THE INFLUENCE OF ENVIRONMENTAL VARIABLES AND SOIL CHARACTERISTICS ON PRODUCTIVITY AND FUEL QUALITY OF BLACK LOCUST PLANTATION IN UMBRIA REGION (ITALY)

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ABSTRACT: The aim of the present paper is to describe the influence of meteorological parameters and soil characteristics on biomass production and on resulting biofuel characteristics by experimental analysis in a field in Umbria (Italy). The plantation is composed by 4 ha of black locust. A data hog station was used to measure meteorological parameters. 35 Plants were monitored measuring every 17 days the height and diameter of each one. The proximate and ultimate analysis of biomass and soil were carried out using a thermogravimetric balance and a CHN analyser; biofuel energetic parameters, such as heating value, were also measured with a calorimeter. Biomass yield was compared to data provided by a simulation model which was obtained from the Literature and modified to accept solar radiation values experimentally acquired. Preliminary results are encouraging for further development of the model, which may include temperature and rain.
Keywords: Short Rotation Forestry, environmental variables, soil characterisctics

1 INTRODUCTION

The 1997 EU White Paper fixed a strategy and an action plan for renewable energy sources in the EU that included 45 Mtoe to be produced in 2010 using energy crops. This means that almost half of the bioenergy produced in 2010 (90 Mtoe) will come from energy crops. Many authors in the Literature showed that Short Rotation Forestry (SRF) could play an important role to fill the gap between increasing demand of wood (for energetic and industrial uses) and shortage of this resource. The production of wood in biomass plantations is very dependent on agronomical and environmental parameters, which strongly affect biomass yields and quality. A model that could relate the mentioned variables to the mass and energy yields could be a useful tool to point out the most promising areas for energy crops cultivation and also to monitor existing plantations for yields estimations.
To this aim the Biomass Research Centre has an ongoing activity of SRF plantation (focused on both biomass yields and chemical-energetic characteristics), together with meteorological parameters and soil characteristics. These will be used to tune and test crop modelling carried out with models available in the Literature and home developed ones.

2 MODELLING BIOMASS PRODUCTION

2.1 SRF state of the art

SRF maximum yield varies from 20 to 35 o.d.t./ha [1, 2]. It depends on agronomic parameters (choice of clones, establishment phase, length of rotation cycle, stand density, fertilisation, harvesting) and environmental ones, such as soil characteristics and meteorological conditions.

Since twenty years several studies dealt with the influence of clones and spacing [3-7], planting density and harvest frequency [8, 9]. It was shown as a good balance between productivity increase and planting costs was given by single row plantations set with distances of 0.5x3 or double rows set with distance of 0.75. Planting density is a very important variable because it affects both radiation use efficiency (RUE) and radiation extinction coefficient (k); while RUE increases with the increasing of density, k decreases.

However few studies that relate SRF physiology to environmental parameters (that is meteorological factors and pedologic characterization of soil) are available in Literature and how this affects productivity and biofuel quality. Poplar conversion efficiency measurements through infrared gas analyser are described in [10], while [11] examines leaf characteristics and leaf morphology for different poplar clones and relates them to above-ground woody biomass production.

Allometric models obtained ‘’biomass equations’’ to evaluate the actual dry matter production of a plantation in a non-destructive way [12-14]. Few models describe growth and yield in poplar short rotation coppice [15]. A deeper focus on physiological processes in SRF plantation can provide a more detailed comprehension of which are the most important factors to influence productivity and fuel quality .

2.2 Crop modelling

According to [16] three different approaches to crop modelling are possible: empirical, mechanistic and teleonomic.
Empirical models are directly derived from descriptions of observational data and the information obtained do not trace back to any physical or biological law. An example of empirical models are allometric models [12-14, 17].
On the contrary mechanistic models break down the system under analysis into components and assigns processes and properties to these components. Mechanistic models do trace back to bio-physics.
Teleonomic models are simpler than mechanistic models because they focus just on one level of complexity and they not go into the deep relationships that are at the base of the phenomena.
Interesting crop models are presented in [18-20], mostly dealing with maize, wheat and soy bean. The actual trend is to use a suite of programs that work co-operatively and simulate each one a particular plant process, such as: phenological development; biomass partitioning; leaf area development; potential biomass production; yield; carbon and nitrogen cycles; water budget.
All these processes are influenced by: environmental parameters (temperature, rain solar radiation), soil properties (N,C content) and plant characteristics (conversion efficiency,

extinction coefficient).

