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Exploring the variability of a photoperiod-insensitive sorghum genetic panel for stem composition and related traits in temperate environments

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ABSTRACT

Over the last decade, the merits of sorghum as a dedicated feedstock have been highlighted. The relevance of sorghum biomass as an energy or biomaterial source relies on the possibility that its composition meets the requirement of the different production processes. In order to better assess the phenotypic variation existing in sorghum for stem composition, 103 accessions representing a broad genetic panel of insensitive and moderate photoperiod-sensitive landraces were evaluated during two consecutive years at Montpellier, South of France. Our data confirmed the existence of a great range of variation for several key parameters of stem composition, in particular for crude protein, lignin content and *in vitro* organic matter degradation and at a less extent for fibre digestibility. Sugar content in stems estimated by Brix was positively correlated with cycle duration and dry stem yield. Lignin content and fibre digestibility, two key traits linked to the potential utilization of sorghum biomass for fodder and 2nd-generation energy source, were strongly (positive and negative, respectively) correlated with plant height but not linked with dry stem yield. These results indicated that both biomass yield and quality can be improved simultaneously. Variability of stem composition was highly structured according to the genetic origins of the accessions. Durra and kafir groups emerged as good sources of high fibre digestibility. The same two groups and the photoperiod-insensitive caudatum from Africa comprised the best accessions for high sugar content in stems. Several Chinese caudatum and bicolor-caudatum accessions included in this panel stand out for high lignin content. This information will be mobilized to broaden the genetic diversity relevant for on-going breeding programs of sweet and biomass sorghum for temperate areas.

1. Introduction

Sorghum is one of the grasses with the highest potential for bioenergy production from ligno-cellulosic biomass, commonly designated as second generation energy pathway (2-G), for both temperate and tropical areas (Berenji and Dahlberg 2004; Rooney et al., 2007; Vermerris et al., 2007; Carpita and McCann, 2008). In addition, sorghum is also a promising crop to support biomass value chains towards biomaterials like plywood, composite polymers, building materials . . . (Reddy and Yang, 2007; Zhong et al., 2010).

As other C4 species, sorghum is very efficient for biomass accumulation. Because of high water and nitrogen use efficiency, it also shows comparative agronomic advantages with other C4 crops as maize and sugarcane when the targeted cropping conditions present limitations in water supply and/or objective of reducing fertilizers inputs. Although a few sorghum hybrids dedicated to feedstock production have been recently released in Europe, USA and China, breeding for biomass sorghum is still in its infancy. With the exception of a few pioneer studies such as Vandenbrink et al. (2010) which assessed the variation of the biomass hydrolysis yield potential in a panel of 381 sorghum accessions of the USDA collection, the current knowledge on the variability of sorghum biomass composition and its relationships with other agronomic traits (yield, adaptation) remains sparse. As a consequence, the development of the value chains from the farmers to the industrial end-users is currently hampered by this lack of knowledge as well as dedicated strategies and adequate policy merging the expectations of the different actors.

In temperate areas, the potential of sorghum to produce high ligno-cellulosic biomass intended for energy purposes was firstly assessed on a few specialized cultivars, usually a low number of

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sweet and fibre sorghum types. These evaluations were mainly set up to test the effects of different sowing or harvest dates, plant density and N fertilization. In Northern China (latitude of 39°56′N), maximum dry stem yields from 16.4 to 23.9 t ha^{-1} were recorded in two successive years for a late sweet sorghum cultivar (160 days to harvest) among the five varieties tested and harvested at 40 days after anthesis (Zhao et al., 2009). In Northern Italy, with latitude around 44°, maximum dry stem yields of 20–22 t ha^{-1} have been reported by Petrini et al. (1993) for sweet sorghum cultivars, while Barbanti et al. (2006) recorded maximum dry stem yields of 18.7 t ha^{-1} and 14.4 t ha^{-1} for late sweet and medium cycle fibre cultivars respectively. In Southern Italy, under optimal irrigated conditions, Garofalo et al. (2011) obtained an average aboveground dry matter yield of 34.6 t/ha with a modern biomass sorghum hybrid. At Montpellier, Southern France, dry aboveground biomass yields above 30 t ha^{-1} are routinely recorded for commercial biomass hybrids in experimental trials with moderate irrigation (150 mm) (G. Trouche, unpublished). These data confirm that sorghum has potential to produce high biomass yield in temperate climates, and particularly in European conditions.

