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Modeling Poplar Growth as a Short Rotation Woody Crop for Biofuels

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Abstract

Short rotation woody crops (SRWC) such as hybrid poplar *Populus spp.* are potential feedstocks for cellulosic derived biofuels. The ability to accurately predict the growth and biomass yields of SRWC under various environmental conditions is important for predicting economic performance and overall sustainability of the biofuel production system. Tree coppicing is often used in the management of SRWC plantations. Modeling the response of the SRWC to the coppice cycle is a requirement in long term predictions of stand productivity. The objective of this study was to develop a model of poplar growth to evaluate feedstock supply potentials under different production conditions including coppicing. This was accomplished by modifying the Physiological Principles in Predicting Growth (3PG) model originally developed by Landsberg et al. (1997) to include a simple root interaction system to simulate the sprouting and regrowth of coppiced trees. The modified model, 3PG-AHB, was tested against published information from three previous hybrid poplar field studies employing coppicing. Soil and weather inputs were parameterized to be as close to the growing conditions as possible for the field trials.

The model parameterized with generic poplar derived values generally predicted crop yield under coppicing to within the variations among different species field tested. The model's predictions were weakest in the first year after coppicing events, improving thereafter. The model has been used as part of a geospatial assessment of regional biomass production for the Pacific Northwest and as an online tool SRWC feedstock estimation.

Introduction

Short rotation woody crops (SRWC) such as hybrid poplar (*Populus spp.*), willow (*Salix spp.*), eucalyptus (*Eucalyptus spp.*), and others have been widely investigated as major bioenergy feedstocks for in the United States and elsewhere [1,2]. SRWC culture has a number of advantages including the potential for coppicing at harvest to allow for regeneration of new plant growth without replanting [3–6].

Cost-competitive biofuel development relies on a dependable supply of affordable feedstock. With purpose-grown crops such as SRWC as contrasted with wastes and residues, the full cost of production is allocated to the feedstock and inputs and yields are more critically important to the overall feasibility. Biomass production varies with spatial location, underlying soil properties, cultivation practices, climate and management practices; hence, the ability to predict plant biomass under different climate and management regimes is important to developing management strategies that facilitate the best use of water, land, fertilizers and other resources. For poplar and other SRWC, modeling the physiological growth is advantageous because it allows for the variation of species parameters and management practices in the presence of dynamic environmental conditions. In addition, because the modeled canopy is carbon balanced, allocations for both above and below ground biomass can be included in lifecycle analyses of biofuel production in comparison to other fuel options.

Various models have been developed for SRWC simulation and applied with good results [7]. One such model used for forest growth simulations is the Physiological Principles in Predicting Growth (3PG) model. The 3PG model has a simplified representation of biophysical processes that control plant growth [8, 9]. The model can easily be applied over large regions and for multiple species with few modifications of the model parameters. Due to this ease of application, 3PG has previously been used for modeling plant growth within forests and plantations [10, 11]. However, missing from prior implementations of 3PG for use with SRWC is a component addressing coppicing and post-coppicing regrowth. Other growth models have incorporated coppicing [12].

We extended 3PG to include coppicing by adding a component that allows for an additional growth contribution from an existing root mass. The model specifies a relatively small contribution to aboveground growth from the accumulated root mass after coppicing in order to initiate the next cycle of production. The model was then parameterized based primarily on previously published results and compared against a number of field tests measuring poplar growth and yields in a coppiced regime.

Methods

Overview of the 3PG Model

3PG is a forest carbon allocation model that is based on physiological principles of using solar radiation for photosynthesis, primary production, and the partitioning to the plant parts, foliage, stem, and roots, to determine the growth of the plant [8, 9].

The physiological components of the original 3PG model comprises sub-modules for estimating growth modifiers, Net Primary Productivity (NPP), biomass allocation, and soil water balance (Figure 1). In general, the 3PG model works by predicting expected productivity based on the soil, the current weather, and their interaction with the species under consideration. The model requires input data in the form of 1) climate variables (maximum and minimum air temperatures (C), solar radiation (MJ m-2 day-1), rainfall (mm), vapor pressure deficit (mbar) and number of frost days per month, 2) site and soil variables including fertility, soil texture and water availability, 3) stand initialization variables such as initial leaf, wood and root biomass and allometric relationships, 4) management practices, for example, irrigation scheduling, and 5) species information. At each time step, a potential maximum value of productivity is calculated based on weather and climate conditions. That potential is scaled by a number of multiplicative limiters derived from plant response to temperature, water availability, fertility, and other species-dependent processes. The resulting productivity estimate is then allocated to the different components of the plant.

A few studies have specifically modeled poplar using the 3PG model [10, 11]. Headlee [11] developed Populus parameters from a set of both laboratory and field studies. These parameters, with a few modifications, were used as the control set to parameterize the growth of a representative hybrid poplar. As shown in Section , when compared to field trials the different Populus clones vary considerably in their growth patterns. Many of these changes can be modeled with appropriate changes to the 3PG input parameters (Tables 1, 2, 3).

Coppicing Model

The 3PG model allocates monthly productivity to the new roots, stems and foliage. In the standard 3PG model, the amount of biomass allocated to the foliage and stems is dependent on the age and size of the trees, while the amount allocated to roots is essentially a constant allocation modified for plant fertility stress. In SRWC, however, coppicing during harvesting results in the stem and foliage being removed while the root ball remains. Because the original model derives its production from transpiration, the original 3PG model has no mechanism to start re-growth following coppicing due to the absence of a foliage fraction.

Figure 2 shows the typical growth of a SRWC poplar tree. Poplars are generally propagated via cuttings of bare poplar stem, (Figure 2a). The cutting provides energy for the establishment of the shoot and root buds (Figure 2b). As tree matures, transpiration photosynthesis, and respiration provide for biomass accumulation and growth. This includes the establishment of the root ball (Figure 2c). By the time the poplar is ready for coppicing (Figure 2d), the plants are well established.

After coppicing, resprouting occurs from the residual root and stem biomass (Figure 2e). In most species, multiple stems will sprout from the same root. The multiple stems affect the plant's regrowth and 3PG parameterization (Figures 2f and 2g). Modeling the growth of the SRWC then becomes, in part, a task of determining the size and timing of the regrowth from the existing root mass.

With no transpiration on which to initiate resprouting in the original 3PG model, coppicing required the augmentation of the model to add this capacity. This augmentation also allowed for model growth after the initial planting of the cutting.

At any given time step, the model augments the productivity from the plants transpiration with an additional production from utilization of reserves with in the root mass. Under normal conditions, this contribution is zero, however, with the initial planting of the cutting, or after a coppicing event, this augmentation is used to add foliage to the tree and restart transpiration-based production.

The parameters of the model are shown in figure 3. Three species specific parameters; Root Contribution ($R_{\Delta\%}$), Leaf Area Index Target (LAI_T), and Root Conversion Efficiency (f_R), control the coppicing model. Combined with the input weather, and other parameters derived in the 3PG model these control the extent and the timing of the regrowth from the coppiced plant.

Limited modifications are required to integrate the coppicing model into the existing 3PG equations. At each monthly time step, the model allocates productivity as before. The only difference is that total monthly growth (ΔW) is now the sum of the net productivity (NPP) and an additional root productivity (RP) (Eq.1). The contribution from RP however, is dependent on the weather, the state of the tree, and parameters characterizing the root mass (Eq. 2).

$$\Delta W = NPP + RP \tag{1}$$

$$RP = \begin{cases} 0 & NPP_{def} <= 0 \\ f_R \; min(\Delta R_{res}, NPP_{def}) & NPP_{def} > 0 \end{cases} \tag{2}$$

$$NPP_{def} = NPP_T - NPP \tag{3}$$

$$\Delta R_{res} = W_R(W_R/W - p_{R\%x})R_{\Delta\%} \tag{4}$$

RP is affected by the potential of a plant to grow under the current weather conditions as defined by the potential productivity of the plant. A target productivity (NPP_T) within a given timestep can be defined from a target leaf area index (LAI_T) that may or may not be realized in the current distribution of biomass. The LAI_T parameter, ≥ 0 defines a minimum NPP that the plant is attempting to reach. A zero value of LAI_Tindicates no root contribution, whereas positive values indicate contribution from the roots simultaneous to NPP generated from foliage.

Because the NPP_T is affected by the current weather conditions, weather also affects the root contribution. If conditions are not conducive to plant transpiration, such as under low sun conditions, then NPP_T is low, and resources are not allocated for growth. The deficit in (NPP_{def}) is defined between the target NPP and the actual NPP(Eq. 3). NPP_{def} defines a maximum contribution needed from the roots to the overall plant growth to achieve the target productivity. The actual contribution from the roots is limited by the amount of energy available in the root mass at any given time.

The 3PG model includes a root allocation parameter, $p_{R\%x}$, that defines the root size with respect to the total plant biomass. After coppicing, the root mass is larger than the current value of $p_{R\%x}$ just before coppicing would specify. A fraction of the extra root mass, ΔR_{res} is available for production (Eq. (4). The parameter $R_{\Delta\%}$ $(0 R_{\Delta\%} 1)$ defines what fraction of this surplus root mass can contribute to RP in a given time step. A value of 0 indicates no root contribution for regrowth while higher values indicate increasing growth potential.

The root conversion efficiency, (f_R), ($0 f_R 1$) determines the mass of new growth from the change in root mass and multiplies the available root mass to determine RP.

In poplar plantations initially planted with cuttings, the original growth is modeled in the same manner but using different values for LAI_T, $R_{\Delta\%}$ and f_R.

