Chapter 5

SUGARCANE TILLERING AND RATOONING:
KEY FACTORS FOR A PROFITABLE CROPPING

Sizuo Matsuoka1,3,* and Rubismar Stolf2

1Universidade Federal de São Carlos, campus ArarasRua Emilio Ferreira Neto,
Araras-SP, Brazil
2Universidade Federal de São Carlos, campus Araras
Departamento de Recursos Naturais e Proteção,
Araras-SP, Brazil

ABSTRACT

Sugarcane is grown all over the world from cultivars of complex genetic constitution ultimately coming from original hybridization mostly made a century ago between Saccharum officinarum and S. spontaneum. With that hybridization the pioneer breeders sought to obtain cultivars of good resistance to hazardous diseases affecting the crop and soon they realized that, doing so, they also united characters to withstand injurious climate and soil, as well as impacting mechanization procedures. The positive contribution of S. spontaneum to those characters is fully recognized. Tillering and ratooning ability are two of them, among others, much inherited from S. spontaneum and are of remarkable value in the profitability of the crop everywhere. The more the tillers grew the higher the chance of increased number of adult stalks to be harvested. Although the higher the number of stalks the thinner the diameter of the stalks, the final result is a higher volume and, thus, higher productivity. Also, the higher the final numbers of stalks the higher the chances of the following ratoon with a favorable stand and, consequently, the higher the chance of extended number of ratoons. S. spontaneum has rhizome and S. officinarum does not. This is a fundamental difference breeders have to be acquainted with. Rhizomes permit more efficient erosion control, more water infiltration, and long lived stands of crops. This last characteristic, besides avoiding costly soil preparation and planting operations, thus affecting profitability, also contributes for a more sustainable management as most soil erosion occurs during those operations. Here we review the basis of tillering and ratooning and go through the practical aspects of increasing them aiming at both increase in profitability and a sustainable sugarcane cropping.

* E-mail: sizuo.matsuoka@gmail.com.
INTRODUCTION

For centuries sugarcane was one of the most important crops in tropical and sub-tropical countries mainly to provide feedstock for making sugar. More recently, Brazil led the way in producing also ethanol from the sugarcane juice for usage as an alternative liquid combustible for transportation (Nemir, 1983; Rosillo-Calle, 1984), which latterly proved to having the most efficient life-cycle’s energy balance among current alternative biomass feedstocks (Macedo et al., 2008). That initiative opened a new era of liquid fuel from biomass and called attention to biomass dedicated crops as an alternative of renewable energy to mitigate at least part of the harmful effect of the petroleum-based energy system (e.g., Fulton, 1995; Wyman, 1999; Kheshgi et al., 2000; Johnson et al., 2007; Yuan et al., 2008). Among them, sugarcane ranks first as a competitive alternative source of biomass for energy (Coombs, 1984; Alexander, 1985; 1988). Nowadays, due to its high productivity and consequent low cost of production sugarcane feedstock and others from the *Saccharum* complex or from derivatives of them is also being considered as competitive alternatives (Ming et al., 2006; FAO, 2008; Tew and Cobill, 2008; Wang et al., 2008; Jakob et al., 2009) for future advanced technologies to be used in biorefinaries aiming at a wealth of chemical products (Ming et al., 2006; Rein, 2007).

The upsurge of interest in sugarcane brought as consequence a worldwide concerted effort in researching sugarcane and its industrial exploitation. On the plant side, the charming area of genomic, molecular biology and plant transformation has gained increased attention (Lakshamanan, 2005; Ming et al., 2006; D’Hont et al., 2008; Matsuoka et al., 2009) which, in its turn, denuded the scanty knowledge on basic understanding of how the plant either at organism level or, pragmatically, at crop level functions (Moore, 2005; Waclawovsky et al., 2010). If high yield is to be persecuted in order to gain competitiveness, plant functioning under field management procedures should be carefully dissected to discover constraints to be overcome with the existing technologies or if more effort in R and D is needed. Yield is result of a complex of interacting processes that the reductionist knowledge on the physiology at the molecular, cellular or organ level must be integrated in a system biology approach to fully realize in the field (Moore, 2005; Waclawovsky et al., 2010), a measure of fundamental importance in a complex plant such as sugarcane governed by quantitative traits much influenced by the environment (e.g., Brown et al., 1969; Hogarth, 1987).

Sugarcane cropping system evolved according to the specific conditions of each country or region and in each of them the level of farming advancement reflected the pragmatic skill of the growers, field administratos and agronomists in adapting the technologic and scientific knowledge developed in situ or introduced from elsewhere, under the influence and determination of environmental, economic, social, and political factors (e.g., Matherne et al., 1977; Matsuoka, 1991; Mariotti et al., 2006; and see chapters on Wilson et al., 1996). The result is a very divergent range of yield in distinct regions or countries, because not all the constraints factors can be easily overcame or not always the best of the knowledge is applied in the field. Examples of high yield attained in some countries is said to be indication of the ceiling capacity of the crop being reached (Garside et al., 1997; Moore, 2005). However, this
issue remains controversial given that the distance between that yield and the high yield reported for specific experiments or small commercial plots (e.g., Bull and Glasziou, 1975; Ming et al., 2006; Tew and Cobill, 2008; Waclawovsky et al., 2010), or even the calculated theoretical potential of the plant, remain very far apart (Irvine, 1983). This raises the question of how much knowledge is being put forth in practical crop management or if a gap in knowledge to be filled up is the case. An additional query is if the eventual change in the specification of the feedstock to adapt to the new demand coming from the energy policy requirement would alter the scene. Whatever the case, critical analysis of the specific factors governing yield should be appropriate and welcome. One previous review focused the underground organs of sugarcane (Matsuoka and Garcia, 2011) whereas this one is centered in the tillering and ratooning ability. Despite their importance in the profitability and sustainability of the crop, tillering and ratooning are two subjects scantily discussed in detail in books on agronomy and breeding of sugarcane and most available information on them are found sparsely in specific research articles. So, this review aimed at gathering and discussing the state-of-art of those two subjects with an integrative view to contribute all people entrusted with this crop in joining to the effort of higher feedstock productivity.

