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Review Article

Chasing the Theoretical Limits of Productivity in Sugarcane (*Saccharum Spp.)*

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Abstract

Sugarcane is one of the most high value crops of agronomic and economic importance enjoying the largest scientific and technological attention in field and factory. It is one of the efficient users of solar energy but sensitive to soil aeration, radiation intensities, temperature and ageing factors when water and nutrients are freely available. It has a long history of chasing the theoretical limits of productivity thru research on all branches of Science. A relook at the theoretical maximum yield is attempted with new data on Net Primary Production (NPP) from solar radiation incident on earth through satellite studies. Recent studies have shown Net Primary Production can reach a level of 200 t C $ha^{-1}yr^{-1}$ (roughly 450 t bio-mass $ha^{-1}yr^{-1}$) which is roughly two times the other estimates.(*delucia et.al*). An attempt to understand the limiting factors to get nearer to maximum yields is made in this paper.

Keywords

Limiting Factors; Theoretical Maximum Productivity.

Introduction

Sugarcane is a valuable crop of economic and agronomic importance known for ages and needs no introduction. It is grown for the stalk which stores sugars and green tops that are used as feeding material for livestock. In recent times, its use as raw material for industrial purposes mainly for distilleries and biofuel improvement technologies is gaining importance; hence there is a constant need for scientific efforts to improve productivity levels and quality parameters. There are two main factors affecting sugarcane growth. They are (1.) Sugarcane is a C4 plant and is efficient at high light saturation and is therefore sensitive to sun shine hours and cloudiness, (2.) Xylem transport face an uphill task in maintaining loading into it from external solution in the roots which has a lower concentration than the one within it. As such it requires more respiration energy for xylem transport and hence soil aeration is important. Water stagnation particularly at tail end of rainy season should be prevented with good drainage system and (3.) Nutrient deficiency particularly that of nitrogen reduces the efficacy of carbon fixation. Of late research activities focus on understanding the ecological significance of coordinated variations in intrinsic light-water-N use efficiencies and the evaluation of significance of their coexistence and competition with C3 sub species. Further investigations on what morphological and physiological characteristics needs to be incorporated in to the new cultivars for dry matter production and its partitioning to various parts are pursued. Some of the important crop and climate details are given below.

1. Sugarcane is mainly a tropical plant grown in regions at latitude 36.7^{0}N to 31^{0}S and at altitude from sea level to 1000 m MSL with mean annual temperature of 21 to 27^{0}C. The critical temperature for growth is 15^{0}C. Between 15 and 21^{0}C the growth is slow and above 21^{0}C it increases reaching a plateau between 30 and 34^{0}C. Above 38^{0}C the net photosynthetic rate decreases. Day degrees for growth is calculated giving one point per degree above 15^0 up to 21^{0}C and two points per degree increase over 21^{0}C. (for 30^{0}C day degrees is (21-15)*1 + (30-21)*2 i.e., 24 day degrees) During ripening phase, i.e., 3 to 5 months ahead of harvesting , dry cold weather at a lower temp regime is required
2. It is a long duration crop requiring uninterrupted water supply for more than seven months. One

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ton of millable cane requires 666 kg bio-mass to be synthesized (See Table 1) and at 250 kg of water on an average per one kg biomass to be synthesized it requires 1.65 ha cm water. A 100 t crop therefore require water equivalent to 165 cm either thru rainfall, irrigation or both. Sugarcane is traditionally grown in regions with an annual rainfall varying between 75 cm and 200 cm with supportive irrigation to sustain economically viable productivity levels. The productivity in most of the regions is limited by water availability.

3. The photosynthetic rate demands a tradeoff among light saturation, water conservation in the tissues, sunshine hours and day length of not less than 10 hours for efficient carbohydrate production. Under water deficit conditions, tissue moisture level is maintained by polymerization of sugars to polysaccharides (fiber and then to pith) which releases water. If the water deficit prolongs for a loner time, then it leads to pith formation with loss of sugars. This happens particularly when prolonged water deficit sets in during ripening stage.

4. There is a growth rhythm in stalk elongation. Within an internode the growth is aero petal - over the node the growth is pushed upwards as the new one develops till it stops and new nodal joint forms. As such within the internode the tissues are older in top than at the bottom. The elongation is rhythmic and it varies between 5 to 8 days depending on cultivars. After this period growth stops a new node is formed and cycle repeats. As–such 4 to 6 inter nodes are formed in a month. The length and health of the internode reflects the growing conditions that prevailed during its formation. As such, about 4 to 6 leaves are formed in a month and about 48 to 60 leaves are formed in a year. Counting the leaves and inter nodes from the top growing point (spindle) tracks their physiological age and this system of nomenclature is used in crop logging procedures.