Using climatic data for regions around Corvallis, Oregon (Figure 4), the modified 3PG-AHB model was used to project biomass yields (Mg ha-1) with coppicing occurring at different times (Figures 5, 6 and 7).

A plant parameterized with $R_{\Delta\%} = 1$, $f_R = 1$ and $LAI_T = 10$ will allocate maximum resources into plant growth as fast as possible. This is an illustrative example to show the effect of the season on the modeled regrowth.

Coppicing modeled in the third year in February, May, August, or November (Figure 5) reveals that during periods with high potential productivity (Feb-May), roots contribute more quickly to the regrowth of the stem and foliage, matching the higher potential NPP. Late season harvests defer growth until the following spring conditions, and at a slower rate to match the lower potential productivity at those times. The total production of the plantation is affected by the timing of the coppicing suggesting an optimal scheduling if model results accurately reflect actual growth, an objective of model calibration and validation. For example, these model results give an increase of 45% yield over five years when coppicing in February vs. November in the third year from planting.

Model predictions show the total foliage and root biomass converging to similar values for all of the coppicing dates.

Root contribution ($R_{\Delta\%}$) for coppicing in August and November during the third year (Figure 6) shows a long term decrease in plant growth for very low values of $R_{\Delta\%}$ (0.001). For but values of $R_{\Delta\%}$ over about 0.05, the foliage and stem growth are similar after the first 6 months of growth. While the root contribution to productivity is smaller for lower values if $R_{\Delta\%}$, the root continues to contribute at each time step even while the root mass is small. The root mass itself shows large differences over a longer period for these variations in $R_{\Delta\%}$. The productivity is closer for coppicing in November as the potential productivity is smaller in the early months and the lower values of $R_{\Delta\%}$ still provide enough production given the environmental conditions. For modeling actual trees, values of $R_{\Delta\%}$ approaching 1 are unlikely as such high values indicate mass that can readily be converted, primarily starches and sugars. For poplar in particular, root starch and sugar contents vary with the root diameter ranging up to as much as 20% of total root mass. A value of $R_{\Delta\%} = 0.1$ is used for the validations against field trials described below.

Changes in LAI_T from 0.1 to 1 (Figure 7) for the same August and November coppicing events in the third year with $R_{\Delta\%}$ set to 0.1 yield up to 10% change in total stem biomass production over five years for the later harvest. There is little dependence on LAI_T for values greater than about 1.

LAI is chosen as the primary target parameter for the 3PG model as it is a simple plant parameter controlling productivity. Its primary effect at a given time step is to affect the light gathering capacity of the tree. That fraction is given in the 3PG model as $1 \exp -kLAI$. For poplar, we have defined $k = 0.5$ and the productivity of the tree starts to become dominated by this value with relatively low values of LAI. Final values of the coppicing parameters selected for use with the modified 3PG model vary slightly between the cutting at planting and the subsequently coppiced trees (Table 4).

Results and Discussion

The 3PG model was tested against results from three published field studies of coppiced *Populus spp.* [13–16]. The field tests chosen included at least one coppicing rotation, measurements of above-ground biomass, and enough information to simulate plant growth and biomass yields with some level of confidence. Along with above ground biomass, additional parameters reported by each field study were compared with the model results when possible. These parameters include allometric relationships for biomass partitioning, ratios of above-ground to root biomass, and additional measurements such as Leaf Are Index, LAI.

In each case, input weather conditions were obtained for the time of the field work, and management practices and soil parameters were either obtained or estimated from the description in the literature (Table 5).

The primary comparison was of model predictions to measured values for woody biomass. Twenty-one measured values were included. A generic set of parameters for poplar were used. However, as described in Section , two methods for determining the partitioning ratios of foliage to woody biomass were included. The number of coppice events ranged from 0 to 5, and the age of the tree for a coppice cycle ranged from 0.3 to 5.3 years. Two studies included multiple poplar clones in the field tests (Table 6).

Field Trial 1 - Pontailler 1999

Pontailler [15,17,18], described the results of biomass measurements over 5 two year coppicing events for a five different poplar species, grown in Orsay, France from 1987 through 1997. Poplar clones studied included fast growing, interspecific Interamerican (*Populus trichocarpa* × *P deltoides*) hybrid clones (Beaupr and Raspalje), a native American *P. trichocarpa* clone (Fri‘tzi Pauley) and one Euramerican reference clone *P. deltoides* × *P. nigra*, cv., (Robusta).

All were planted from cuttings. At each coppicing event, woody biomass yields, stem diameter, tree height, number of stems per stump and LAI were among the parameters measured. Weather data were obtained for Orsay during the same period of time from solar and weather networks [19,20] (Figure 8).

For the most part this field study reported consistently high biomass. It was reported that the first two coppicing cycles the plantations included some fertilization and irrigation, but applications stopped after the second coppice. These affect the 3PG fertility and water availability inputs. There were variations in yields for the final three coppicing events and these differences, especially the lower yields in 1991-1992, were attributed to drought conditions for the region.

Comparisons with 3PG-AHB model predictions (Figure 9) show that the model described above under-predicts most yield data results obtained.by Pontailler, et al. Some differences due to different management practices as compared to implicit assumptions of the control model, in particular the inclusion of high repetition coppice cycles. Two important considerations are the high density of plantings and the frequency of coppicing, both of which affect model assumptions.

An important component of 3PG is the allocation of NPP to roots, stems, and foliage. This is controlled primarily with the p_{FS}, the ratio of W_F to W_S, $p_{FS} = W_F/W_S$, which helps determine the above-ground allocations. p_{FS} is in turn calculated from a pair of allometric relations. In 3PG, p_{FS} is obtained in a two step process, first obtaining an estimate of *dbh* from the current W_S, and then using *dbh* to determine p_{FS} through a measured relationship. These relations are typically determined from comparisons of more mature trees, for example, Headlee's estimates are based on poplars with a range in *dbh* of about 3.5 - 25 (cm) [11]

For frequent coppicing with small trees at harvest, an alternative set of allometric relationships to determine p_{FS} for the 3PG might be required. For SRWC, Pontailler et al. [17] proposed a set of parameterizations based on volume index (VI) where $VI = HD^2$, H is height (m), and D is tree diameter (m) at 22cm.

Pontailler et al. [17] described power relationships between VI and both above ground dry matter and leaf area per stem. These can be used in a similar manner to define p_{FS}, where W_S is inverted to estimate VI for each stem, and then used to predict leaf area per stem (LA) and along with specific leaf area (SLA), W_F and p_{FS}. As these relationships were defined for each poplar variation in the field tests, the 3PG model was modified to predict p_{FS} with these relationships, and the model run with the parameters shown in Table 7. Because of the high density of tree plantings, the canopy coverage ($CanCover$), which determines when the poplar canopy has closed was scaled from 1.5 years post-coppicing to 0.6 yrs (Figure 9). The poplar stem biomass demonstrates a wide variation under the same management practices. However, without more information relating to the various *Populus spp.* clones, modifying 3PG parameters to obtain a better fit is mostly speculative. The 3PG inputs can be adjusted to more closely match the predictions for each clone, but justifying which particular parameters to adjust from one field test is more problematic as multiple variables can affect the predictions in similar ways.

To illustrate, the variation of one poplar clone, Raspalje, is demonstrated over a few of the more important 3PG inputs (Figure 10). The quantum efficiency directly affects the monthly NPP. Although this is constant in the 3PG model, lab measurements show clonal and seasonal variations of up to 0.02 mol C/mol PAR, usually with maximum in the region of 0.08 mol C/mol PAR [21].

Other interesting observations relate to the variations from year to year. Certain 3PG parameters, such as growth modifiers that are dependent on temperature or the available soil water should show dependence on the input weather parameters. Matching this inter-coppicing variability would lend some justification for modification of those parameters.

Model stem yield is also influenced by the optimal temperature and maximum tree conductance (Figure 10). Neither can account for the changes in the field trials, especially the dip in 1992-1993, or the peak in the following coppice cycle. The tree canopy conductance shows a small variation with a shape somewhat more weather dependent, but not at the scale shown in the trials. The general downward trend in yield over the last three coppicing cycles is due primarily to weather condition. The weather estimates from the data obtained for the model may not have adequately represented variations during the field trial.

The 3PG model includes a tree aging limiter, parameterized in part by the age where the limitation is one half. This is the primary modifier affecting decreased productivity of multiple copping cycles.

The 3PG model uses a linear relation with the stand age to determine canopy cover, which also linearly affects the NPP for each month. In the parameterization of the poplar trees, Headlee et al. [11] used canopy cover as a variable to match the observed yields of some of the field tests. However, on a highly dense plantation, the canopy might close more quickly, resulting in higher productivity in the months after a coppicing event.

As an exercise, the 3PG inputs were modified for each poplar type, to determine if the overall shapes of the measured growth could be replicated by some parameterization of the model. These results are shown in Figure 11. Some of the inputs shown in Figure 10 were modified independently for each type. Without independent verification of the input values used, using parameters obtained with such a method are speculative.

