Marcos. The full set of options available in the model was not explored for erosion scenarios. Especially settings for regeneration of soil structure through soil fauna were kept static for the sake of simplicity. Contrasting to the real conditions at Cienda, a protecting canopy was not modelled for the scenarios, so that rain had its full impact on the ground.

Among weather parameters, potential evapotranspiration is an influential factor, especially for plants like abaca, which is not well adapted to water stress. Soil temperature, in

contrast, was not expected to play a major role for plants. The effect of rainfall could be most clearly observed, in the model as well as on the field. Especially for *Gmelina*, dry spells led to a reduction of biomass through leaf-shedding, which was reflected in the model. Farmers confirmed, that water stress could lead to tree mortality even several years after planting. If weather data are generated by WaNuLCAS, attention should be paid to variability, e.g. El Niño patterns. During calibration and validation it is advisable to use measured real time data. This is especially true for sensitive and young plants.

Among the multitude of plant-related input parameters, many of which are not measured but indirectly derived or estimated, those governing potential growth rates and light use efficiency were the most influential. The importance of light as a limiting factor became obvious, when other potential constraints such as P, N and water were excluded and T_RelLightMaxGr was varied. Below certain *discrete* threshold light levels, other factors did not have any influence on plant growth anymore as light was limiting. Beyond, biomass depended almost exclusively on plant-intrinsic parameters, as external constraints were not relevant. To obtain any growth under canopy, T_RelLightMaxGr was often set to values such as 0.15 or 0.2, which may appear very low. On the other hand it has been shown in section 5.1.8, that PAR as low as 20% of above-canopy levels was still sufficient for good plant growth on subplots 2-5.

Key intrinsic factors governing tree growth were T_GroMax, the maximum growth rate, and T_GroResInit, the growth reserves stored in the young plant. T_GroMax could lead to a logistic curve, where at a certain critical point in a sensitivity analysis minimal changes had tremendous effects on tree biomass, overriding most other parameters. T_GroResInit rules initial development of the plant; when this parameter was chosen too low, biomass kept increasing steadily, while tree height stagnated and then suddenly increased up to tenfold (e.g. from 30cm to 3m) within one day. On the other hand, setting T_GroResInit too high, e.g. at the default level, eliminated the influence of most other factors. Both parameters cannot be measured on site, so that field experience would not accelerate the calibrating procedure. Correspondingly for crop growth, C_GroMax, the potential growth rate, seed weight (Cq_GSeed) and shading (Cq_RelLightMaxGr) were critical factors.

Depending on seasons, litterfall can significantly reduce aboveground biomass, especially of young trees, when lignified parts still make up for a low share. This can also be concluded from litter inputs shown in fig. 107. Since for most of the planted trees these temporal dynamics were not exactly known, a periodicity of leaf-shedding was deselected, so that dropping of leaves depended solely on water-stress. To avoid litter-dependent fluctuations, growth could have been evaluated on the basis of tree height as was the case for Cienda demo and LSU, where biomass data were not available. For the small plants this approach was not chosen, because biomass can increase even at stagnating height – which was correctly reproduced by the model – and due to the aforementioned strong influence of T_GroResInit.

Another impact factor with respect to plant growth was spacing in and between lines. This needs to be considered for calibration of taller trees, where interactions play a major role. For the case of Cienda 1-10 this was not yet relevant, but for the randomly planted LSU plot, distances were important and had to be estimated. Related difficulties arose in context with literature review, where values are often given as biomass per hectare, but planting schemes are not described in detail.

Environmental conditions exercise their strongest influence on plants during the critical initial phase after planting, when small variations of a single parameter can lead to either exponential growth or mortality. Considering this, it was remarkable, that a calibration performed for seedlings during the first two years gave satisfactory results for validation even of grown-up trees, as was the case in the main stand of LSU and Cienda demo site.

Still, further validation of big trees, including more species as well as individuals beyond 10 years of age, would be desirable to extend simulations. The modelling exercise presented here can be understood as a first step to depict multi-storey systems, but only includes a small part of plant-plant interactions in complex systems. An approach such as rainforestation, which aims at maximum diversity, will remain a challenge for modelling. For the given research question, mainly biomass and C balances, the modelling approach appears appropriate, especially when compared to the standard approaches used for CDM evaluation.