TILLERING

One of the bases of modern sugarcane feedstock production worldwide is the high performing adapted cultivars (Heinz, 1987; Tew, 1987; Matsuoka, 1991). They are highly heterozygous interspecific hybrids derived mainly from the introgression of a small genomic proportion of Saccharum spontaneum into a predominantly S. officinarum genome. The predominant characteristic of S. officinarum, a tropical plant, is low tillering, with large diameter culms (stalks), low in fiber, juicy, and broad and short living leaves, whereas S. spontaneum has high tillering ability, small diameter and fibrous stalks, with narrow and long living leaves (van Dillewijn, 1952; Artschwager and Brandes, 1958; Moore, 1987). In a complex mating process, the hybrids have about 80% of the genome of the latter and 10% of the former, with the remaining 10% as recombinants (D'Hont et al., 1996; Grivet and Arruda, 2001; Cuadrado et al., 2004). S. officinarum is important for transmitting high sucrose content and good milling characteristics, while S. spontaneum contributes characteristics that allow the hybrids to be grown in diverse environments throughout the world (Tew, 1987). This is possible because S. spontaneum is more genetically diverse than S. officinarum and thus contributes important characteristics such as better adaptation to biotic and abiotic stresses, high tillering and increased ratooning ability (Panje, 1972; Roach, 1977; Jackson, 1994; Tew and Cobill, 2008). Generally speaking, subtropical or temperate cane cultivars have more of S. spontaneum complement compared with tropical cultivars and, consequently, higher tillering ability (Kapur et al., 2011). The reconnaissance that tillering and ratooning ability are inherited from S. spontaneum can help breeders efficiently tailor cultivars best fitting the requirements of a particular environment, crop management system or feedstock quality and type.

Tiller is a shoot that sprouts from the base of a grass plant, so that tillering is the ability to do that. Tillering is a primordial characteristic of sugarcane: the main sink of the product of photosynthesis are the stalks formed from the growth of the tillers and, thus, the profitability
of the crop depends primarily on the tillers produced that will dictate the final number of harvestable stalks. Among plant characters associated with yield, population of stalks at harvest showed the highest correlation, followed by diameter and height of the stalks; diameter correlated negatively with number of stalks. (Brown et al., 1969; James, 1971; Mariotti, 1972; Miller and James, 1974; Rosario and Musgrave, 1974).

After planting the sett (the propagative portion of the stalk), the bud sprouts to form the primary shoot. The classical studies of C.A. Barber in the second decade of the 20th century (e.g., van Dillewijn, 1952; Moore, 1987) showed that in the base of this shoot forms a number of very short internodes, joined together, each node containing a very small bud. From those buds sprout secondary shoots with same morphology of the primary so that from them sprouts the tertiary shoots, and so on. Also Barber’s study showed that *S. officinarum* and *S. spontaneum* differs fundamentally in this trait. The species *S. officinarum* has the simplest tillering model that can be roughly represented by a primary shoot, three secondary and three tertiary shoots; conversely, *S. spontaneum* has a very intricate model with many secondary, tertiary, quaternary and even higher order shoots (see figure in Moore, 1987). Thus, the first species has a tendency to show a determinate tillering form whereas the second, an indeterminate form. However, in both species not all shoots grow onto the adult phase, the extent of tiller/culm mortality depending on several stressing factors acting over its genetic back ground. After the classical Barber’s study, tillering (and ratooning as well) has been only studied using commercial cultivars. From the practical standpoint it is understandable why, but the genetic background of each cultivar that determines the phenotype of tillering and its functioning has scarcely or never been taken into account. In the breeding and selection process a favorable combination of the contrasting characteristics of the two cited species is pursuit aiming at a tradeoff between the agronomic performance under the specific crop management procedures and a good feedstock quality for the industrial process; the more or less shift to the genome of one or other species that affects the tillering ability of the cultivars comes indirectly during the selection process in the breeding programs.

