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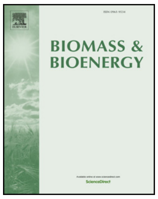

Research paper

Variety earliness effect on field drying of biomass sorghum

M. Colauzzi, P. Serra, S. Amaducci*

Department of Sustainable Crop Production, Università Cattolica del Sacro Cuore, 29122 Piacenza, Italy

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ABSTRACT

A major constraint to the use of biomass sorghum varieties (*Sorghum bicolor* (L.) Moench) to generate electricity by direct combustion is the high biomass moisture content at harvest that, under unfavourable weather conditions during field drying limits the possibility to achieve a suitable moisture content for baling.

In this work, the CropSyst model was calibrated and validated with data collected in experimental trials conducted in the Po Valley (northern Italy). It was then used to simulate biomass production of three sorghum varieties of contrasting earliness (early, medium-late, and late). In order to simulate the dynamics of biomass moisture content during field drying, a specific model, "sorghum haying model", was developed and validated.

The two models combined were used to simulate, for three sorghum varieties of contrasting earliness (early, medium-late and late), biomass production and the probability to achieve during field drying a biomass moisture content suitable for baling.

In a long term simulation (140 years), the late sorghum variety achieved the highest dry biomass production (16.5 Mg ha^{-1}) followed by the medium-late (15.4 Mg ha^{-1}) and early (15.1 Mg ha^{-1}) variety. The early variety had the highest probability (0.66) of being baled at a moisture content $\leq$ 18%, followed by the medium-late (0.53) and late (0.37) varieties. The early variety, also having the shortest average field drying (9.2 days), was considered the most suitable for the selected environmental conditions.

1. Introduction

Among annual biomass species, sorghum (*Sorghum bicolor* (L.) Moench) could have an important role in energy production as a dedicated lignocellulosic energy crop in anaerobic digestion, second generation bioethanol production [1–4] and in heat and power generation by direct combustion [3].

Sorghum is a C4 herbaceous plant of tropical origins, yet it readily adapts to different growing conditions [5–8]. This large adaptability is due to its relatively low agronomic requirements and inputs compared to other crops [3,9].

However, one of the main constraints hindering the use of biomass sorghum to generate heat and power via direct combustion is the high moisture content at harvest time (approximately 70%) with slight variation among varieties and harvest dates [3,9]. Field drying is therefore essential to reach the optimal moisture content at baling time [10] and consequently to guarantee long-term storage of sorghum [11]. High moisture content during storage favours the development of fungus and dry matter losses that might lead to problems at the power plant [12,13].

To minimize quantitative and qualitative damage and losses [14] during storage, the moisture content of biomass at time of baling must be 15–20% [8] as a lower limit and 30% as an upper limit [15].

To reach this moisture content, a correct harvest mechanization technology is necessary [15]. As in other herbaceous crops (i.e. fodder crops) biomass sorghum mechanization relies on a common chain of machines that includes conditioning, tedding, windrowing, and harvesting [15]. Due to the considerable thickness of sorghum stalks [16], an intensive conditioning treatment at harvest is needed [15,17] to reduce the field drying time.

Field drying duration is also affected by climatic conditions at harvesting; using early sorghum varieties in the climate of North Italy reduces the risk of adverse weather conditions after harvesting when the biomass is left on the field to dry [18], however biomass production is generally lower with early than with late varieties [9]. Therefore, farmers trade-off between biomass production and the risk associated with field drying.

A number of studies have dealt with the dynamics and mechanization of field drying in sorghum [8,15,17–20], but a study to model field drying in relation to variety earliness in sorghum has not yet been carried out.

The objective of this study was to simulate the biomass production and the field drying dynamics in relation to the earliness of three biomass sorghum varieties. The CropSyst model was used to simulate

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* Corresponding author.
E-mail address: stefano.amaducci@unicatt.it (S. Amaducci).

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biomass sorghum production while a new empirical model, the "sorghum haying model", was developed to simulate the duration and the dynamics of field drying of sorghum biomass. The sorghum haying model was then used, in combination with CropSyst, to identify the optimal sorghum variety to reach the best trade-off between biomass production and moisture content at baling time.

2. Materials and methods

The work presented in this article is based on the use of two simulation models; CropSyst [21] and the "sorghum haying model". The first was used to simulate the biomass production of three sorghum varieties characterized by different earliness (early, medium-late and late), while the second was developed to simulate field drying and net harvestable biomass (baled) of biomass sorghum.

2.1. CropSyst model

CropSyst is a process-based, multi-year, multi-crop, daily time step cropping system simulation model developed to evaluate the effects of different pedoclimatic and management conditions on crop growth and on environmental impact [21].

In this work the calibration of CropSyst was carried out on a medium-late sorghum hybrid (Biomass 133, commercialized in Italy by Syngenta) using the measured crop growth stages and total biomass production (Table 1) and CropSyst default parameters.