Biomass production is mainly regulated by two phenomena: phenological development and plant growth. Phenological development is an ordered sequence of processes which take place in a period of time and bring the plant to maturity. It is deeply influenced by temperature, that has an important effect also on the correlated processes of partitioning and Leaf Area formation.

Moreover temperature affects deeply transpiration that is responsible of plant water status that influences: photosynthesis, leaf area expansion, root partitioning and respiration.

Solar radiation, and most of all Photosynthetically Active Radiation (PAR), affects obviously plant growth and the photosynthesis process, that also depends on: conversion efficiency and light extinction coefficient of the plant, Leaf Area Index (LAI), etc.

Rain affects the growth of the plant limiting the rates of ponderal increment when it is deficient. This is because it influences transpiration that is linked with stomatal diffusion resistance.

Carbon (C) and Nitrogen (N) concentration in the plant are also very important for plant growth. Shoot and root specific activities depend on C and N concentrations, which are directly influenced by partitioning process, that is the way resources are allocated inside the plant.

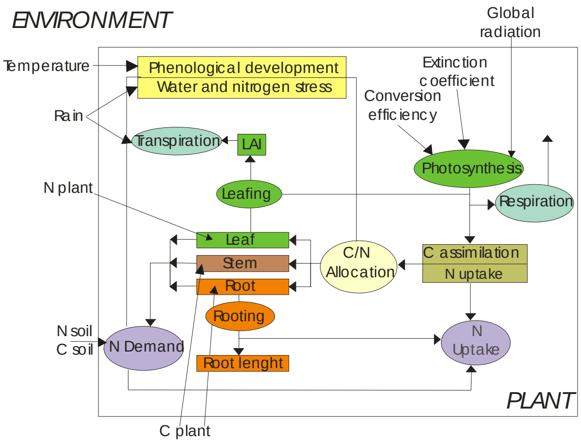

Figure 1: Plant physiology modelling [21]

Table 1 summarizes the excursion of main physiological characteristics of most important species currently cultivated in Short Rotation Forestry (poplar, salix and eucalyptus) derived from [22].

The above mentioned characteristics can be used to implement top-down and bottom-up models of SRF plantations, according to [22]. That is they can be inserted as constants in the implementation of a mathematical model that describes the processes seen in figure 1.

3 SRF PLANTATION MODELLING

3.1 Model Assumption

To asses the influence of soil properties and meteorological variables on the growth of SRF a model that simulates different plant processes, reported in figure 1 and available in the Literature, was modified to focus deeply on the effect of solar radiation on biomass production.

Table 1: SRF physiological parameters [22]

Parameter	Symbol	Mean value
Energy conversion efficiency	e	0.32-2.11 g/MJ
Leaf Area Index	LAI	2.4-4.5 m^2 leaf /m2 ground
Extinction coefficient	K	0.4-0.7 m^2 ground/m2 leaf
Number of sprouts per stump	NSPS	1-8
Sprout mortality and stump survival	SM	1-8%
Roots biomass	RM	15-20% of aboveground biomass

The assumption of the model are:

- plant substrates C and N are uniformly distributed throughout the plant;
- for light interception and photosynthesis, the Monsi-Saeki law for light attenuation in the canopy and a non-rectangular hyperbola for the leaf response to irradiance are used;
- the light flux density above the canopy is measured with a meteorological station (see par.4.2);
- the partitioning coefficients inserted in the equations that express C and N substrate variations are supposed to be constant, attending to an exponential growth model;
- temperature effect on development and on the growth of LAI is not taken into account;
- water stress is not taken into account.