A model of tillering in a hybrid cultivar can be summarized as follows, based in a comprehensive study made by Rocha (1984) in Brazil. In an autumn planting (Apr.) using one-budded sett of the cv. NA56-79, the first secondary tiller appeared 26 days after the sprouting of the primary shoot and the second one, 18 days later; then appeared three other secondary shoots in subsequent intervals of 8, 8 and 10 days, to appear one tertiary shoot 22 days later, followed by a sixth secondary shoot three days later. At harvest, with 17 months of age, only were surviving four secondary tillers, the first three and the sixtieth. It is noteworthy that the primary tiller had died. That pattern was somewhat similar when a three-internode sett was used (only the central bud was permitted to sprout), however surviving the primary tiller and three secondary ones, although not in the same age order. The death of the primary tiller in the case of one-budded sett was probably due to the weakness of it as result of low energy available to the shoot in the small vegetative propagation tissue (van Dillewijn, 1952), aggravated by the stressing winter condition that the plant had to pass during the formative phase of the stool (Ramesh and Mahadevaswamy, 2000). As a matter of fact, in his experiment of summer planting the primary tiller survived till the harvest, in which period temperature and water were in a more favorable conditions for normal growth. It is important to have in mind that this pattern can basically be determined by the cultivar genetic constitution, that is, the tradeoff between characteristics of the two mentioned species during its selection.
In commercial planting systems the tillering model, apart the genotype effect, is tailored by several factors, spacing of the plants being prominent, and having ongoing tiller formation and subsequent mortality as a common feature in most variable conditions (e.g. van Dillewijn, 1952; Kanwar and Sharma, 1974; Irvine et al., 1980a; Soopramanien and Julien, 1980; Machado et al., 1982; Inman-Bamber, 1994; Muchow et al., 1994; Robertson et al., 1996; Ramesh and Mahadevaswamy, 2000). So, tiller dynamics is largely determined by crowding which is influenced by spacing of plants (Kanwar and Sharma, 1974; Irvine and Benda, 1980; Irvine et al., 1980a; Irvine et al., 1980b; Shih and Gascho, 1980; Bull and Bull, 1996), if considered a fixed effect of the other environmental factors. In general, the closest the spacing the highest the number of tiller per area basis and, so, the resulting yield at harvest is higher, although without linear correspondence (van Dillewijn, 1952; Irvine and Benda, 1980; Irvine et al., 1980a; Irvine et al., 1980b; Bull and Bull, 1996). But not always it is as simple due to the unaccounted sources of variation as will be discussed hereafter.

Growers like to get a profuse tiller formation, considering this pattern as a good crop establishment. They don’t concern the high level of tiller mortality thereafter, usually reaching 50% and sometimes 70-80% (e.g., van Dillewijn, 1952; Robertson et al., 1996; Soopramanien and Julien, 1980; Kapur et al., 2011); in fact they consider the profuse tillering an insurance against eventual shooting and tillering failure due to uncontrolled external factors and the consequent gaps, which are cumulative and may increase in each successive ratoons. However, too much tillering is actually a waste of input (van Dillewijn, 1952; Soopramanien and Julien, 1980), both natural and anthropogenic. If in the grand growth phase is given the plant ample condition for tillering, in the adult phase the available resources will not be in full and so will not enough to sustain all those tillers, resulting on death of many of them. This means a lot of resources being utilized without reflecting in yield at harvest. Oliveira et al. (2004) in Brazil evaluated the growth progress of three cultivars with distinct patterns in a time span of 497 days after planting (DAP) in nine intervals of evaluation. When they compared a medium tillering (RB72454) with a high tillering cultivar (RB855536) they found 69% more tiller in this second cultivar at 182 DAP and a tiller mortality of 57% thereafter until the final harvest, against only 27% of mortality in the former. Both cultivars presented the same stalk height at the final harvest but the first presented a higher diameter of culms, which resulted in higher dry mass yield per area. This is a clear example of the sink efficiency of a cultivar.

In the initial phase of growth the canopy of the crop do not entirely cover the ground and the wider the spacing between rows the longer is the time for canopy closure (Singels and Smit, 2002), resulting longer time with a low leaf area index (LAI) (Shih and Gascho, 1980; Muchow et al., 1994). Being LAI low, the radiation use efficiency (RUE) in terms of area of soil will be lower by consequence, that is, the radiation interception is under optimized and the canopy closure is retarded (Irvine and Benda, 1980; Shih and Gascho, 1980). Conversely, after the canopy closure, the excess of leaf will shade the lower leaves (Sheu et al., 1983; Ramesh, 2000) and the smallest shoots will gradually weakens and died at the end, also as result of competition for resources (e.g. Inman-Bamber, 1994; Ramesh, 2000; Ramesh and Mahadevaswamy, 2000), the magnitude of this process depending on a interaction of the width of inter-row spacing (Singels and Smit, 2002), canopy architecture of the plant, resources available and extension of the cycle (Sheu et al., 1983; Muchow et al., 1994; Robertson et al., 1996). If plant cane is compared to ratoon cane, shoot growth pace and subsequent tiller formation is higher in the second (Robertson et al., 1998).
Irvine and Benda (1980) made a comprehensive study to elucidate the question of spacings. When they compared a wide inter-row spacing of 183 cm, the highest yield obtained was in the closest intrarow spacing between plants (19 cm), meaning that at larger spacing there was a waste of space that the plants did not utilize to perform full growth. When they tested an equidistant inter-plant distance in a checkerboard design (19, 28, 76 and 152 cm) the yield of millable stalks increased significantly with decreased spacing; the number of shoots from the 19-cm spacing was almost four times that from the 152-cm spacing, resulting in fresh biomass yield almost three times bigger. As result of crowding, the diameter of the stalks decreased significantly and, conversely, the LAI increased. In a third experiment they tested equidistant spacings ranging from 26.7 to 179.1 cm in a wheel design. The LAI of the two evaluated varieties showed almost a tenfold increase from the widest to the closest spacing, as influenced by population density, even though the leaf area per plant steadily decreased with spacing. In the closest spacing occurred an early rapid rise in tiller population per area during the first three months and then a drop, first abrupt, then more gradual for the remainder of the season. In the three closest spacings the population at harvest was higher than in the others. However, it should be reminded that their experiment was harvested at 8 months of age. Should it be harvested in a longer cycle like is practiced in tropical conditions prevailing in most sugarcane areas of the world (12 to 18 month cycles) the result would be expected to be quite different. In this condition the death of tillers in the closest spacings would be much higher, and the intermediate spacings would be most appropriate, as indicated the results by Kanwar and Sharma (1974) and Singels and Smit (2002). It is important also to have in mind that all the studies discussed so far (and others to be discussed below) is based in cultivars selected in specific inter-row spacing so that a bias could be expected. Bull and Bull (1996) showed that in an unselected population can be identified genotypes responsive for specific spacings and Garside and Bell, (2009) confirmed that the response of cultivars could be differentially expressed in distinct row spacings.