6.6.2 Magnitudes of stocks

Carbon stocks and mean annual increments (MAI) for different land uses in the Philippines have been compiled, mainly based on data collected by LASCO (for quotations see tab.28) and co-workers in Leyte, on a site located 50km north of the research sites for this study. Following their ranking, Philippine old growth dipterocarp forests as natural climax vegetation can store $>200\text{MgC ha}^{-1}$, followed by secondary forests, tree plantations, agroforestry, brushland and grassland, while mean annual increment is lowest in old growth forest and highest in tree plantations. As a rule of thumb, LASCO & PULHIN (2004) propose that agroforestry systems contain about half of the carbon of natural forests, but still substantially more than grasslands and pastures. On the other hand, these data are based on different approaches and stand age as well as spacing were not always determined. This becomes obvious from the broad range of *Gmelina* data or references by ALBRECHT & KANDJI (2003), who estimate C sequestration potentials of agroforestry systems in Southeast Asian humid ecosystems to be $12 - 228\text{MgC ha}^{-1} 50\text{a}^{-1}$. Complementary to these references, a data base provided by the Intergovernmental Panel on Climatic Change was used to estimate LUC-induced carbon sequestration for a Philippine wet climate and high activity clay during a 20 years period⁹⁰ (see table 28). Compared to the literature review presented, annual sequestration rates based on IPCC were more conservative. In context to what has been mentioned in previous sections, it is of importance that all MAI values cited do not include changes in soil carbon.

As examples from South America, estimates of standing C stocks for 5-6 year old fallows by BROWN & LUGO (1990), UHL (1987) and TREXLER & HAUGEN (1991) as cited from SCHROEDER (1994) range from $7-12 \text{MgC ha}^{-1}$, similar to the values by LASCO & SUSON (1999). In contrast, UHL & JORDAN (1984) found MAI of $10\text{Mg biomass ha}^{-1} \text{a}^{-1}$ for natural regeneration after forest disturbance at the Upper Rio Negro, a nutrient-poor blackwater river in Amazonia.

⁹⁰ Settings for the IPCC tool: Philippines, tropical wet climate, high activity clay mineral (existing C stocks 44MgC ha^{-1}). From moderately degraded grassland (management factor 0.97, land use factor 1, input factor 1, predicted C stock 42.7MgC ha^{-1}) to native ecosystem / nominal management as best fit (management factor 1.23 for no-tillage, input factor 1, land use factor 1, predicted C stock 44MgC ha^{-1}). Change $0.1\text{MgC ha}^{-1} \text{a}^{-1}$ over 20 years. For severely degraded grassland (predicted C stock 30.8MgC ha^{-1}) the improvement would be $0.7\text{MgC ha}^{-1} \text{a}^{-1}$.

Table 28: Carbon stocks and mean annual increase in biomass carbon under different land use systems in the Philippines; literature review. All stocks and MAI refer to aboveground biomass.

Land use, location	Pools	Stock [MgC ha ⁻¹]	Mean annual increment [MgC ha ⁻¹ a ⁻¹]	Reference
Rain forest humid tropics	AGB		> 20Mg dry matter (not C!)	YOUNG 1997
Dipterocarp forest 80 years	AGB	126-241		LASCO ET AL. 2004
Secondary forest Leyte	AGB plus necromass	199.4	0.9	LASCO ET AL. 2002
Natural forest Leyte	AGB	188	0.9	LASCO ET AL. 2002
<i>Gmelina</i> 6a, N. Ecija	AGB	3.47-7.75	0.58-1.29	LASCO 2001
<i>Gmelina</i>	AGB	32	7.9	LASCO 2001
<i>Gmelina</i>	AGB	55.8	8.2	LASCO ET AL. 1999
<i>Gmelina</i> + Cacao, Makiling	AGB	113.4		LASCO ET AL. 2001
Mixed species plantation	AGB, not C	48.77 dry matter, not C		LASCO ET AL. 2005a
Tree plantation	AGB		10.1	LASCO ET AL. 2002
Fallow, Cebu	AGB	14.4	5.3	LASCO & SUSON 1999
Brushland	AGB	29	4.3	LASCO ET AL. 2002
<i>Saccharum spontaneum</i>		15.2		LASCO ET AL. 1999
<i>Imperata</i> grassland		8.9		LASCO ET AL. 1999
Grassland	AGB	17.15		LASCO ET AL. 2005a
Undergrowth	AGB	0.08-0.42		LASCO ET AL. 2005a
Moderately degraded grassland to natural vegetation, 20a	AGB	From 42.7 to 44 within 20 years	0.1	IPCC tool
Severely degraded grassland to natural vegetation, 20a	AGB	From 30.8 to 44 within 20 years	0.7	IPCC tool