Field Trial 2 - Proe et al. 2002

Proe et al. [13] described the results of different SRWC field trials, including annual measurements of biomass, root:shoot ratio, leaf/stem ratios, LAI and other parameters. The studies were developed over a 5 year period in central Scotland from 1989 through 1999. For the coppicing study, balsam spire poplars (*Populus balsamifera* var. *Michauxii* (Henry) × *Populus trichocarpa* var. *Hastata* (Dode) Farwell) were planted at uniform 1 (m) spacing. However, there was only one coppicing event in the first year for comparison. Proe et al. destructively tested plantation samples over the course of the growing cycle. The field test of Proe et al. differs from the previous field study by Pontailler et al. in having a longer coppicing cycle, additional measurements within a cycle, and alternative data collected, in particular the ratios of the various fractional constituents of the poplar plants. Comparisons with the 3PG model were made by simulating the plantings under the conditions described. Weather information (Figure 12) for the Scotland field plots was obtained for Paisley, Scotland [13, 22]. Calculated clear sky radiation was moderated by the ratio of observed daylight hours to total daylight. Comparisons of woody biomass, LAI, and fraction of foliage to above ground biomass were made between the 3PG model and the measured values for single stem and coppiced practices. In addition, two different allometric relations were used, the dbh version from Headlee et al. [11] and a representative VI relation (Raspalje) from the Pontailler study, (Figure 13).

The additional measurements in the Proe et al. study, highlight the affects that differences in the allometric relationships have on the predictions. The VI relation based methods seems to track the foliage estimations better, while the *dbh* relation tracks stem biomass slightly better. Both models are over predicting the total biomass, with the partitioning affecting the measurement comparisons. The fact the that the VI model tracks $fracWFWF+WS$ fairly well, but not LAI for the coppiced model indicates that the modeled form of LAI is not especially accurate for this field test, requiring possibly a different SLA parameter for these poplar trees. Proe et al. also noted low values of LAI were related to insect damage, especially in the third and fourth years. Proe independently showed the canopy to close in about 16 months from initial planting for both trials, which is considerably longer than the model parameter of 6 months for full canopy closure.

Because Proe et al. include root:shoot ratios, an over prediction of root biomass is indicated. Though not shown, modifications to the root allocation parameters, can model these measured values. These changes possibly due to the very wet nature of the field trial soil.

Field Trial 3 - (Afas 2008)

Starting in 1996, Afas, [16] studied multiple poplar clones over the course of 11 years for a field study in Belgium [23, 24]. The study included measurements of three separate coppicing events. The study found relatively high mortality rates for some of the genotypes. Comparisons between the 3PG and measured values were made for the genotypes with a survival rate of over 85%. No measurements of below ground biomass were included. Afas did propose an allometric relationship for non-destructive biomass estimations based on diameter measurements of the stems from the stool, but for consistency, the allometric relations identified in the Pontailler et. al study were used in the model comparisons. Based on the field description, plant densities were determined, and soil conditions estimated (Table 5).

These results are similar to the Pontailler study, with a fairly large distribution among the varieties, but differ in that the model in this case does not follow the measurement patterns in the same way. The first noticeable difference is the model generally over predicts the final woody biomass measurements, immediately preceding the coppicing events, although the *dbh* based estimates are within the envelope of the clones. At the same time, the intermediate comparisons often show the model under predicting the measured values, especially in the earliest post-coppicing measurements. As with the Pontailler study, individual parameterizations of the 3PG model would result in better fitting, (Section), (Figures 10 and 10), with the same considerations. One additional consideration, however, is that the plant configuration chosen for this study, using alternating inter-row distances and closer row spacing, positively affects the canopy closure for this plantation. This would show increased productivity in the earlier stages of growth after coppicing. The fact that this isn't a consistent trend in the 2nd and 3rd cycles would be harder to capture in the model.

Conclusions

The model introduced in this paper to add coppicing events to the 3PG application seems to behave adequately. In fact, parameter variation suggest that the modified 3PG model is somewhat insensitive to the parameters when chosen in reasonable bounds. We have used this coppicing model in the validation section above to predict poplar regrowth in multi-coppicing scenarios. However, when comparing the model to field validation, the published studies focus on yields over complete coppicing cycles or at least at yearly timesteps. Observations to test the model in those important months directly after a coppice, or under a more complete range of coppicing event types are lacking for comparison.

Although not considered in current model, there are other considerations when coppicing during the growing season. Also, the current model defines a constant value for $R_{\Delta\%}$. Studies of the available starches and sugars in a poplar root suggest a seasonal dependence on these values, with higher values as the plants enter into cooler seasons [25]. The field trials above all coppiced at the end of the growing season, but these are important considerations when considering other strategies, like store on stump management for more continuous feedstock delivery. The 3PG model includes a stump mortality component, but not one based on coppicing, and that was not included in these studies. However, Afas in particular identified high rates of tree mortality, and the tree mortality estimations, especially in the context of coppicing events can be revisited.

Validation of the model with respect to previously published field trials of poplar for a number of different locations and management strategies, led to a number of conclusions, regarding poplar growth. First, the differences among clones in terms of the productions and yields are often quite large. A generalized model is only an estimate on behavior. The model discussed here comes in somewhere in the middle of the field trials investigated.

For high density plantations of SRWC with higher coppicing cycles, using allometric relations based on a parameter like the Volume Index (VI) as opposed to the *dbh* is probably preferable. It should be noted however, that these relationships are also possibly dependent on the planting density, and care should be used when applying under different management scenarios. These relationships seem to vary with the duration of the coppicing cycle as well.

For SRWC the relationships between canopy cover, plantation density, and stems per stump resprouting could be investigated to determine some repeatable relationships between this parameters that could be added into the 3PG model as well.

In general it can be a difficulty task to identify what parameters can be reasonably varied in the 3PG when attempting to understand the differences in growth between clonal varieties. Section included some discussion for this task. However, multiple parameters can effect the growth in the same way. This is especially true for consistent bias between the model and measurements, where many parameters can uniformly decrease or increase the amount of potential productivity that is captured for plant growth.

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References

1. Perlack, RD Wright, LL Turhollow, AF Graham, RL Stokes, BJ Erbach D (2005) Biomass as a feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. Technical report, US Department of Energy, Oak Ridge National Laboratory, Oak Ridge,TN.

2. Tuskan G (2008) Short-rotation woody crop supply systems in the United States : What do we know and what do we need to know ? Biomass and Bioenergy 14: 307–315.

3. Hinchee M, Rottmann W, Mullinax L, Zhang C, Chang S, et al. (2009) Short-rotation woody crops for bioenergy and biofuels applications. In vitro cellular & developmental biology Plant : journal of the Tissue Culture Association 45: 619–629.

4. Aust C, Schweier J, Brodbeck F, Sauter UH, Becker G, et al. (2013) Land availability and potential biomass production with poplar and willow short rotation coppices in Germany. GCB Bioenergy .

5. Sims RE, Venturi P (2004) All-year-round harvesting of short rotation coppice eucalyptus compared with the delivered costs of biomass from more conventional short season, harvesting systems. Biomass and Bioenergy 26: 27–37.

6. Joslin, JD and Schoenholtz S (1998) Measuring the environmental effects of converting cropland to short-rotation woody crops : a research approach. Biomass and Bioenergy 13: 30–31.

7. Gold S, Seuring S (2011) Supply chain and logistics issues of bio-energy production. Journal of Cleaner Production 19: 32–42.

8. Landsberg J, Waring R (1997) A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95: 209–228.

9. Landsberg JJ, Sands P (2010) Physiological ecology of forest production: principles, processes and models, volume 4. Academic Press.

10. Amichev BY, Johnston M, Van Rees KC (2010) Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG). Biomass and Bioenergy 34: 687–702.

11. Headlee WL, Zalesny RS, Donner DM, Hall RB (2012) Using a Process-Based Model (3-PG) to Predict and Map Hybrid Poplar Biomass Productivity in Minnesota and Wisconsin, USA. BioEnergy Research 6: 196–210.

12. Deckmyn G, Laureysens I, Garcia J, Muys B, Ceulemans R (2004) Poplar growth and yield in short rotation coppice: model simulations using the process model SECRETS. Biomass and Bioenergy 26: 221–227.

13. Proe MF, Gri JH, Craig J (2002) Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry. Biomass and Bioenergy 23: 315–326.

14. Proe MF, Craig J, Gri J, Wilson A, Reid E (1999) Comparison of biomass production in coppice and single stem woodland management systems on an imperfectly drained gley soil in central Scotland. Biomass and Bioenergy 17: 141–151.

15. Pontailler JY, Ceulemans R, Guittet J (1999) Biomass yield of poplar after five 2-year coppice rotations. Forestry 72: 157–163.

16. Afas NA, Marron N, Van Dongen S, Laureysens I, Ceulemans R (2008) Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). Forest Ecology and Management 255: 1883–1891.

17. Pontailler J, Ceulemans R, Guittet J, Mau F (1997) Linear and non-linear functions of volume index to estimate woody biomass in high density young poplar stands. Ann For Sci 54: 335–345.

18. Ceulemans R, Pontailler JY, Mau F, Guittet J (1993) Leaf allometry in young poplar stands: Reliability of leaf area index estimation, site and clone effects. Biomass and Bioenergy 4: 315–321.

19. Geiger M, Diabaté L, Ménard L, Wald L (2002) A web service for controlling the quality of measurements of global solar irradiation. Solar Energy 73: 475–480.

20. Tutiempo Network (2013). European Climate Information. URL `tutiempo.net`.

21. Bernacchi CJ, Calfapietra C, Davey Pa, Wittig VE, Scarascia-Mugnozza GE, et al. (2003) Photosynthesis and stomatal conductance responses of poplars to free-air CO2 enrichment (PopFACE) during the first growth cycle and immediately following coppice. New Phytologist 159: 609–621.

22. MetOffice (2013). Historic station data (Paisley). URL `http://www.metoffice.gov.uk/`.

23. Laureysens I, Pellis A, Willems J, Ceulemans R (2005) Growth and production of a short rotation coppice culture of poplar. III. Second rotation results. Biomass and Bioenergy 29: 10–21.