Solar radiation is the source of energy for plants’ growth. High productivity of crops is achieved improving the efficiency of solar energy utilization in growth processes of crop population. Shimabuku et al. (1980b) found positive and high correlation between the efficiency of solar energy utilization (RUE) and crop growth rate in almost all growing period, and that the magnitude of leaf area index (LAI), the rate between leaf area and ground area, in the period of rapid growth, affected significantly the RUE. In other words, if in the early growth period RUE is much affected by the magnitude of LAI any rapid and early growth (tiller plus leaf formation and persistence) will make the crop more efficient. Shimabuku (1976) found a negative correlation between light extinction coefficient (K) and LAI, indicating that varieties having smaller K tend to have higher LAI. This means that cultivar presenting a canopy with low light extinction coefficient should have high RUE. The RUE evolvement throughout the crop cycle (Shimabuku et al., 1980b) will depend on leaf morphology and architecture, as shown by Rosario and Musgrave (1975) in combination with its physiology under distinct environmental conditions; this is an issue deserving multidisciplinary integrated studies, which is lacking. Cumulative light interception (CLI) and thus RUE in the entire crop cycle is more important in higher latitudes than in the tropics due to the obvious reason of its lower radiation, as the same in particular conditions of higher number of cloudy days. In a high altitude condition of Mauritius, where prevail cloudy days, Koonjah and Nayamuth (2005) obtained higher productivity in a condition of planting system
allowing a rapid canopy cover to maximize solar radiation interception, with the added benefit of diminishing weed competition.

Although Irvine and Benda (1980) were not able to find differential effect on yield between two basic leaf architecture grouped cultivars, erect or spreading leaves, other authors claim the contrary. Van Dillewijn (1952) in compiling several studies concluded that POJ2878 requires less space for an optimal productivity among several contemporary cultivars evaluated and conjectured that the reason could be its more erect leaves. Rosario and Musgrave (1974) related cultivars with higher net carbon exchange with those possessing erect, narrow and thick leaf morphology (characteristics of S. spontaneum), claiming that in those cases mutual shading effect would be minimized. Bull and Glasziou (1975) found that erect leaved cultivars gave significant increased yields at high stalk densities due to better light penetration in the canopy. Shimabuku et al. (1980a) found that high yielding cultivars with few dead stalks at harvest were characterized by high plant height and erect leaves. Incidentally can be remarked that the cultivar RB72454 above mentioned in the study of Oliveira et al. (2004) has an architecture of erect leaves, resulting in an open canopy in terms of light penetration, against a very tight closed canopy of RB855536. The higher rate of tiller formation and consequent rapid canopy closure usually observed in commercial fields of this second cultivar, and recorded by Oliveira et al. (2004) when they measured LAI, give a false impression of yield superiority of it that do not confirm at all at harvest. In this particular case, the improper water balance could be the restriction factor. In drought intolerant cultivars like it (Matsuoka, Personnal communication), Smit and Singels (2006) found plant inability to maintain for longer the stomata conductance and leaf water potentials during the drying process, with high shoot and leaf senescence as consequence. Sheu et al. (1983) compared three cultivars and found one of them (ROC1) to be the most efficient in solar radiation utilization even having lower leaf area, as its better leaf architecture permitted good illumination of all leaves in the canopy; although being the cultivar with the lowest number of tillers per stool under full light, it showed to be less affected in tiller formation when light was reduced by 30 and 70%.

Here it is necessary to consider that individual plant architecture is not the same as crop architecture. Crop canopy architecture results from the crowding of individuals and the final leaf spatial arrangement is genotype-dependent. Although not studied in sugarcane yet, in other plants, including maiz, has been shown that there are plastic genotypes that have the ability to modify leaf orientation according to the available space (Maddonni et al., 2001). In sugarcane, the crowding results from the number of emerging primary shoots and the subsequent tillering under the influence of the environment and is not known what that plasticity means in terms of leaf arrangement, if any. In sugarcane cultivars, leaf disposition in the spindle is variable, basically being two alternate ranks on either side of the stem but the orientation of them can vary from ellipsoidal to fan-shaped, which, in interaction with number of active leaves, their width and length, and erectness also, can result in particular canopy format. Plants are able to detect neighbor proximity using sensitivity and response systems to detect changes on the quality of ambient light, basically the ratio of red to far-red light (Smith, 1995, as cited by Fellner et al., 2003) within the canopy. To avoid shade, plants respond to close neighbor proximity with morphological changes such as stimulation of elongation growth, reduced branching and a redistribution of leaves to the top of the canopy (Morgan and Smith, 1979, as cited by Fellner et al., 2003). Additionally, the water relations of plant canopies differs from what would be predicted from the studies of individual leaves,
because each leaf interferes in the environment of adjacent leaves, either on irradiance, wind speed, and vapor pressure, thus affecting the canopy functioning (Lambers et al., 2008). Another point completely ignored in sugarcane, to our knowledge, is how much the leaf sheath contributes to the photosynthesis. The level of this contribution, if any, could be much influenced by the light extinction coefficient. Results by Cordukes and Fisher (1974) indicated that leaf sheaths exert influence on stem elongation of Kentucky blue grass, which effect is to be expected in sugarcane also, with its easily recognizable importance.