Crop growth was modelled through thermal time accumulation by counting the growing degree days-GDD (thermal units) for different phenological stages that were estimated from the base temperature (°C) as a lower limit and cut off temperature (°C; optimum temperature for thermal time accumulation) as an upper limit and daily mean temperature. Other crop parameters were estimated using the software SciLab [22] function *fminsearch* with the classical approach to minimize the target function *f*:

$$f = \sum_{i}^{n} (Yobs_i - Ysim_i)^2 \tag{1}$$

where $Yobs_i$ and $Ysim_i$ are respectively the observed and simulated values of total biomass at crop maturity and n is the number of observations. Parameters were changed in the optimization process starting from the default parameter values and within a biologically logical range. Table 1 lists the values of all the parameters applied in the CropSyst model, indicating them as default values (D), calibrated values (C) and "local experience" values (L).

2.1.1. CropSyst calibration

To calibrate CropSyst, biomass production data of a medium-late sorghum hybrid (Biomass 133) was collected in a mid-term experimental trial conducted in Gariga di Podenzano (PC), in the Po Valley Italy (44°58′59″N, 9°40′48″E, altitude 84 m a.s.l.) between 2006 and 2010 [23]. Biomass 133 was compared to an hybrid maize (Arma – Syngenta FAO class 700) in a split-split-plot design with four replicates (only three in 2009) to evaluate the effect of irrigation and nitrogen fertilization on biogas production. Different nitrogen and irrigation levels in factorial combinations were applied. The biomass dry matter production (Mg ha^{-1}) was estimated by harvesting three rows per subsubplot (8 m^2 in total per sub-subplot) at hard dough stage (BBCH87).

2.1.2. CropSyst validation

To validate CropSyst, Biomass 133 was grown in twenty experimental fields (on a total of 39 ha) located in the Po Valley (Lombardy Region, Italy) in 2010. Experimental fields were prepared by conventional tillage (30 cm deep ploughing followed by 1 passage of a tandem disk harrow and 1 passage of a power harrow) and sowing was performed with a pneumatic drill (Maschio Gaspardo SP Dorata 6 rows) planting 20 seeds m^2, with an inter-row distance of 0.7 m and interplant distance of 0.1 m. Tables 2A and 2B provide details of the soil types of the 20 experimental fields; in addition Table 2B lists the preceding crop, the sowing date, the total amount of nitrogen applied during the experiment, and irrigation level.

Table 1

CropSyst model parameters for three sorghum genotypes and source of information (C: calibrated parameters; D: CropSyst default values; L: "local experience").

Parameter	Determination	Genotype			Unit
		Early	Medium-late	Late	
Aboveground biomass-transpiration coefficient (BTR)	C	10.768	10.768	10.768	kPa kg m^{-3}
Light to aboveground biomass conversion (LtBC)	C	3.811	3.811	3.811	g MJ^{-1}
Actual to potential transpiration ratio that limits leaf area growth	D	0.95	0.95	0.95	–
Actual to potential transpiration ratio that limits root growth	D	0.5	0.5	0.5	–
Optimum mean daily temperature for growth (Topt)	C	22	22	22	°C
Maximum water uptake	D	12	12	12	mm per day
Leaf water potential at the onset of stomatal closure	D	1900	1900	1900	J kg^{-1}
Leaf duration	D	1400	1400	1400	° C day
Wilting leaf water potential	D	2700	2700	2700	J kg^{-1}
Maximum rooting depth	L	2	2	2	m
Maximum expected leaf area index (LAI)	L	7	7	7	m^2 m^{-2}
Fraction of maximum LAI at physiological maturity	L	0.9	0.9	0.9	–
Specific leaf area (SLA)	L	22	22	22	m^2 kg^{-1}
Stem/leaf partition coefficient (SLP)	D	2	2	2	–
Extinction coefficient for solar radiation (k)	D	0.5	0.5	0.5	–
ET crop coefficient at full canopy	D	1	1	1	–
Degree days emergence	L	79	79	79	° C day
Degree days begin flowering	L	910	1012	1400	° C day
Degree days begin filling	L	1187	1345	1500	° C day
Degree days begin senescence	L	1134	1285	1550	° C day
Maturity	L	1600	1725	1950	° C day
Base temperature (Tbase)	D	5.76	5.76	5.76	° C
Optimal temperature	C	26.3	26.3	26.3	° C
Cutoff temperature (Tcutoff)	D	32	32	32	° C
Maximum uptake during rapid linear growth	C	8.182	8.182	8.182	g m^{-2} day^{-1}
Nitrogen demand adjustment	C	0.4943	0.4943	0.4943	–
Phenologic sensitivity to water stress	D	0	0	0	–