24. Laureysens I, Bogaert J, Blust R, Ceulemans R (2004) Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. Forest Ecology and Management 187: 295–309.

25. Regier N, Streb S, Zeeman SC, Frey B (2010) Seasonal changes in starch and sugar content of poplar (Populus deltoides x nigra cv. Dorskamp) and the impact of stem girdling on carbohydrate allocation to roots. Tree physiology 30: 979–87.

Figure Legends

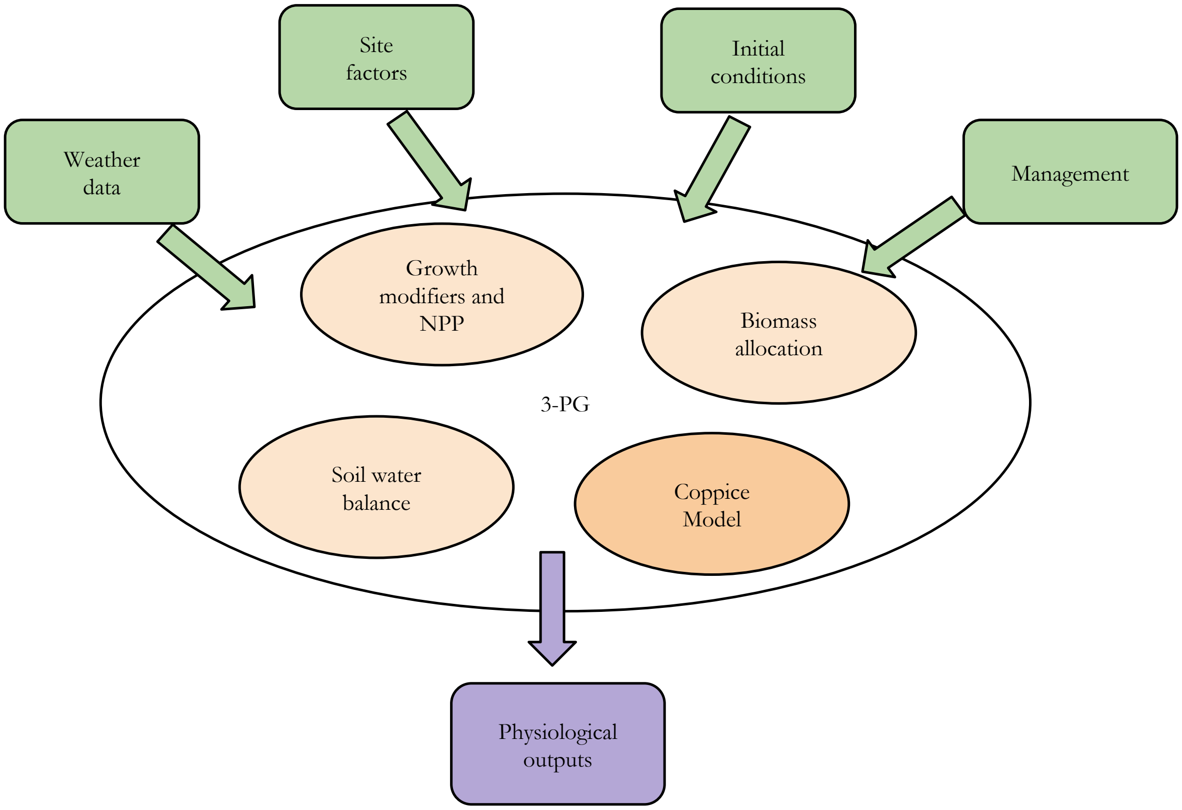

Figure 1. 3PG Overview.

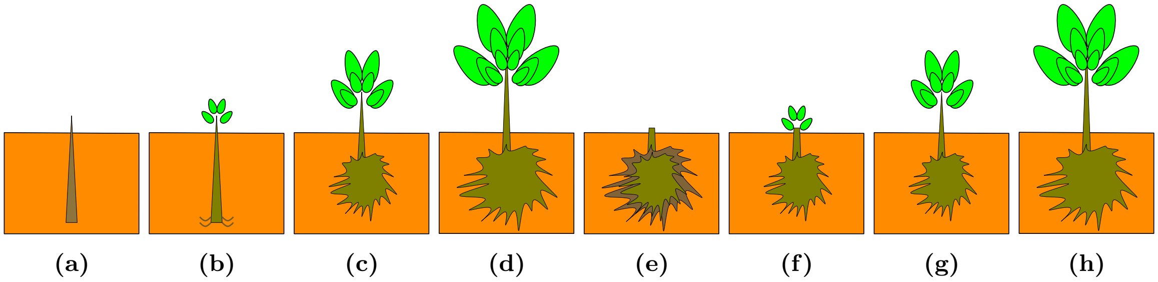

Figure 2. Poplar SRWC growth. The growth stages for poplar grown as an SRWC with one coppicing cycle shown.

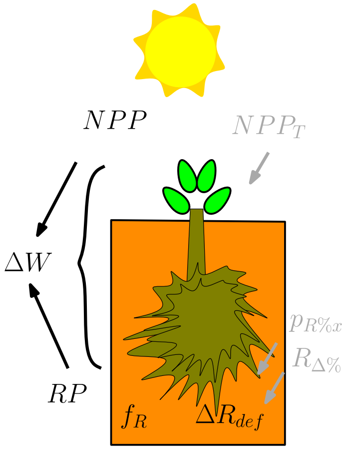

Figure 3. Coppice Model Overview.

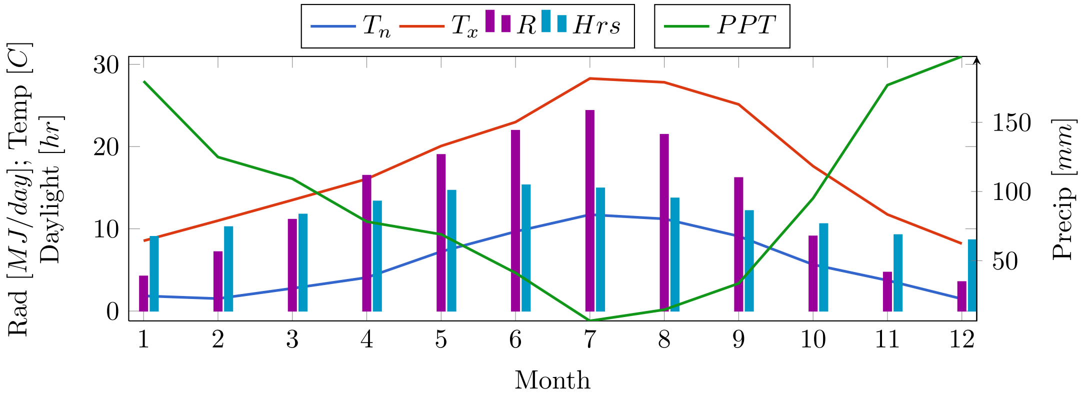

Figure 4. Illustrative weather data. Weather parameters replicating conditions similar to those found in Corvallis, OR

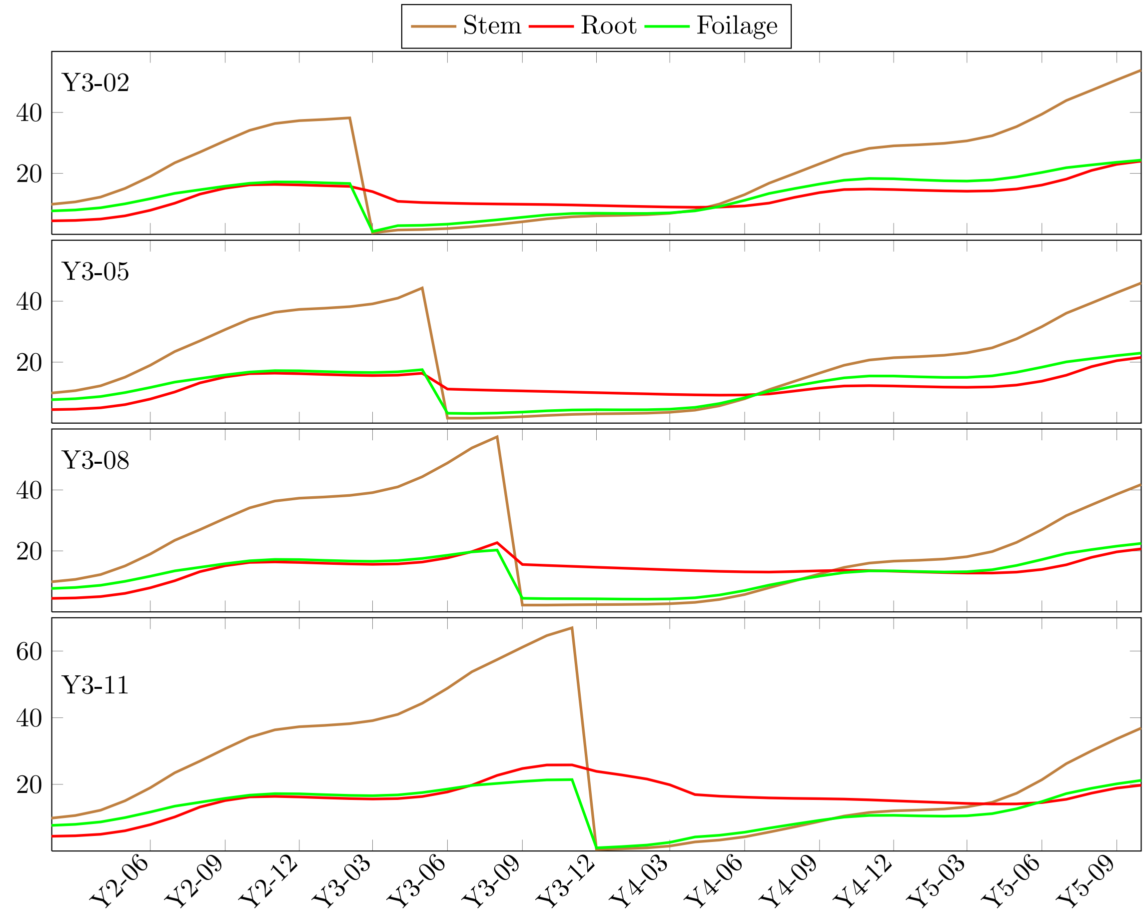

Figure 5. Coppice regrowth model results. Results for various coppicing dates. Y-axis is the dry mass of each component of the plantation, in terms of $\frac{T}{ha}$.