Bonnet (1998) observed that the rate of leaf appearance, which determines the growth rate, is positively correlated with a smaller leaf lamina. Irvine (1975), additionally demonstrated that the photosynthetic rate on an area basis of \textit{S. spontaneum} is nearly twice those of \textit{S. officinarum} and 30% greater than that of hybrid cultivars. As \textit{S. spontaneum} has a narrow leaf lamina, diverting the selection of cultivars from broad-leaf \textit{S. officinarum} types is expected to indirectly give individuals with greater photosynthetic efficiency and, thus, of greater yield potential (Rosario and Musgrave, 1974). The ideal condition is the one where there is a closest possible equilibrium of LAI throughout the entire cycle in order to intercept photosynthetic active radiation (PAR) in an amount strictly necessary to maintain an equilibrated number of tillers (Singels and Smit, 2002) or, in other words, maximizing the production of leaves early in the growth phase and then only replacing the senescing ones (Bonnett, 1998; Robertson et al., 1998). To this happen it is necessary a concerted effort of breeders to select a cultivar for a specific spacing combined with fixed crop management in a given climatic condition. It is worth to note that all this discussion is considering the absence of any external stressing factor like disease or pest attack, soil compaction, water and nutrient imbalance, etc. Precision agriculture aims to level off all those factors.

From the viewpoint of feedstock quality, continuous tillers formation is not desirable: young tillers could have lower concentration of sucrose than the older ones (Ramesh and Mahadevaswamy, 2000). Then, the rapid increase in tiller number till the peak tiller population (PTP) to subsequently reach the plateau as early as possible, that is, a synchronous tiller formation, should favor uniform ripening to favor better cane quality in terms of sugar content at harvest (Kapur et al., 2011). Usually that plateau is reached 3 to 5 months after sprouting, this interval depending mainly on environmental conditions, basically dictated by thermal time (Inman-Bamber, 1994) and water, thereafter following a period of death of stalks (Irvine and Benda, 1980; Robertson et al., 1996; Ramesh and Mahadevaswamy, 2000; Kapur et al., 2011). The extreme case would be those in which the density of primary shoot is so high (high planting density) that the primary stalks grow rapidly, the tillering is strongly diminished to avoid the death of them near canopy closure, thus exploiting soil water and nutrients more efficiently than conventional planted crops, resulting in a harvestable stalk population physiologically more uniform in maturity and, thus, a better feedstock (Bull and Bull, 1996; Kapur et al., 2011). Zhou (2005) found the thermal time to reach peak tiller population (TTRTPP) to vary according to the season of planting, which is expected; the negative correlation of that parameter with yield he found means that the fastest the plant reach (PTP) the higher will be the yield. The PTP and the final tiller population (FTP) also were influenced by the season of planting and both showed strong correlation with yield, meaning that there is a seasonal influence in tillering and survival rate, and consequently in yield. However, he observed higher correlation between PTP and yield in cultivars of high tillering ability compared to low tillering ability cultivars and, conversely, higher correlation of yield with FTP in cultivars of lower tillering ability. This reinforces the correct choice of
growers for high tillering cultivars to minimize the risk of external deleterious factors depleting the yield.

Studies have shown that, during the phase of high tiller mortality, there is no impairment of the growth of living shoots (Muchow et al., 1994; Robertson et al., 1996; Otto et al., 2009); by the contrary, shoot growth may even be favored in the remaining shoots, as hypothesized by Buso et al. (2009). Kapur et al. (2011) adverted that breeders should look for this issue in their selection process. Another point not much taken into account is the shoot-root relationship (Matsuoka and Garcia, 2011). Shoot and root are intimately connected so that root dynamics depend on shoot dynamics and vice versa (van Antwerpen, 1999). Clements (1980) found a gradual decrease in root number and length of each new tiller. Probably this happens because each new tiller is weaker than the preceding ones due to disadvantage in resource acquisition in a very competitive habitat. Kays and Harper (1974) pointed that a stool functions like a matriarchal tribe of shoots, many generations of individuals living together, with eventual severance from the parent plant and independence upon one another, resulting in an inevitable competition between generations. Ross and Harper (1972) have shown that hierarchy is largely determined by quite small differences in emergence time resulting in differing success of the various tillers in the capture of resources, with the elimination of the smallest members as consequence. Stolf (1989) showed that the height of total tillers in any time throughout the entire 12 months cycle of a 4th ratoon cane, but more evident after the grand growth phase (6 to 8 months of age), follows a bimodal curve with the valley represented by those tillers in the critical height of competition or in the “valley of death”. He also observed that tiller formation and tiller mortality is a continuous process during all the cycle, at least in the particular variety he studied.