5. Sugarcane has three distinct growth phases- 1) formative phase up to 120 days when the germination and tillering take place. 2) Vegetative growth which extends up to 270 days when the biomass is built and the yield is stabilized and 3) three to five months of ripening phase which is planned and controlled by regulating irrigation to bring down tissue moisture level to 74%. On an average 50% of tillers die stabilizing the population density before starting of grand growth period by 150 days, and 10 to 30% of stalks die during vegetative growth phase due to competition for resources. Control on the mortality of tillers and stalks during these periods are required to achieve high yield levels.

Productivity Limits in Sugarcane

NPP: The maximum productivity indicated from NPP varies widely depending on parameters used in calculating it. Two views are summarized in Tables 1 and 2 - traditional one by early Sugarcane workers and the other one using the recent estimate on solar energy conversion efficiency to biomass Earlier estimate pins the theoretical maximum around 388 t millable cane (@ 67% average moisture content), while the recent one at 675 t under unconstrained supply of resources. Be it any estimate, it shows a large gap between the maximum achievable and the current productivity levels throwing challenges for narrowing it.

Table 1: Theoretical maximum yield (after monteith 1977, evans and fisher 1999)

SR $TJha^{-1}yr^{-1}$	E to B $17.5MJkg^{-1}$	EiCi	Biomass $Kgha^{-1}yr^{-1}$	MC $Kgha^{-1}yr^{-1}$	Biomass distribution $kg ha^{-1}$			
					Roots	Trash	Tops	Stalks
75.256	17.5	0.06	258.0	387.5	38.0	49.6	42.6	127.8

SR - Annual integral of incident solar radiation ($TJha^{-1}yr^{-1}$)
E to B - Energy to biomass MJkg-1
EiCi – Energy captured and used (Theoretical daily energy stored in biomass of C4 plants (6%))
MC- Equivalent mill able cane at 67% moisture

Table 2: Theoretical maximum yield (after deluce et.al)

NPP© $tCha^{-1}yr^{-1}$	NPP(B) $tBMha^{-1}yr^{-1}$	MC $Kgha^{-1}yr^{-}$	Biomass distribution $Kg ha^{-1}$ roots	trash	tops	stalk
200	450	675	66.2	86.5	74.3	223.0

NPP© – Net Primary Production as tons carbon per ha
NPP(B) –as tons biomass per ha (@ 40 % mean carbon content of biomass)

Biomass partitioning to various parts is shown in Table 3. Almost 50% of biomass is diverted to stalks which is the commercial end product as far as the farmer is concerned. Dry matter within the stalk is also shown in Table 3.

Table 3: Bio-mass distribution in sugarcane

Millable cane Kg		Associated dry matter distribution Roots	Thrash	Foliage	Stalk	total	Composition of Millable cane Fiber	Sugars	Non sugars	Moisture
A	150	14.7	19.2	16.5	49.5	100	20±3	21±3	4±2	102±7
B	100	9.8	12.8	11.0	33.0	66.6	13±2	14±2	3±1	68±5

mc - millable cane as stalks delivered at factory (also referred as air dry weights) at an average moisture content of 67% (variability 63t073%) in millable cane delivered at factory - mc wt. = dm *3.03.
Stalk dm * 1.50 = millable cane equivalent : mc wt. * 0.66 = dm of all parts put together
Dm = dry matter
A- Dry matter distribution (total 100 kg dry matter from 150 kg mc)
B- Dry matter distribution in 100 kg mc

Climate Related Constraints

In absence of soil and nutrients related constraints, water is the main limiting factor. Water use efficiency coefficient of rain or irrigation water is only around 0.8 because of sugarcane's sensitiveness1) to water deficit and 2) soil aeration when water is in excess. As such only 80 % of NPP could be achieved. For the rainfall pattern and irrigation frequency, the water use efficiency is calculated using the one developed for tea productivity. (Ranganathan, IJPS, 1: 2014). Theoretical maximum yield achievable under different water availability situations is shown in Table 4:

Table 4: Water as a constraint to achieve theoretical the productivity

	NPP as millable cane Kgha^{-1}	Rainfall ha cm	Irrigation ha cm	Total water ha cm	% of total water requirement	Water use efficiency coefficient	Max. productivity achievable mc kg ha^{-1}
A	675	1114	0	1115	100	0.8	540
B	675	150	200	350	31	0.8	167
C	675	100	0	200	18	0.5	30
D	675	50	250	300	26.9	0.8	145
E	675	150	0	150	31	0.4	84