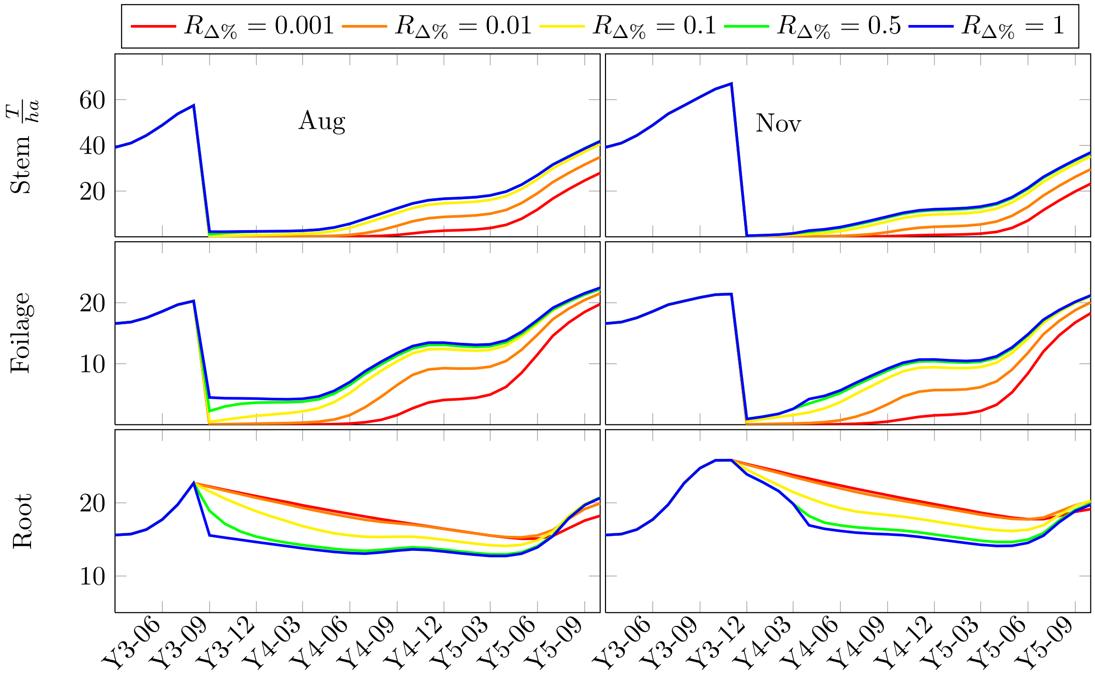

Figure 6. Coppice regrowth model results for various levels of Root contribution $R_{\Delta\%}$. Y-axis is the dry mass of each component of the plantation, in terms of $\frac{T}{ha}$. $R_{\Delta\%} = 100$ and $f_R = 1$.

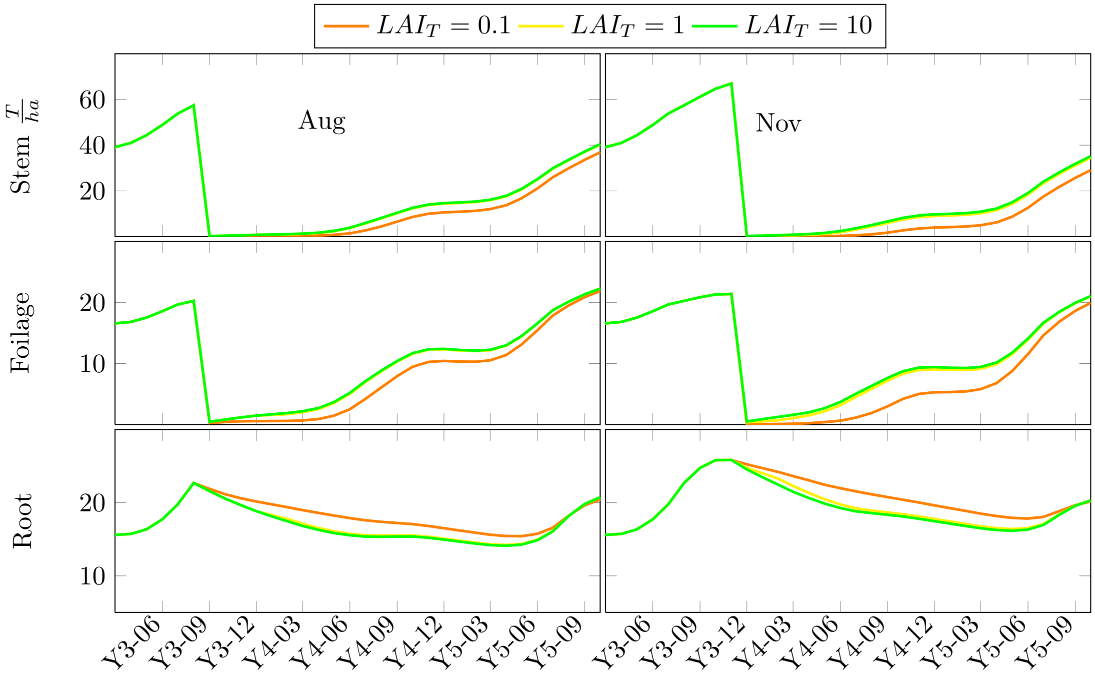

Figure 7. Coppice regrowth model results for various levels of Target LAI (LAI_T). $R_{\Delta\%} = 0.1$ and $f_R = 1$. Y-axis is the dry mass of each component of the plantation, in terms of $\frac{T}{ha}$.

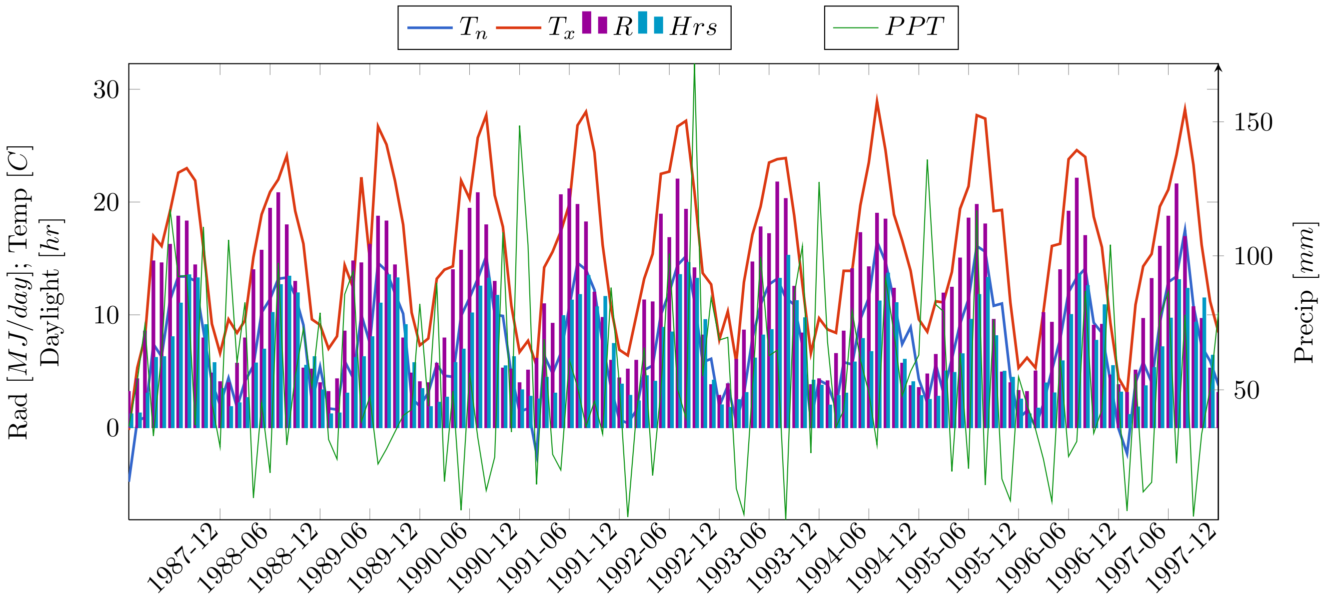

Figure 8. Weather data for Pontailler [15] study [19, 20].