As has been said, the crop canopy will be determined by the combination of tillering model, leaf arrangement and spacing. Due to managerial necessity and economic requirements, sugarcane plants are not conducted in an ideal geometrical disposition in terms of light capture and even other resources. The most common design is to plant in lines (rows) with variable inter-row spacing but predominantly between 1.00 to 1.80 meters, trying to accommodate requirements of mechanization and other agronomic and economic drivers, like drainage, weed control and seed propagation rate (Richard, Jr. et al., 1991; Kapur et al., 2011). The rapid canopy closure in smaller row spacing has a significant impact in weed control cost but, conversely, is said the cost of seed cane increase significantly with decrease in row spacing (Singels and Smit, 2002) and a compromise between those two contrasting factors should be met. However, the alleged higher cost of seed cane is a point requiring clearing. Stolf and Barbosa (1990), in discussing this point, and based in the evidences brought in the literature, claimed that the quantity of buds should be fixed in terms of area and not in terms of length of row, meaning that at least the cost of seed-cane is not to be altered. Another point is that studies of spacing and/or geometric dispositions could present some bias if the row distance is distinct from that under which the cultivar had been selected. In other words, as the cultivar is selected in a pre-fixed spacing value, its performance in narrower or wider spacing than the original could be different (Irvine and Benda, 1980; Richard, Jr. et al., 1991; Bull and Bull, 1996).

In breeding populations it is common to have clones that persistently emit excessive number of shoots some cases even later in the growth cycle (suckers or bull shoots) usually because the canopy does not shade completely the ground or when some inducing factor came in (lodging, gaps and consequent excess of light reaching the ground, diseases or pests attack,
nutritional imbalance, etc.). If this happens, the clone detected with this particular feature should be penalized in the breeding process but happens that some of them reach the commercial scale. In long lasting crop cycle of 24 months like in Hawaii, suckers are important component of productivity, as they appear at the end of the first year cycle, but in normal cycle from 12 to 16 months, they constitute a problem in terms of feedstock quality (lower sugar content and higher reducing sugars (Bonnett et al., 2001; Gravois et al., 2002)). Suckers are usually very vigorous and thicker than normal canes (Bonnett et al., 2001; Salter et al., 2008) and this is suggestive that much energy is stolen from the stalk from which it is growing (Bonnett et al., 2001); Hart and Kortshak (1962) and Bonnett et al. (2001) showed that young tillers can draw sugar from the established culms indeed. Jordan et al. (2004) speculated that increase in suckering could be due to selection of cultivars with high tillering capacity. These authors found stalk number and suckering markers located within or near QTLs (Quantitative Trait Loci) associated with tillering and rhizomatousness in sorghum, a species closely related to *Saccharum*. They inferred that appears that there are unlinked regions of the genome associated with stalk number and sucker number, suggesting that “it should be possible to select concurrently for high stalk number, low sucker types (…) and that it should be possible to select for homologous and (or) homoeologous sugarcane chromosomes with alleles for high stalk number and reduced sucker numbers”.

Robertson et al. (1999), when imposing water deficit early in the season observed marked reduction in LAI, stalk number and biomass production by the end of the deficit period. However, by the harvest time the biomass was not affected, primarily due to the ability of the crop to produce leaves and tillers at a rapid rate during subsequent well watered conditions. The high number of tillers can help the plant to counteract the detrimental effect of water starvation at that stage; conversely, water deficit imposed in later stages of plant growth will affect the yield because the detrimental effect fall directly upon the stalks that will make the yield.

It is not necessary to register that in all the review above the effect of temperature in the tillering is implicit. The base temperature for tillering appearance and thus shoot growth was established as 16°C by Inman-Bamber (1994) but Campbell et al. (1998) established the base temperature for node appearance, therefore leaf appearance, as between 7.6°C and 7.8° for two Australian cultivars.

The base temperature is essential to get the thermal time, an essential parameter in any study of growth. If distinct results are to be compared, time measured in terms of days, months or years are of no comparative value because they are influenced by the prevailing temperature in each period of measurement. Also, among other external factors that influence tillering, the incidence of pests and diseases is easily and clearly recognized but this issue should be the scope of other review. The same applies to the nutritional issue and other factors like imbalance of water (drought or flooding), salinity or sodicity, weed competition, toxic substances, etc.

**RATOONING**

Ratooning is a trait of fundamental importance in the profitability of sugarcane exploitation. In distinct farms, regions or countries of the world the number of ratoons they
can get establishes the level of economic competitiveness attained. This happens because the high cost of establishing a sugarcane plantation can be amortized over a number of lower cost ratoons crops (Chapman and Wilson, 1996). Given that sugarcane is propagated vegetatively, using as “seed” the stalk, the rate of multiplication is limited to as low a rate as one to ten, aggravated additionally by the cost of its harvest and transportation due to the high volume and weight per unit of area normally used. For example, in the harsh condition of Louisiana where two ratoons are hardly obtained, the release of a variety like LCP85-384 permitting at least one more ratoon was considered a hallmark (Salassi and Breaux, 2002; Gravois and Bischoff, 2008). In terms of environmental benefits, ratooning is also of striking importance, reducing the frequency of soil preparation for establishing a new crop with the consequent reduction in inputs and, mainly, soil erosion. Soil erosion, one of the biggest environmental concerns in agriculture (Lal, 1998), occurs mainly when tillage is applied to the soil for new sowing. So, the more the number of ratoons, the less the occurrence of erosion, which makes ratooning ability as one of the most desired traits in sugarcane cropping. Longer ratooning also increases the proportion of land in effective use in the farm, which results in a large economic gain and increased competitiveness, mainly in areas of strong competition for land with other crops or land diversion for other more value-added purposes. Moreover, the advantage of perenniality in sustainable agriculture is to be fully exploited (Lynch, 2007; Glover et al., 2007; Glover et al., 2010).