In relation to orders of magnitude from the Philippine references, the biomass produced in scenario 1a appears more realistic than in relation to the field observations in Baybay: *S. contorta* biomass for subplot 10 was 0.01kg m⁻² at the last inventory date (two years after planting), while the modelled value was 2.1kg at a corresponding time. This was surprising in so far as T_MaxGro as well as T_RelLightGroMax had been modified in a direction that would slow down growth, especially during the later stages, if compared to the initial calibration. Further increasing T_RelLightGroMax would immediately have led to zero growth. Under the given circumstances, biomass for *S. contorta* was modelled 8.65kg m⁻² at a time of 5 years after planting. At the end of the simulation, *S. contorta* had reached approx. 18 and durian about 1.8kg m⁻². This would be equivalent⁹¹ to approximately 99MgC ha⁻¹, half of the level given by LASCO ET AL. (2002) for secondary forest in Leyte, but achieved within only ten years and only 400 trees, 100 *S. contorta* and

⁹¹ assuming C contents to be 50% of plant dry matter

300 *D. zibethinus*, per ha. Even if a sigmoidal growth curve, i.e. slower growth during old-age, and better resource use of the plantation due to two storeys, are considered, the predicted values still appear too high.

Dividing the carbon stocks by numbers of years results in a mean annual increase of 0.33MgC ha⁻¹ a⁻¹ for the *S. contorta* component under the plot settings of PN1. This is well within the range given by the literature data for plantations (10.1MgC ha⁻¹ a⁻¹) cited above. When the 30-fold higher literature MAI would be applied to the Cienda plot neglecting plant interactions, this would correspond to a planting density of 2x2 instead of 10x10m. From this perspective, modelled predictions may just slightly overestimate observations, but all in all be very realistic.

Transforming *S. contorta* diameters from Kolb's study into biomass following the allometric equation presented in chapter 5⁹² gave 10.19kg per tree, or 0.1019kg m⁻² of dry matter for Cienda after 5 years and 6.60kg per tree, corresponding to 0.66kg m⁻², for LSU after 10 years. Dividing predicted by observed values for *S. contorta*, this quotient decreases from 210 after 2 years through 85 after 5 years to 30 after 10 years, indicating that growth was most severely overestimated during the first years. When tree height of *S. contorta* is regarded instead of biomass, the simulation still clearly overestimated growth after 10 years compared to the Cienda demo or LSU plots and even more when compared to the new plot at Cienda.

Modelling durian gave a similar picture: Measured 0.008kg m⁻² after two years were modelled as 0.44kg m⁻². For LSU, KOLB (2003) measured 0.12m² basal area per ha, shared between 10 trees. This can be transformed into 12cm diameter and then converted into biomass using the allometric equation from chapter 5. This results in 97.25kg dry matter per plant and, at a planting density of 300 trees per hectare, in 2.9kg dry matter per square metre at year ten after planting. This would roughly correspond to 14MgC ha⁻¹.

In summary, predictions for *S. contorta* strongly overestimated observed stocks at Cienda and LSU, with decreasing tendency during later years, while predictions compared to literature values, especially annual increase, are realistic. This may point to factors responsible for suboptimal growth at Cienda site, which the model settings did not account for. Examples could be pests and diseases (set zero), weeds (set 0.5 on a scale of 0-1) and plant physiological estimates. CEC and base saturation cannot be manipulated in the model; although these were not limiting if judging by profile data, intercostal chlorosis observed on *L. domesticum* plants on the upper part of the plot may point to Mg deficiencies (see discussion in chapter 4). LASCO ET AL. (2005a) mention in a case study on reforestation of a watershed in Luzon, that carbon sequestration rates are generally low under *the harsh and sub-marginal conditions in grassland areas*.

Abaca, however, gave quite accurate values of 0.228kg m⁻², while 0.249kg m⁻² were calculated from field measurements after 21 months.

Gmelina biomass was below the 29Mg ha⁻¹ measured by MERCADO ET AL. (2006) after 2 years in Mindanao. Apart from different planting systems (hedgerows in Mindanao, approx. 2x3m in Marcos) an important difference between Mercado's plot and the ones in Leyte were soil P contents: In Mindanao, 4-5mg kg⁻¹ P_{Bray} were found in the upper soil layers from 0-30cm. Under these elevated P conditions *Gmelina* biomass would correspond well with the increased root length density scenario shown in fig. 107.