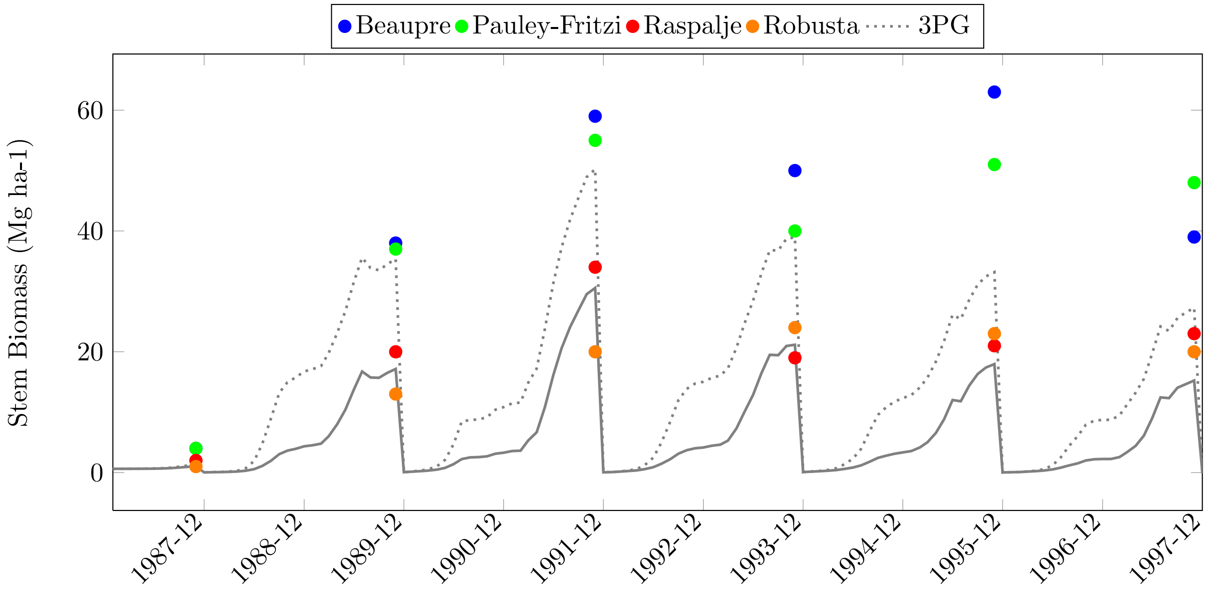

Figure 9. 3PG model vs. Pontailler et al. stem biomass measurements. Solid lines indicate dbh based allocations, dashed indicate VI based for one representative variety (Raspalje).

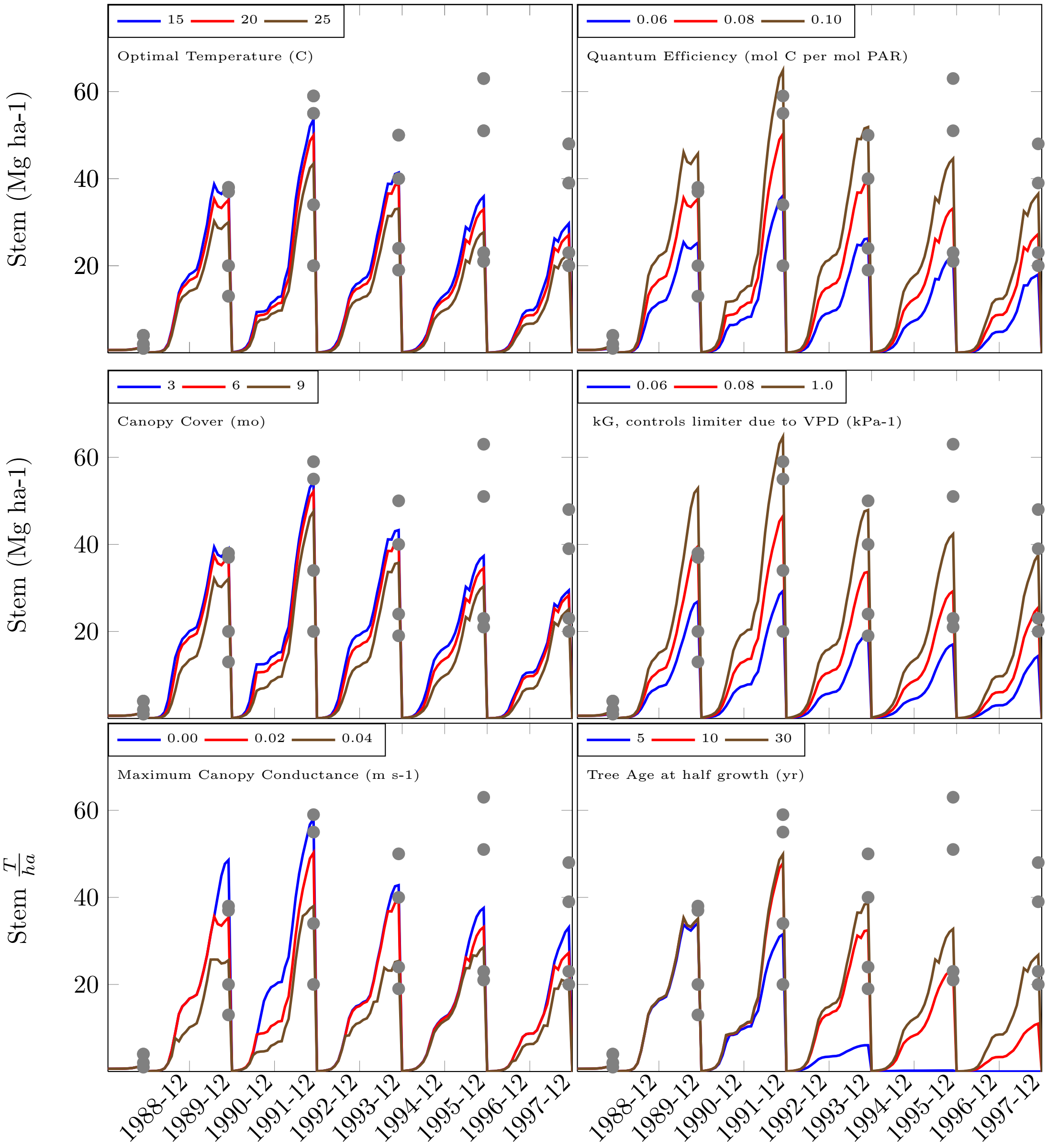

Figure 10. Model to measurement results for various 3PG parameters.

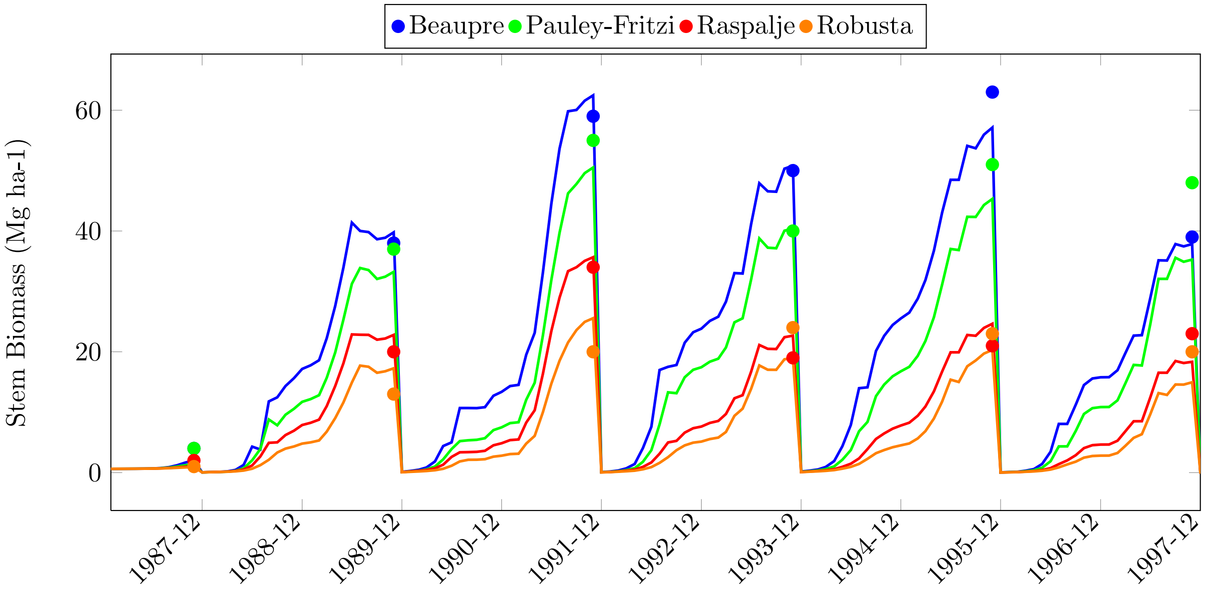

Figure 11. Fitted parameters to measurement comparisons for yearly growth over five coppicing events.