It is of long common sense that ratoon crop canopy develop earlier and faster than plant crop canopy. Thompson (1988) indeed found that ratoon crop produced a leaf canopy much faster than plant-cane and also initially accumulated dry matter at a faster rate. Robertson et al., (1996) concluded that the quicker biomass accumulation of ratoon crop over plant crop is associated with a greater fraction of incident radiation intercepted. The ratoon cane has a much greater number of buds to sprout than plant cane due to the dense stubble (crown) left after harvest. Here it is necessary to consider that the persistence of roots from a previous cycle could also be one prominent inducer; part of the driving force to the new shoots is probably the input of water and nutrients provided by these persistent roots, mainly during a dry period (Smith et al., 2005; Matsuoka and Garcia, 2011). Counteracting previous claims (as reviewed by van Antwerpen, 1999; Smith et al., 2005), Ball-Coelho et al. (1992) found that deep roots from the stubble of previous crop remain alive at least until the flush of new roots coming from the new tillers, in consonance with some previous results, as reviewed by van Antwerpen, 1999. They found also that the root system of ratoon crop is more developed than that of the plant cane; likewise, Vasconcelos (2002) found continuous root mass increase from plant cane to third ratoon, which fact contradicts the claim that the ratoon yield decline has as one of the causes the less developed root system. However, this point is controversial and requires further studies.

Glover (1968) concluded that persistence of old root system is critical to survival of the stool and growth of the ratoon crop during dry periods after harvest. Difference in root mass between cycles may result from climatic conditions differentially affecting each cycle (Alvarez et al., 2000; Vasconcelos, 2002) but the genotype effect is high, obviously (Rodriguez et al., 2010; Vasconcelos, 2002;) and the field management procedures (harvesting method, being it burnt and manual or unburnt and mechanical) showed interaction with genotype and soil profile (Vasconcelos, 2002). The heavy harvesting machine’s traffic elevates the soil bulk density, thus affecting the rooting but, conversely, the trash blanket covering the soil when the cane is harvested unburnt helps in maintaining higher humidity in
the shallower soil depth during periods of water starvation, what favors root survival and, consequently, better plant development (Vasconcelos, 2002).

Rhizomatous characteristics of commercial sugarcane cultivars, if any, come from *S. spontaneum* as *S. officinarum* does not have this trait (Paterson, 2009). As rhizomatousness is of capital importance in the tiller and ratooning capability of a cultivar the readers are kindly remitted to Matsuoka and Garcia (2011) where a complete discussion of this issue has been done. In the current cropping systems the number of ratoons in distinct places varies according to the prevailing environment in terms of soil and air and the agronomic technology adopted (Kingston, 2003). In analyzing this issue what turns clear is that there is room for increasing the number of ratoons with some basic agronomic measures, as briefly will be discussed later.

After harvest, the mentioned rapid flush of new shoots in the ratoon usually does not result in higher productivity. What is most common is a gradual yield decline with increasing number of ratoons, leading to the necessity of plough out at a certain breakeven point. This decline is not a result of any genetic deterioration but rather an environmental effect: there is an unaccounted number of influencing factors like soil compaction, more shallow root system with advancement of ratoons and consequent difficulty in getting water and nutrients, systemic diseases, root and stubble diseases, soil insect pests and nematodes, permanence of abnormal drought, etc., if excluded the occurrence of gaps, which will be discussed further. Botanically there is no reason for degeneration; sugarcane being a perennial plant its ratoon is to persist for ever, with reported cases of 20 to 25 successive harvests or even 36 in good managed fields under irrigation or small manual harvested areas (Kingston, 2003; Nuss, 2001; Chapman and Wilson, 1996; Tonta and Smith, 1996;). In the current management system prevailing in most sugarcane grown areas at least seven ratoons under intensive but careful management is economically feasible (Tonta and Smith, 1996) and one to six is the prevailing average (Kingston, 2003).

Heavy machine traffic during cultivation and mainly during harvest and haul-out process is the main constraint to be minimized. The planting in line was developed to accommodate mechanization and the struggle has been always to reach a combination of inter-row spacing and appropriate machines to cause the less harmful effect on the plants (Garside et al., 2006). It is not the scope of this review going through this agronomic issue but rather discuss aspects interfering on ratooning (and tillering as well). The “controlled traffic” or the “permanent furrow” technique, with or without combined spacing, for example, is being proven to be of extreme value in increasing productivity and prolonging the number of ratoons (Garside et al., 2006). Whatever the case, cultivars with weak ratooning propensity, called gappy cultivars are less profitable (Chapman and Wilson, 1996). Gappy fields, either plant cane or ratoons, are a signal of bad crop management in most cases: bad soil preparation, inappropriate cultivar, improper seed cane, improper season for planting, unexpected disease or pest occurrence, herbicide damage, salinity, bad mechanical operations, mainly during harvest in the case of ratoons, if set aside climatic factors like freezing temperatures, lightening and extreme drought.