Generally, it is difficult to compare tree plantations, if planting densities and age are not known exactly. It is even harder to realistically estimate mixed stands or biomass estimates that have been calculated from allometric equations, another potential source of

⁹² $B = 19.0824 D^{3.0651}$ for *S. contorta*, $B = 18.9759 D^{3.4375}$ for *D. zibethinus*

error. Despite this, it can be stated, that biomass of *S. contorta* as predicted by the model overestimated biomass measured on the Baybay plots. This contrasts the general observation by CAREY ET AL. (2001), that old-growth forest biomass is oftenly underpredicted due to a multi-storey structure, which is not considered by the respective models. Predictions for *D. zibethinus* were much more realistic and such for *M. textilis*, which could be best verified in the field, were excellent. These differences in accuracy are due to the number of individuals used for calibration and validation as well as the range, over which measurements were available. Further, predicting growth of young plants depends strongly on exact coincidence of observation dates and weather, whose influence on biomass varies within short intervals.

Soil carbon was the most important C pool in all systems, pointing to the relevance of erosion control and soil cover. Based on the profile data, $122\text{MgC}_{\text{org}} \text{ ha}^{-1}$ were calculated for PN1⁹³, compared to roughly $300\text{MgC} \text{ ha}^{-1}$ in the simulation. Both calculations refer to the same depth, not taking subsoil carbon below 1m into account. Average C values for fine earth of moist climates in tropical Asia given by BROWN ET AL. (1993) estimate $116\text{MgC} \text{ ha}^{-1}$. Soil below 1m depth can contain about 30% of soil carbon (SCHWENDENMANN (2002) for more deeply weathered Mesoamerican soils), which mostly belongs to the passive pool with turnover times of millennia. This portion is not affected by land use change. The first calculation does not include aboveground nor root litter, which are included in WaNuLCAS. Root biomass typically amounts to 20-50% of aboveground biomass and orders of magnitude of root litter can be roughly deducted from mortality of *Gliricidia* hedgerow fine roots, about $1\text{Mg} \text{ ha}^{-1}$, assuming annual renewal (YOUNG 1997). Both litter pools, however, are initially small in the scenarios which started from cleared land, so that all litter inputs necessarily come from the planted seedlings and weed. In reality, decomposing roots would provide an important pool of carbon and nutrients after clearing a fallowed plot.

A literature review conducted by MURTY ET AL. (2002) showed, that conversion from forest to pasture does not necessarily imply reduction in soil C contents. V. NOORDWIJK ET AL. (1997) studied soil carbon stocks as affected by land use change in Sumatra. They compared data from a broad range of soils and concluded that conversion of forests into well-managed pastures does not necessarily reduce carbon levels in soils. GUO & GIFFORD (2002), in a meta study on soil carbon balances after land use change from 74 publications, concluded that even a change from native forest to pasture would result in 8% increase in soil carbon stocks. Installing a plantation after pasture would lead to a loss of 10% soil C. For such a scenario, it may be justified, that the IPCC methodology does not take belowground carbon into account for land use changes over a 20 year horizon as additionality is expected to be low. For the scenarios described above, the IPCC tool drew a too optimistic picture since soil carbon clearly dropped during the first years and did not fully recover to its original level within 20 years. From a theoretical point of view, loss of soil carbon, if caused by the plantation, should enter as leakage into calculations. In practice, it is not clear how far these fluxes can be evaluated during the verification of CDM projects.

6.6.3 Lessons learnt from modelling with WaNuLCAS

Modelling agroforestry systems with WaNuLCAS was intended to assess the prospects of agroforestry under the aspect of a C balance in CDM projects. Conclusions on the modelling process itself and on implications for such systems will be discussed here.

WaNuLCAS is based on Stella and can be easily explored by less experienced users but

⁹³ From C_{org} contents and bulk density, considering stone contents

also allows experts to go into details and modify interactions and algorithms on a graphical and command line basis. The input parameters for basic soil function sheets (pedotransfer and P) are confined to the necessary minimum and were found straight forward to be measured. So are weather data, although soil temperature could not be obtained from a meteorological station and had to be derived through a regression.