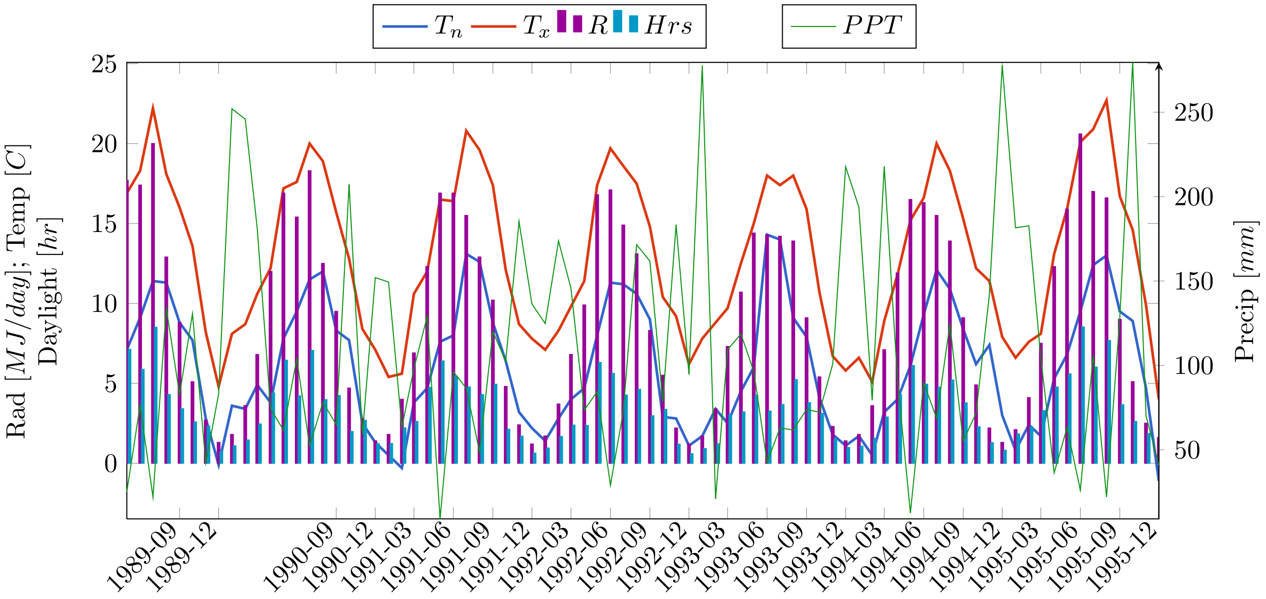

Figure 12. Weather data for Paisley Scotland for Proe et al. 2002 study [13, 22].

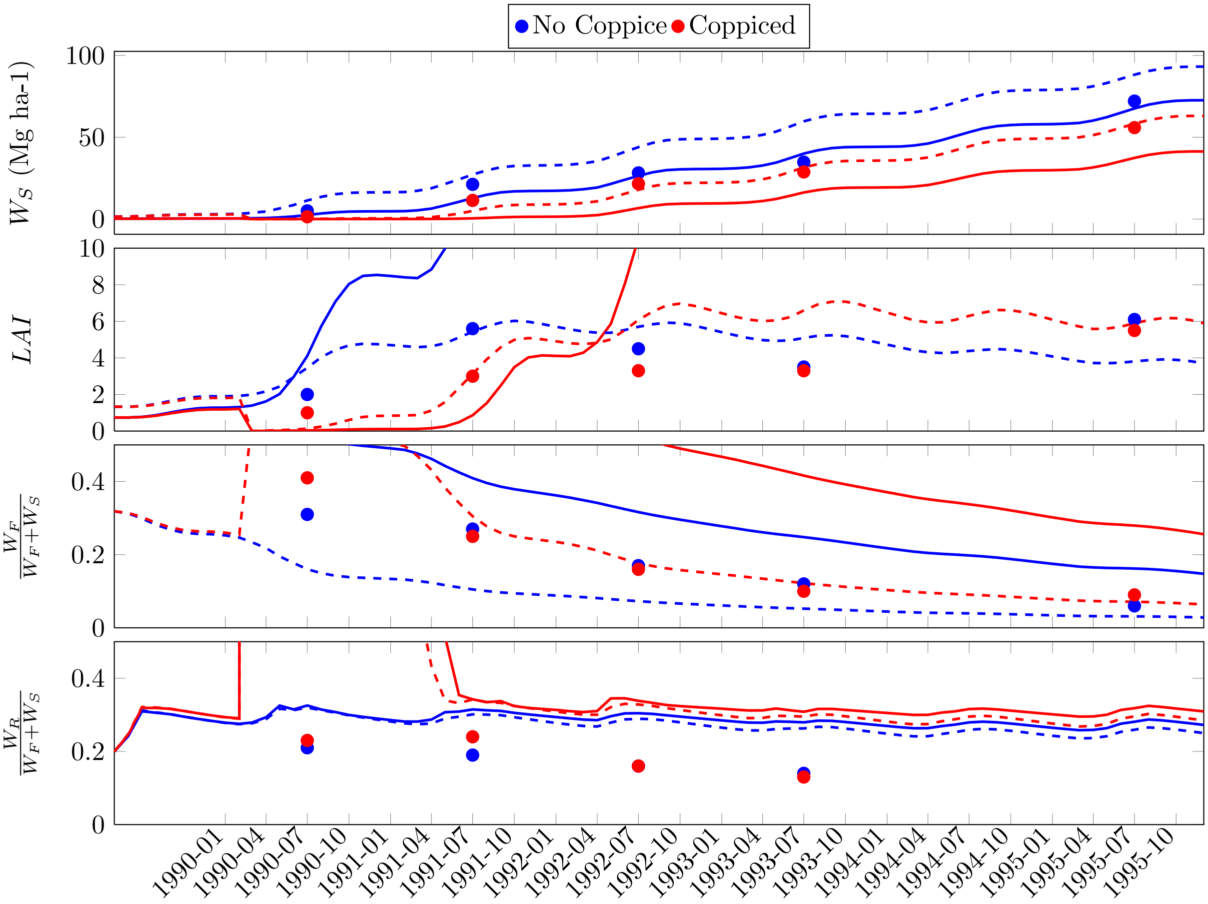

Figure 13. 3PG model vs. Proe et al. measurements. Measurements include stem biomass, W_S, Leaf area index, LAI Foilage to aboveground biomass $\frac{WF}{WF+WS}$ and root:shoot ratio, $\frac{WR}{WF+WS}$. Solid lines indicate dbh based allocations, dashed indicate VI based.

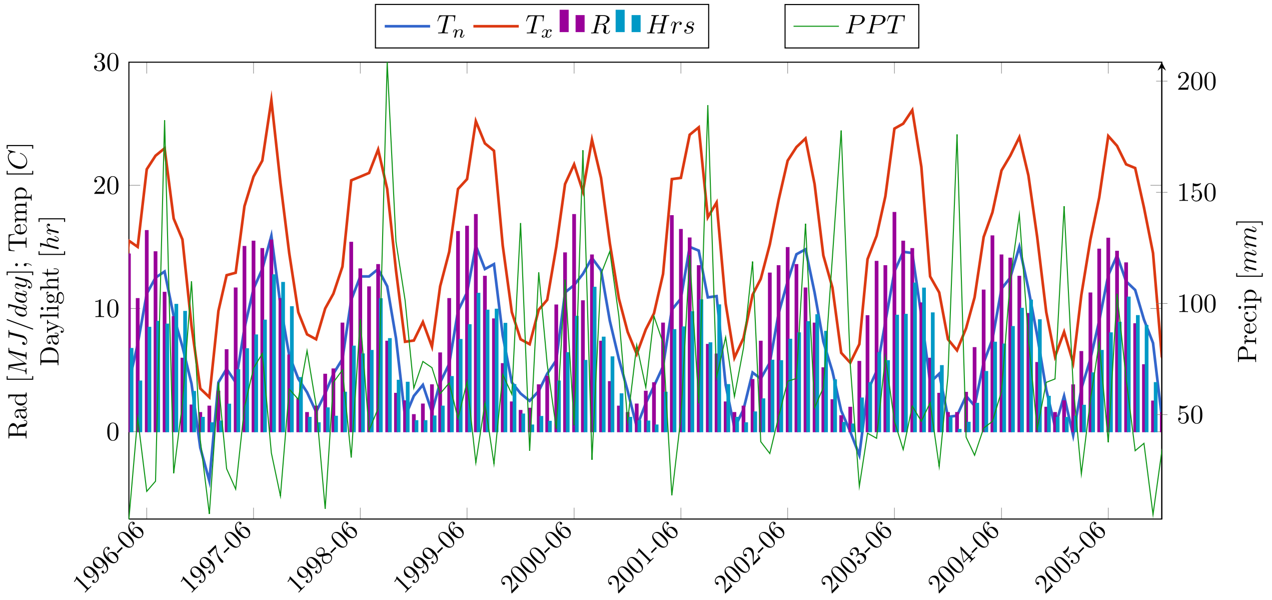

Figure 14. Weather data for Afas [16] study [19, 20].

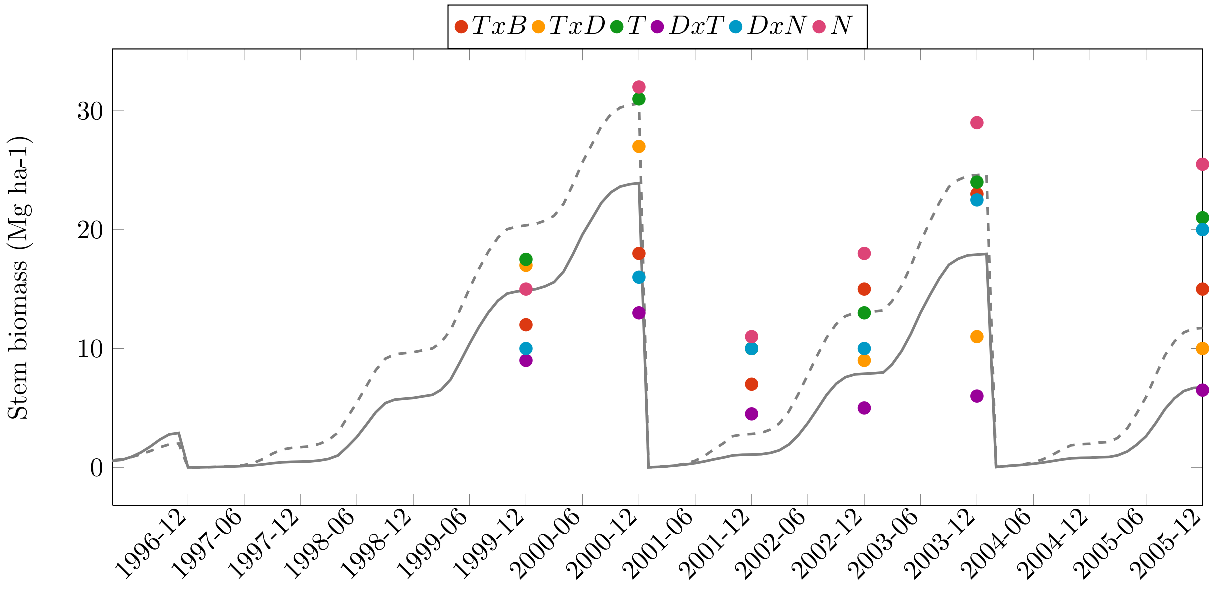

Figure 15. Model to measurements comparisions to Afas [16]. dbh based partitioning is shown with the solid line, and VI based p_{FS} from Pontailer et. al (Raspalje). Afas identifies exact clonal varieties for abbreviations shown in the legend.