In a group of three experiments using inter-row spacing of 130 cm (two) and 140 cm (one) Stolf et al. (1986) found in plant cane harvested with 18 months a linear decreasing in yield in a rate of 3.2 % for each 10% increase in gaps. Although they considered gaps of above 50 cm, their results suggested that below 80 cm the plants were able to fill it up. Conducting the experiment until 3rd ratoon they found the same rate of yield reduction for a
cycle of 12 months each (Stolf et al., 1991). Replanting of gaps is quite common in case of
gappy fields detected early in plant cane or in special cases of ratoons (peasant farms for
example). In doing it Soopramanien (1996) recommend the use of pre-germinated cuttings or,
in ratoons, dig them out split the stubbles and replant them. In a fourth ratoon cane, Stolf and
Tokeshi (1990) demonstrated that the yield can duly be recovered by splitting the stubble and
replanting them in the furrow as seed-cane.

The economics of ratoon cycle length has been always a matter of concern in sugarcane
cropping, for obvious reason. However, the decision to plow out an old stubble field and
establish a new planting is not an easy task. Gappy fields had been shown to affect yield
negatively (Chapman and Wilson, 1996; Stolf 1986) and if replanting is not feasible, they
should be plough out in case of gaps above 50 % (Stolf, 1986). In other words, crop shows
high capacity to recover part of the gaps. That limit value, however, is cultivar dependent;
Chapman and Wilson (1996) showed that gappy cultivars were three times less profitable
than those of good ratooning ability cultivars and that those later yielded as high in sixth and
seventh ratoons as in the plant cane and first ratoons.

Another factor driving the renewing of a field is the yield decline along the cycles
without being linked to gaps. In these cases the main causative factor is usually soil
compaction resulted from the heavy machinery traffic during harvesting and haul-out (e.g.
Kingston, 2003; Garside et al., 2006), if eliminating other external factors like diseases and
pests attack, mineral deficiencies, etc. Sometimes a genetic shift has been speculated to
explain yield decline but definitively this has been proven to be a mistake (Mangelsdorf,
1959; Moore et al. 1993). Sugarcane being propagated clonally it is not possible to degenerate
genetically, indeed. It is known that in an insignificant number of buds can give somaclonal
variation (chimeras) naturally (Hughes, 1964; Wismer and Hughes, 1964), which usually are
deleterious. However, those degenerated individuals, unless selected for some reason, are
eliminated by competition. The economic side of the decision of “go or not go” one more
ratoon in a field basis is a kind of gain-lose game where some rationale is adopted but it is not
scope of this review discussing it.

CONCLUSION

Despite sugarcane being an old exploited crop there still remains a gap of understanding
of its functioning as an organism either taken at the plant level or as a population at the crop
system. In a very competitive world if an activity is to survive efficiency must be the goal.
Even though sugarcane being taken as one the most efficient plant to convert CO₂ from the air
to organic compound there are still constraints to be overcome to reach a higher level of
competitively for long-term success of this agroindustry. Recent advancements in molecular
biology studies of this plant (Lakshmanan et al., 2005; Moore, 2005; Ming et al., 2006;
D’Hont et al., 2008; Hotta et al., 2010; Manners and Casu, 2011) evidenced that both classical
biology and physiology side lag behind (Moore, 2005; Singels et al., 2005; Hotta et al., 2010;
Waclawovsky et al., 2010; Azevedo et al., 2011). Both these issues are basic knowledge
necessary not only for advancement of molecular biology studies per se but also for better
understanding the complex interaction plant-environment that drives production of this crop.
Previous reviews like by Smith et al. (2005) and Matsuoka and Garcia (2011), added by this
one are expected to help future approaches to eliminate remaining gaps of our knowledge on those issues.

Particularly in the issues of tillering and ratooning this review showed that if a considerable effort has been done to better understand them, gaps still exist to be cleared and effort to fully exploit the knowledge should be done for betterment of field productivity and sustainability.

One of the faults is that many studies had been conducted under a disciplinary approach or with an insufficient collection of data. The multifaceted process of sugarcane feedstock production requires an urgent need of a shift from reductionism to an integrative system’s approach. The challenge is to bring together all the diverse specialists of not only agronomy but also biology, ecology, chemistry, physics, mathematic, engineering, economy and informatics to develop a dependable modeling approach for the complex sugarcane crop.

In the present-day focus on biomass production as one of the contributor for a sustainable energy system the productivity is one of the main factors for the eligibility of a feedstock as sound alternative. To conform to this new emphasis on bio-energy crops sugarcane ranks first (Ming et al., 2006) and its potential productivity can still advance further if the paradigm of traditional sugar-making plant is to be broken, partially or totally, that is, a shift to a fiber-making plant. In this new purposed-bred plant (energy cane) the fiber comes as the wonder product instead of sucrose and the productivity will be directly dependent on the level of this shift (Alexander, 1985; Ming et al., 2006; Tew and Cobill, 2008; Matsuoka et al., 2010). In any case, tillering and ratooning will be essential for high productivity, and actingadditively, they can make not so difficult the task of breeding superior biomass cultivars.

Concluding, if in the global sense renewable energy and sustainability are the drivers, tillering and ratooning, either of sugarcane or of the energy cane, have much to contribute. At the same time they help a more efficient renewable food and bio-energy production they also contribute to mitigate soil erosion. Commitment to preserve the soil should be the driver of any agroindustry exploitation as it is the essential environment component for food and biomass production.

REFERENCES


Sizuo Matsuoka and Rubismar Stolf