3.2 Model description

The structure of the model is based on 6 state variables: C substrate, N substrate, Shoots, Roots, LAI, N in soil.

Starting from C substrate, this depends by photosynthesis (positive term) and by partitioning and N uptake (negative terms). N uptake is a negative term because it requires C (that is energy to get N inside the plant).

The first equation considered is the following:

$$\frac{dW_C}{dt} = P - \frac{f_C}{Y}(G_{sh} + G_r) - aNU \qquad (1)$$

which describes the carbon uptake. The term P will be examined later, fc and a are constants and stand for: the fractional carbon content of structural dry mass, cost parameter for nitrogen uptake respectively.

Y is the conversion efficiency or yield, and it is supposed to be constant. Gsh, Gr and NU stand for shoots mass, roots mass and nitrogen uptake respectively.

The second equation describes nitrogen mass balance. N substrate depends on nitrogen uptake and partitioning.

$$\frac{dW_N}{dt} = NU - fn*(G_{sh} + G_r) \qquad (2)$$

where fn is a constant and defines the nitrogen content of biomass.

The third and fourth equations describe the roots and shoots mass balance as a function of partitioning and senescence:

$$\frac{dW_{sh}}{dt} = G_{sh} - g_{sh}W_{sh} \quad (3) \qquad \frac{dW_r}{dt} = G_r - g_r W_r \quad (4)$$

g_{sh} and g_r are respectively shoots and roots senescence coefficients.

The fifth equation expresses the growth of Leaf Area Index (LAI) as a function of leaf production and senescence.
Leaf production is the resulting product of: a fraction of shoots growth (f1*Gsh) and an incremental specific leaf area (h).

$$\frac{dL}{dt} = hf_1G_{sh} - g_{sh}L \qquad (5)$$

The sixth equation describes the evolution of nitrogen in the soil, which depends from nitrification rate (nr) and nitrogen uptake:

$$\frac{dN_s}{dt} = nr - \frac{NU}{dr_s} \qquad (6)$$

3.3 Solar radiation and photosynthesis

The term P of eq. (2) represents the daily photosynthetic input which is calculated from the instantaneous rate of canopy photosynthesis(Pc). According to [16], Pc is a function of the irradiance incident on the surface of leafs of different depth within the canopy, obtainable taking into account the carbon formed by the absorbed CO2, through Beer's law:

$$I(l) = I_0 e^{-kl} \qquad (7)$$

where l is cumulative leaf area index. I0 is the PAR above the canopy and it can be calculated from the radiation measured by a meteorological station using Literature equations.
Figure 2 describes the PAR trend obtained from the solar radiation measured at the plantation site described in the following section.

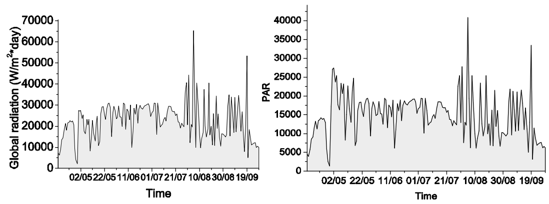

Figure 2: Global radiation (left) and calculated PAR (right) trend during the season

4 EXPERIMENTAL FIELDS

4.1 Description of the field

The field under analysis is situated in central Italy near the city of Perugia. In the past it was a peat quarry and now the plantation aims to improve soil composition and restore fertile conditions. The plantations was set in April 2004 and it has interested 4 ha. The breeding material consisted of black locust seedlings and the planting distances were 0,5 m* 3m (on single rows), so that the density was about 6600 plants/ha. The harvested wood will be used to heat a plant nursery that is quite close to the field.

4.2 Experimental apparatus

Meteorological parameters at the plantation were measured with a Minimet meteorological station (figure 4) to log daily measurements of: temperature, rain global radiation, air moisture, pressure and wind velocity and direction.
Plant and soil samples composition were analysed using a CHN analyser and a Thermogravimetric balance (TGA). Sample LHV was measured through a calorimeter. All equipment is available at the CRB Laboratory [23].