A - Full water requirement satisfied ; mc – millable cane
B - rain fall and irrigation thru out crop period
C - Rain fed : D - irrigated low rainfall area: E- rain fed high rainfall

Nutrients: The importance of nutrients is well known, As Nitrogen is the major component next to carbon, hydrogen and oxygen, nutrient requirement is primarily based on it. As all other nutrients bear definite ratios to N and also they are important in one way or the other to sustain biomass synthesis and quality parameters, they are applied in proportion to N rates. At low and at moderate productivity levels, nutrients available thru natural recycling processes are given weightage based on soil and plant analysis. Alternatively Nutrients are calculated for the targeted yield above the threshold yield supported by soil nutrients available thru natural recycling processes. But at high target productivity programs, Nitrogen level is fixed for the targeted productivity and other nutrients are given in ratios found in whole plant analysis. Nutrients available in the soil thru natural recycling processes take care of soil physicochemical properties and in maintaining higher concentration in solution for maintaining high diffusion rate in rhizosphere to match with the high uptake rates demanded by the plant during growing periods for efficient use of the resources made available to them so that the target is achieved. (Ranganathan 2015)

Nitrogen content of whole plant is 0.37%, the above ground parts 0.34%.and below ground parts 0.59%. Sugarcane requires 2.53 kg N per ton of millable cane, out of which o.58 kg N is retained in the soil by the roots. Only above ground parts are taken away from the field – stalks to the factory, green tops as cattle feed and trash as fire wood. If crop residues other than millable cane is retained in the field, then every ton of mill able cane removes 1.12 kg N. Tops and trash remove 0.81 Kg N and if they are removed N removed from the field will be 1.93 Kg per ton of millable cane (Table-5).

Table 5: N removal per ton of millable cane

	Part of Plant	DM per t of mc in kg	N% dry matter basis N	P	K	N removal kg per t mc
A	stalks	330	0.34	0.11	0.28	1.12
	tops and trash	238	0.34	0.11	0.28	0.81
B	above ground parts	568	0.34	0.11	0.28	1.93
	roots	98	0.59	0.11	0.19	0.58
C	below ground parts	98	0.59	0.11	0.19	0.58
	Total	666	0.38	0.11	0.27	2.53.

DM – Dry matter : mc – millable cane :# -Van Dillewijin Botany of Sugarcane

If tops and trash are removed for one reason or the other, the equivalent quantity of organic manures are to be incorporated at the time of land preparation before planting and after burning stubbles for ratoon crop by broadcasting – minimum works out at 238 kg per ton of millable cane targeted or harvested and for a 100 t crop it is about 25 tons per ha. Only 30 to 50% of N available in the soil is utilized by the plants and taking the mean value of 40% N to be applied works out to 2.80 kg per ton of millable cane provided sufficient care is taken to maintain organic matter equilibrium in the soil. Other nutrients are applied in the ratios found in whole plant analysis or nutrients removed away from the field (Table 6).

Table 6: Elemental composition of sugarcane compared to mean of other crops

	Elements going into chemical composition of the bio-mass %				Macro elements%		Mineral nutrients present in ionic form to control bio-cycles and hydration of tissues Micro elements PPM							
	N	P	Ca	S	Mg	K	Cl	B	Fe	Mn	Zn	Cu	Mo	Si
A	1.5	0.20	0.50	0.10	0.20	1.00	100	20	100	50	20	6	0.01	N / A
B	1.20	0.17	0.52	0,24	0.36	1.60	100	30	101	30	6	5	0.01	3.31

A- Mean of other crops ; B- mean of the reported values

Threshold Limits Due to Soil Factor

Soil structure defined in terms of porosity, bulk density and aggregation is built over hundreds of years with humic-acid and related acids released during the decomposition of organic matter. Though humic-acids are fairly stable a small fraction is lost every year by decomposition. To compensate this loss and to maintain the soil structure, fresh organic matter is added every year which on decomposition releases humic acids which move down the profile and make up the annual losses. Organic matter further breaks down into organic acids and finally to inorganic ions and carbon dioxide. Organic matter decomposition is fast in tropical conditions – 90 to 95 % of organic matter is lost in a year. To maintain OM content around 1%, annual addition of 26 tons of organic matter is required at the above decomposition rates.IT is difficult to main OM status around 0.8 % under tropical conditions and 1.5 % in subtropical conditions. Soil structure helps in water storage in the soil and, in the movement of water, nutrients, and air in the rhizhosphere. Organic acids, interim product of decomposing OM, increase the retention time of micro nutrients by chelation and regulating their concentration in the soil solution by their hydrolysis constants. Inorganic ions released on decomposition are taken by the plant and this natural recycling of resources support a crop without fertilizer inputs. This is known as threshold productivity or what one can achieve without fertilizer inputs. One percent of OM on mineralization release around 150 to 200 Kg N along with other nutrients of which the biomass is made. The natural recycling of nutrient elements occur thru weathering of soil, alluvial and erosion deposits, decomposition of crop residues and added organic manures and, raising green manure crop and plough it in situ. In low and moderate targets, soil available nutrients are given due weightage based on soil tests and plant analysis. Nutrients are based on whole plant analysis as discussed earlier. Other soil related problems such as acidity, alkalinity, salinity and texture are to be treated appropriately. The threshold productivity of soil under various systems of OM replenishment systems are shown in Table 7.