For a better understanding of the genetic determinism of traits related to biomass yield and quality for fodder or energy production, several QTL studies were recently carried out, based on RILs or $F_{2:3}$ populations derived from crosses between a grain sorghum cultivar and a sweet sorghum cultivar (Murray et al., 2008a,b; Ritter et al., 2008; Shiringani et al., 2010; Guan et al., 2011). Except the study of Murray et al. (2008b), which addressed stem and leaf structural composition, these studies largely focused on sugar contents as well as stalk juice production, intended for 1st generation ethanol production. They revealed strong genotypic effect as well as high environment effect and GxE interactions for most of the traits evaluated. Although several of the QTLs identified for biomass composition corresponded to the pleiotropic effects of major dwarf and maturity genes, some of them, mainly linked to sugar content, seemed to involve specific sugar related genes (Ritter et al., 2008; Murray et al., 2008a).

In grasses, lignin content, composition and distribution in the stem represent key issues for determining the usefulness of the biomass. In sorghum, four major genes, controlling lignin synthesis pathways have been identified; they are currently identified as bmr2, bmr6, bmr12, bmr19 (Saballos et al. , 2008). Bmr2, 6 and 12 have been cloned. These bmr genes induce lower lignin content in stems and leaves, which is of undoubted interest in the context of feed (Oliver et al., 2005), and methane or ethanol production through biochemical processes (Dien et al., 2009). But their interest is often questioned in germplasm development for optimal biomass production because of lodging problems with tall cultivars targeted for this purpose (Brenner et al., 2010). As observed in other grasses, it is expected that polymorphisms in these bmr genes or in other genes affecting cell wall composition and structure which do not express brown midrib phenotype, will be interesting for decreasing lignin content and enhancing biomass degradability without lodging constraints (Brenner et al., 2010). However, regarding some specific purposes such as the direct combustion of whole biomass to produce heat or power, high lignin content in stems will be an advantage. As a consequence there is a clear need to evaluate the potential for manipulating the lignin content and its components either for decreasing or increasing, as for some final products the lignin ideotypes remain currently not well defined.

Thus, there is a clear need for a global exploration of sorghum diversity regarding the variability for traits related to biomass composition as well as their correlations with biomass yield components. Moreover the available phenotypic variation, within and among botanical races and geographical origins, remains to be clarified.

The objectives of this study were therefore (i) to explore the phenotypic variability of a broad-based panel of cultivated sorghums for stem composition traits relevant for fodder, biomaterials and energy production, (ii) to specify their relationships with phenology and morphology traits, and (iii) to understand the genetic structure of this phenotypic variation.

2. Materials and methods

2.1. Plant material

This study was conducted on 103 sorghum accessions able to flower under the long-days conditions of the European summer season, i.e. photoperiod-insensitive and low photoperiod-sensitive genotypes. Because previous studies on maize and sorghum showed a great effect of development stage on stem composition traits (Jung and Casler, 2006; Zhao et al., 2009), we decided to consider only these “photoperiod-insensitive” accessions that enable us to perform the harvest at the same physiological stage for an accurate assessment of the studied traits.

This panel included 95 accessions originating from the CIRAD core collection, which provides a world-wide coverage of cultivated landraces of sorghum, with sampling based on geographical origin, race classification, photoperiod sensitivity and mode of cultivation (Deu et al., 2006). Two landraces from the guinea group of Southern Africa and six modern varieties from different genetic background completed this panel which gives a fairly good representation of five among the ten genetic clusters identified in Deu et al. (2006) (Table 1). The five other genetic clusters, characterized by high reaction to photoperiod which impedes them to flower in temperate areas were completely excluded from this study. The varietal checks (controls) were two commercial hybrids for silage, one commercial hybrid for biomass and one early tropical grain variety.

Table 2 gives the complete list of the 103 accessions assessed in this study with their country of origin, botanical race and genetic classification as defined by Deu et al. (2006).

Table 1
Geographic and genetic origins of the sorghum accessions evaluated in this study.

Region of origin	Number of accessions	Genetic cluster: name and group number[a]	Number of accessions
Western Africa	8	Durra from Africa and Asia (GC-III)	16
Central Africa	8	Caudatum and bicolor from China (GC-IV)	11
Eastern Africa	13	Photoperiod-insensitive caudatum from Africa (GC-V)	23
Southern Africa	42	Kafir and intermediate from Southern Africa (GC-VII)	30
India–Yemen	12	Guinea from Southern Africa (GC-VIII)	6
China–Korea	12	Bicolor not linked with other clusters (GC-XI)[b]	9
Other	8	Other (modern breeding material + not classified)	8

[a] Based on Deu et al., 2006.

[b] This group number is proposed by the authors.