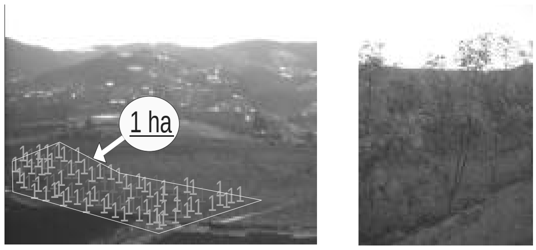

Figure 3: Plantation site and plantation particular

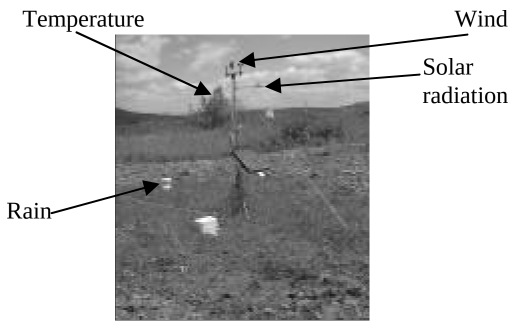

Figure 4: Meteorological station

Moreover every 17 days plant diameter at breast height (dbh) and height were measured on a sample of 35 random selected plants.
Given a confidence interval of 95% and a length of the confidence interval of 20% of the mean of the sample, it was calculated that the minimum sample size for height measuring was about 8 plants and for measured diameter was about 22 plants.

4.2 Preliminary data

Once mean height and diameter were measured, the weight of the mean plant can be calculated, using the following function:

$$o.d.t = 0.5 + \left(\frac{25000 * dbh^{2.5}}{dbh^{2.5} + 246872} \right) \qquad (8)$$

where o.d.t indicates the oven dry weight and dbh represent diameter at breast height.
The meteorological parameters that were proved to be most effective on biomass weight increase were: cumulative radiation, cumulative temperature and cumulative rain. So these quantities were correlated to plant growth and the regression curves in figure 5 were obtained
The best correlations seem to be the one that involves cumulative temperature and cumulative solar radiation. Concerning soil and plant composition, in figures 6-7 are reported C and N trends.
The content of carbon in biomass rises during the growing season, then it decreases after 1/8/05, being C transferred to roots. Nitrogen in biomass reaches its maximum when N in the soil is lower. Carbon in the soil decreases with the rising of temperature.
These preliminary data show that plant uptake diminishes soil concentration of main constituents C and N (together with microbial activity, percolation and erosion).

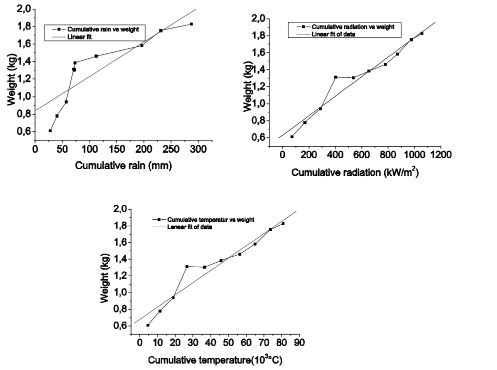

Figure 5: Meteorological parameters vs plant growth

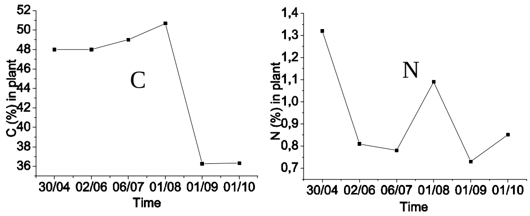

Figure 6: Carbon and nitrogen in plant (measured)

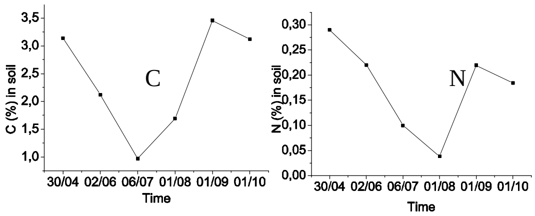

Figure 7: Carbon and nitrogen in soil (measured)

5 RESULTS AND DISCUSSION

The model described in paragraph 3 was solved in Matlab environment through a fourth order routine considering an integration step of 1 day and the Runge-Kutta method.