Table 7: Soil Threshold productivity (without fertilizer application and water not limiting)

System	Cultivation system	A	B	C	D
1	Crop residues retained	100	40	2.53	15.8
2	A+ OM additions	200	80	2.53	31.6
3	Om At 25 t / ha to compensate removal of crop residues	150	60	2.53	23.7
4	Green manure crop raising and in situ ploughing once i3 t0 5years	200	80	2.53	31.6

A : Soil available Nitrogen kg ha^{-1}
B : Nitrogen used at 40 % efficiency- N kg ha^{-1}
C : N requirement kg t^{-1} millable cane
D : Threshold productivity - mc t ha^{-1}

Harvest Index: There is a conflict of interest between field and factory as far as Harvest index is concerned in sugarcane – Farmer is interested in the weight of millable cane and the factory in the commercial cane sugar percent (CCS) which decide the recovery of sugar per ton of millable cane delivered. The productivity equation as millable cane from farmers' point of view is given below:

$$\text{Mc t ha}^{-1} = \text{stalks ha}^{-1} \times \text{Wt kg cane}^{-1} \times 1000\text{-}3$$

(***all at harvest)***

Number of stalks at harvest depend on the number of setts planted per ha, germination percent, tillering capacity and mortality during tillering phase and grand growth period following it. The average weight of cane which varies between 0.8 to 1.2 Kg is determined by genetic factors and agronomic practices.

The commercial cane sugar percent (CCS) is the maximum sugar recoverable per ton of millable cane and calculated from Sugar recovery % (SR%) as shown below.

CCS t ha-1=(Y t ha-1×SR%/100
SR%=[S-0,4(S-S)]×) 0.73
Where S-sucrose% and B-Brix% (corrected) in juice

Sugar recovery is affected by non-sugars content of extracted juice and is related to the difference between Brix and Sucrose and extraction percent achieved at sugar mill. Distribution of biomass of sugarcane stalk and factory break up of end products are shown in Table 8.

Table 8: Stalk analysis and sugar recovery

Factory- inputs	: Composition of millable cane		
Fiber	**Sugars**	**Non-sugars**	**Moisture**
13±2%:	14±2 %	3±1 %	63 t0 73 %
Factory- out puts : end products			
Bagasse	Sugar	Molasses	Filter Press mud
12 ± 2 %	10 ± 1%	3 ± 1%	1.5 ± 1%;

After the vegetative phase i.e. 7 to 10 months after planting depending on the duration of the crop, the crop enters in to the ripening phase. Sugars start accumulating in the stalks. Cool dry weather and water deficit which have negative influence on vegetative growth favors the ripening. All fertilizer applications particularly that of N should be completed at least 5 to 6 months ahead of starting of the ripening phase. In most of the Sugarcane growing areas, ripening phase coincides with the tail end of rainy season and it's entering into cold dry weather. Three to five months ahead of planned date of harvest. Irrigation is controlled to bring down the sheath moisture from 78 to 80% to 70 to 74% on a phased pre-determined manner. A cane crop is normally harvested when the sucrose content reaches a minimum value of 16% with purity above 85%. Current research investigations focus on improving commercial can sugar content (CCS) to 14% and to find better uses for molasses, bagasse and filter press mud.it is a challenge to geneticist to perk up the accumulation of sugars to more than 16% in its culm dry weight to reach CCS values above 14%.

Summing up: Sugarcane is a photosyntheticaly efficient crop, but sensitive to water deficit and soil aeration. It is highly responsive to nutrients when water is not a limiting factor. Several crop log procedures to monitor the growth from the time of planting to harvesting have been developed from both the farmer and the factory points of interests. Limits to productivity due to various constraints are discussed to enable to plan a targeted approach to its management

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