Tables

Table 1. 3PG Model Productivity Parameters

Parameter	Source	Value
y	Assimilation use efficiency. Used in calculation of the NPP.	0.47
kG (kg Pa-1)	Determines the response of the canopy conductance to the vapor pressure deficit.	0.5
alpha (kg mol-1)	Canopy quantum efficiency.	0.06
BL_{cond} (m-1)	Canopy boundary layer conductance. Used in the calcuation of transpiration	0.2
k	Radiation Extinction Coefficient	0.5
SLA (m2 kg-1)	Specific Leaf Area. Defined as a function of the tree age. Used in the calculation of LAI.	
$f0_{SLA}$	SLA at initial time	10.8
$f1_{SLA}$	SLA at infinite timestep	10.8
tm_{SLA} (y)	Time in years where value is the average of $f0$ and $f1$	1
n	$n >= 1$; Parameter specifing the rate of change around tm. $n = 1$ is approximately a linear change, as n increases, change becomes more localized around tm.	2

Table 2. 3PG Growth Modifier Parameters

Parameter	Source	Value
y	Assimilation use efficiency. Used in calculation of the NPP.	0.47
kG (kg Pa-1)	Determines the response of the canopy conductance to the vapor pressure deficit.	0.5
alpha (kg mol-1)	Canopy quantum efficiency.	0.06
BL_{cond} (m-1)	Canopy boundary layer conductance. Used in the calcuation of transpiration	0.2
k	Radiation Extinction Coefficient	0.5
SLA (m2 kg-1)	Specific Leaf Area. Defined as a function of the tree age. Used in the calculation of LAI.	
$f0_{SLA}$	SLA at initial time	10.8
$f1_{SLA}$	SLA at infinite timestep	10.8
tm_{SLA} (y)	Time in years where value is the average of $f0$ and $f1$	1
n	$n >= 1$; Parameter specifing the rate of change around tm. $n = 1$ is approximately a linear change, as n increases, change becomes more localized around tm.	2

Table 3. 3PG Tree allocation Parameters

Parameter	Description	Value
pfs	This defines the foliage to stem ($\frac{WF}{WS}$) fraction in allocating aboveground biomass of the tree.	
$stemCnt$	Average number of stems per stump	2.8
$stemC$ (cm-1)	Constant in relation of $dbh$to woody biomass	0.18
$stemP$	Power in relation of $dbh$to woody biomass.	2.4
$pfsMx$	Maximum possible pfs value allowed	2
$pfsP$	Power in relation of $dbh$to pfs	-1.161976
$pfsC$ (cm-1)	Constant in relation of $dbh$to pfs.	1.92
pR	Along with a physiological parameter, specifies the amount of new growth allocated to the root system.	
mn_{pR}	Minimum allocation to the root, when the physiological parameter is 1.	0.25
mx_{pR}	Maximum allocation to the root.	0.34
$m0_{pR}$	Dependence on f_R. $m0 = 0$ indicates full dependence on fertility, $m0 = 1$ indicates a constant allocation, independent of fertility	0
$turnover$	Specifies the monthly root turnover rate.	0.005
lf	Specifies the fractional monthly loss of foliage. This is a time dependent parameter.	
$f0_{lf}$	Value at initial timestep	0.0015
$f1_{lf}$	Value at infinite timestep	0.03
tm_{lf} (yr)	Time in years where value is the average of $f0$ and $f1$	2
n_{lf}	$n >= 1$; Specifies the rate of change around tm. $n = 1$ is approximately a linear change, as n increases, change becomes more localized around tm.	2.5

Table 4. 3PG Coppicing Parameters

Parameter	Description	Cutting	Coppiced
$R_{\Delta\%}$ (mo-1)	The fractional amount of root biomass that exceeds the aboveground requirements that can be supplied in a given month.	0.01	0.1
LAI_T (m2 m-2)	Determines a target NPP, based on weather conditions.	1	1
f_R (kg kg-1)	Specifies the efficiency in converting root biomass into aboveground biomass.	0.6	0.75

Table 5. Field Test Management and Site Specific Parameters

Parameter	Pontailler	Proe	Afas
Stocking Density (trees ha-1)	16025	10000	10000
Seedling Mass (kg)	0.4	0.6	0.4
Soil Maximum Available Water (cm)	10	100	10
Fertility factor	0.7[1]	0.5	0.7
Irrigation Facto	0 (0.7)[2]	0	0

[1] Pontailler reported soil amendments in first 2 years of growth, for that time fertility factor 1.0.

[2] Pontailler reported some irrigation in first two coppice cycles, modeled as 0 through 1989, 0.7 through 1991.

Table 6. 3PG Model versus Field Test Woody Biomass Estimation Summary.

Study	p_{FS} type	Coppice Number	Years from Coppice	Model (Mg ha-1)	Measurments (Mg ha-1)
Afas2008	dbh	1	3.0	14.90	13.42 ± 3.61
Afas2008	dbh	1	4.0	23.92	22.83 ± 8.18
Afas2008	dbh	2	0.9	1.08	8.75 ± 2.48
Afas2008	dbh	2	1.9	7.88	11.67 ± 4.63
Afas2008	dbh	2	2.9	17.90	19.25 ± 8.78
Afas2008	dbh	3	1.8	6.73	16.33 ± 7.18
Afas2008	vi	1	3.0	20.36	13.42 ± 3.61
Afas2008	vi	1	4.0	30.61	22.83 ± 8.18
Afas2008	vi	2	0.9	2.81	8.75 ± 2.48
Afas2008	vi	2	1.9	13.07	11.67 ± 4.63
Afas2008	vi	2	2.9	24.59	19.25 ± 8.78
Afas2008	vi	3	1.8	11.73	16.33 ± 7.18
Pontailler1999	dbh	0	0.8	1.03	2.75 ± 1.50
Pontailler1999	dbh	1	1.9	17.16	27.00 ± 12.46
Pontailler1999	dbh	2	1.9	30.57	42.00 ± 18.31
Pontailler1999	dbh	3	1.9	21.16	33.25 ± 14.31
Pontailler1999	dbh	4	1.9	17.96	39.50 ± 20.81
Pontailler1999	dbh	5	1.9	15.24	32.50 ± 13.28
Pontailler1999	vi	0	0.8	1.30	2.75 ± 1.50
Pontailler1999	vi	1	1.9	35.36	27.00 ± 12.46
Pontailler1999	vi	2	1.9	50.24	42.00 ± 18.31
Pontailler1999	vi	3	1.9	38.96	33.25 ± 14.31
Pontailler1999	vi	4	1.9	33.19	39.50 ± 20.81
Pontailler1999	vi	5	1.9	27.27	32.50 ± 13.28
Proe2002	dbh	0	1.2	2.52	5.00
Proe2002	dbh	0	2.2	12.82	21.20
Proe2002	dbh	0	3.2	26.42	28.20
Proe2002	dbh	0	4.2	40.02	34.80
Proe2002	dbh	0	6.2	67.58	72.10
Proe2002	dbh	1	0.3	0.01	1.40
Proe2002	dbh	1	1.3	0.44	11.40
Proe2002	dbh	1	2.3	6.68	21.60
Proe2002	dbh	1	3.3	16.25	28.80
Proe2002	dbh	1	5.3	37.38	55.90
Proe2002	vi	0	1.2	11.36	5.00
Proe2002	vi	0	2.2	27.18	21.20
Proe2002	vi	0	3.2	43.95	28.20
Proe2002	vi	0	4.2	59.72	34.80
Proe2002	vi	0	6.2	88.22	72.10
Proe2002	vi	1	0.3	0.10	1.40
Proe2002	vi	1	1.3	4.98	11.40
Proe2002	vi	1	2.3	17.89	21.60
Proe2002	vi	1	3.3	31.56	28.80
Proe2002	vi	1	5.3	58.27	55.90

[1] For Proe, coppice number 0, indicates no coppice field test comparison. [2] Proe did not report values for a range of poplar types.

Table 7. 3PG parameter variations of 3PG among genotypes.

Parameter	Beaupre	Fritzi Pauley	Raspalje	Robusta
γ_{DM}	0.854	0.863	0.887	0.838
β_{DM}	166.0	157.6	161.5	162
γ_{LA}	0.428	0.481	0.495	0.496
β_{LA}	$e^{-0.161}$	$e^{-0.198}$	$e^{-0.287}$	$e^{-0.273}$
n_{stems}	4	3.5	2.8	5

$DM = \beta_{DM} VI^{\gamma_{DM}}$, and $LA = \beta_{LA} VI^{\gamma_{LA}}$ [15, 17, 18].