In the case of soil organic matter, the different carbon pools were determined following the TSBF fractionation method and microbial biomass was determined separately. Still, total soil carbon deviated from what was calculated on the basis of total C_{org} measurements. A direct input of total C_{org} fraction and proposed segregation into different pools could have provided a valuable hint for cross-checking data.

Tree inputs, however, were not always easy to collect. While aboveground FBA analysis was found a very useful procedure, that gave reproducible results, root FBA proved to be impracticable specifically for clayey and dry soils. Fine roots can be easily cut and then overlooked in heavy soils; to avoid this, excavations sometimes followed archaeological rather than agricultural principles. Factors p and q usually disqualified root systems to be estimated by FBA because of fine roots branching off main roots. Setting minimum diameters on the other hand would have implied the necessity of wider excavations. Root systems in nutrient-poor or shallow soils can be extensive, which made sampling labour-intensive and, in dense plantations, destructive. Alternatively, extracting soil cores to destructively measure root length density required sufficient numbers of replicates to obtain reliable results (BÖHM 1978). These were difficult to collect in the proximity of the stem and from deeper soil horizons. Subsequently, labour-intensive procedures were needed to quantify root length density from the extracted cores.

Especially for crop input parameters, some plant physiological parameters like root and harvest allocation, root water potential, hydraulic conductivity and light use efficiency, among others, were difficult to determine. This was complicated in the very specific case of abaca due to the phenological characteristics mentioned before. For trees, the *tree survey* questionnaire greatly helped to semi-quantitatively estimate inputs which could not be measured exactly.

When parametrising systems, the most challenging issue was to simulate sequential planting since interactions in the relatively dense systems were crucial. On some plots, the system to be simulated was enrichment planting rather than agroforestry. It was not possible to simulate this at a reasonable accuracy, because the existing overstorey was diverse in species and age and could not be entered into the model for calibration purposes. Generally, it was not possible to simply apply the same plant settings under changing canopy. A mere replacement of soil functions was possible where a similar canopy existed (subplots 8 and 10). Another critical point for accuracy was validation. Own inventories of old stands would have gone beyond the capacities available for this study. The data collected by KOLB (2003) were helpful but additional datasets for other rainforestation sites would definitely have contributed to better representativity.

Under the given circumstances, WaNuLCAS gave satisfactory results for the targeted purposes:

- The most relevant carbon pools could be identified for each of the tested land use systems
- Changes in magnitudes of C pools could be traced back to planting and management options, new alternatives could be tested and their effects on the system be separated (BAYALA ET AL. 2004) and evaluated. Availability of nutrients as depending on root length density and other factors were plausibly represented and nutrient cycles followed from the soil through the plant into the litter component.
- A systems comparison with respect to carbon stocks was possible and could give

valuable indications for land use optimisation.

Statistical evaluation of the calibrated and validated model showed that there was still potential for improvement. Coefficient of determination was good in most cases, while other statistical parameters were not always as desired. Among these, RMSE is widely agreed on for modelling purposes, while modelling efficiency is less frequently used. Mean absolute error, forecasting coefficient and others have also been suggested (s. YANG ET AL. 2000), but were not used here. Determining exact magnitudes could not be expected, because most of the planted species had not been used for modelling before, so that few references were available. In addition, these species are, if planted, mostly grown by smallholders in mixed systems, so that the few existing reference data are often not well-defined with respect to growing conditions. At any case, the importance of soil carbon became very clear as did the relatively modest contribution of abaca over the entire rotation. The greater potential of *S. contorta* over a longer term as compared to *Gmelina* was also shown.

The presented results were achieved after time-consuming measurements, parametrisation and calibration processes of the model. As long as the model is not widely used and unless tested species data bases are available for different sites, WaNuLCAS cannot be employed for rapid exploratory assessments, like the IPCC tool. Anyway, considering the numerous options and flexibility the model provides, superficial use would waste the full capacities provided.

More specialised models for single compartments or processes exist, like CO₂Fix for carbon sequestration, CABALA (BATTAGLIA 2004) for forestry or RothC for soil carbon dynamics. The strength of WaNuLCAS is its ability to simulate interactions of different plants on the same plot. Additional expertise in the form of modules like CENTURY for the SOM compartment or WOFOST as a pre-processing tool has been integrated into the model and WaNuLCAS is being continuously refined and expanded. As any model, WaNuLCAS will become more and more relevant and applicable with an increasing user community.