The dry matter obtained was calculated from the growth in total shoot dry mass. Data for constant values were obtained from Literature and particularly from [16] and [22].

Data for photosynthesis were obtained from solar radiation measurements, as described in 3.3.

The growing season analysed is comprised from 30/4/05 to 28/9/05.

The global growing trend obtained for a period of 170 days (using average values of PAR) is shown in figure 8.

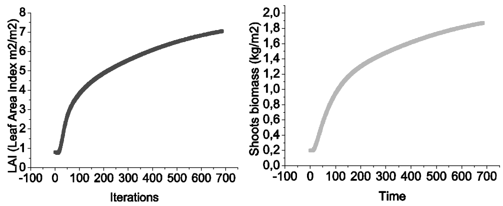

Figure 8: LAI trend (left) and shoots trend (right)

The trend of LAI is quite realistic when compared to Literature data [22], however it needs further experimental verification.

The trend of carbon and nitrogen has also to be checked out.

Figure 9 shows the resulting weights obtained every 17 days from the model, compared to the measured weight (estimated from diameter and height of the 35 sample plants with eq.8).

The model overestimates biomass growth during the beginning phase, while the error diminishes with time becoming not significant at the two last measurements, where a more important information on yield is required. Further running of the model and more experimental measurements are however required.

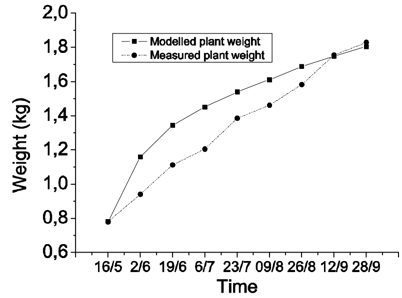

Figure 9: Comparison between modelled and measured weights

6 CONCLUSIONS

The Italian Biomass Research Centre is monitoring a SRF field situated near Perugia (Umbria Region). Climatic and pedologic factors were analysed and a model that describes their influence on productivity was implemented, derived from Literature data. Data obtained proved to be acceptable compared to experimental measurements, however they have to be checked out more precisely. Further development of the model will take into account temperature and rain effects on biomass growth.

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8 NOMENCLATURE

a	Cost parameter for nitrogen uptake	kg C/kg N
g	Senescence rate constant	Day^{-1}
e	Energy conversion efficiency	g/MJ
h	Incremental specific leaf area	m^2 leaf/ kg structure
r	Density	

C	Carbon substrate concentration	kg C/kg structural mass
D	Root depth	M
Dbh	Diameter at breast height	Cm
DM	Dry matter	Ton
Fc	Carbon structural fraction	kg C/ kg structure
Fn	Nitrogen structural fraction	kg N/ kg structure
f1	Faction of the shoot structural growth	/
G	Growth	kg structure $/m^2$*day
I	Irradiance per unit horizontal area within the canopy	W/m^2 ground
I0	Irradiance per unit horizontal area above the canopy	W/m^2 ground

k	Extinction coefficient	m^2 ground /m^2 leaf
L	Leaf area	m^2 leaf/ m^2 ground
LAI	Leaf Area Index	m^2 leaf/ m^2 ground
N	Nitrogen concentration	kg N/kg structural mass(kg soil)
nr	nitrification coefficient	kg N/ kg dry soil*day
NU	nitrogen uptake rate	kg N /m^2*day
o.d.t	oven dry tonnes	ton
PAR	Photosynthetically active radiation	W/m^2 ground
P	Daily photosynthetic input	kg C /m^2 * day
RM	Root biomass	%
Pc	_Istantaneous rate of photosynthesis	kg CO^2/m^2 soil s^{-1}
SM	Sprout mortality	%
RUE	conversion efficiency	kg CO^2/J
W	weight	kg
Y	conversion efficiency or yield	/

9 SCRIPTS

C	carbon	
N	nitrogen	
Sh	shoots	
r	roots	
s	soil	

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