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Why are yields of sugarcane not increasing as much as sugar beet (or other crops)?

Phillip Jackson

CSIRO Agriculture and Food, Townsville, Australia; phillip.jackson@csiro.au

Abstract Average worldwide farm-realised yield of sugar beet has increased by approximately 250% since 1961, while that for sugarcane has increased less than 50% over the same period. The yield increase of sugar beet is within the range observed in other major crops, while that of sugarcane is much less. Genetic improvement through breeding has made a major contribution to gains observed in the major crops since the 1960s. In sugarcane it has been suggested that factors associated with sugarcane monoculture may be at least partly responsible for slow yield increases. However, there is no evidence that such factors have been increasing over time which would nullify genetic or agronomic gains that would be otherwise arising. There is clear evidence of a lack of systematic long-term gain in yield or sugar content being generated in sugarcane-breeding programs. This appears due to persistence of a breeding system worldwide that does not deal effectively with complex non-additive genetic effects, unlike breeding systems that have evolved for some other crops. Reasons for less effective innovation in sugarcane breeding compared with other major crops are perhaps related to less investment and competition from large-scale multi-national institutes specialising in crop breeding and genetics. It seems likely that the conditions giving rise to past trends in yield improvement in sugar beet or sugarcane will persist. Given recent yield-improvement trends, and although there is expected to be a slight reduction in beet production levels to 2030, it seems likely that in the longer term a greater proportion of sugar production worldwide will be derived from beet than cane.

Key words Sugarcane breeding, sugar beet breeding, yield improvement

INTRODUCTION

World sugar production has been dominated by sugarcane and currently about 80% of sugar consumed in the world is from cane (http://www.fao.org/faostat). This is mainly because of the lower cost of production of sugar from cane. Despite higher production costs, beet cultivation has been protected from competition by governments in the European Union (EU) and the USA. Up until 2017 the EU maintained a quota system together with a guaranteed a minimum price for European producers (Heno *et al.* 2018). In the USA, imports of sugar remain restricted, providing protection for both domestic beet and cane producers from lower-cost producers (e.g. Brazil, Thailand, Australia).

In 2017 the quota and minimum pricing arrangements in the EU were abolished in favour of a more liberal approach in which the price of sugar will be linked more closely with world price (European Commission 2018). Production of sugar beet in Europe has been predicted to decline slightly up to 2030 due to some farmers switching to more profitable crops and overall industry rationalisation (European Commission 2018). However, because of major achievements in reducing costs of production from beet in recent decades, particularly via improvements in yield as detailed below, some observers are very optimistic about the longer-term future of sugar beet. Some sugar-beet industry participants forecast recent strong yield improvements to continue, and that costs of production from beet will become increasingly competitive with lowest cane producers (http://www.kws-uk.com/aw/Sugarbeet/Profitability-Made-by-Breeding/Sugarbeet-vs-Sugarcane).

In contrast to the impressive yield improvements in beet in recent decades, sugarcane industry participants in many countries are increasingly raising concerns about rates of improvement in sugarcane yields, especially in countries with long-established sugarcane-breeding programs. In this paper I compare the productivity trends of some major crops, including sugar beet and sugarcane. For most major crops there has been major yield improvements in recent decades, and the rates of improvement in sugar beet are somewhat similar to those in other major crops. For most crops it is clear that breeding and genetic improvement have played a major role in increasing yields. Sugarcane appears to be an outlier in these comparisons with increases in farm-realised yields being much smaller since the 1960s and contributions by breeding being less clear.

Here, I explore likely reasons for low rates of yield improvement in sugarcane relative to sugar beet and other crops, both from a technical and an organisational perspective. I suggest that the underlying factors probably contributing to slower progress in yield improvement in sugarcane are probably difficult to change. Given persisting prevailing trends in sugar-beet and sugarcane improvement, and the associated greater rate of decline of cost of sugar production from beet relative to cane, it is possible that sugar beet may take an increasing share of worldwide sugar production in coming decades.

PRODUCTIVITY GAINS OF MAJOR CROPS

The three largest cereal crops (wheat, corn, rice) plus soybean collectively contribute nearly 70% of the calories consumed in the world (by comparison sugar contributes approximately 8%) (FAO, http://www.fao.org/faostat). In long-term historical analyses of yield trends of these major crops, relatively low rates of improvements are observed up to the 1950s followed by more rapid improvements (e.g. Calderini and Slafer 1998; Fischer *et al.* 2014; Hafner 2003). Gains for the four major crops since 1960 are shown in Figure 1. Between 1960 and currently, averaged worldwide, farm-realised yields of most major crops have more than doubled (FAO, http://www.fao.org/faostat). In general, the trend of improvement of these crops and many others (not shown) has been constant and approximately linear and in no cases does a plateauing trend appear. The data in Figure 1 represent averages on a worldwide basis, and variations across particular countries occur (http://www.fao.org/faostat) but rates of gain in most major producers are reasonably similar. Yield trends for many less important crops, while variable, also demonstrate impressive gains in many cases. An example is shown for strawberry in Figure 1, which like sugarcane is a genetically complex polyploid species.

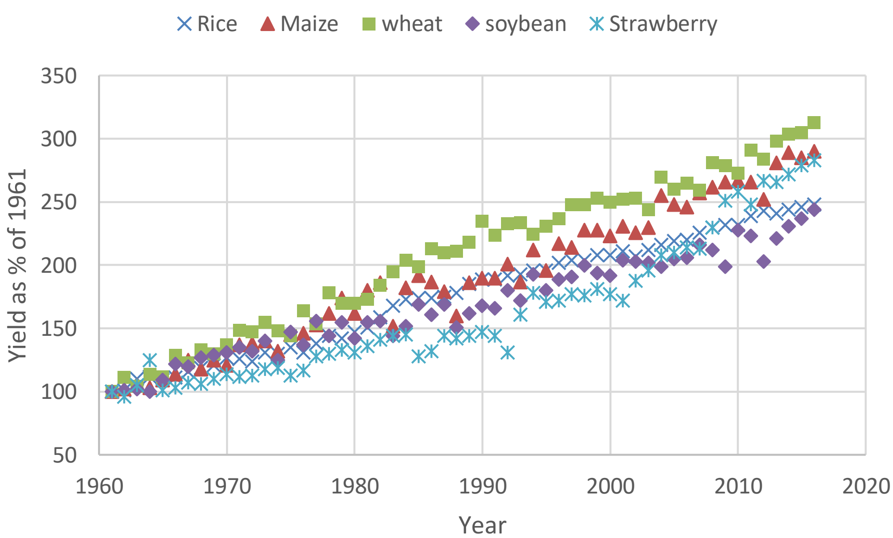

Figure 1. World average farm-realised yields of rice, maize (corn), wheat, soybean, strawberry between 1961 and 2016, expressed as a percentage of yield in 1961 (source: FAO, http://www.fao.org/faostat).

Changes in farm-realised yields in Figure 1 are due to multiple confounded effects (either positive or negative) including genetic improvement, changes in agronomy and mechanisation, levels of inputs applied (e.g. changes in labour, fertilizer, irrigation, pesticide inputs), and other factors. Crop scientists have partitioned change in farm-realised yield over time into change in "potential yield" (PY) and "yield gap" (YG) (eg. Evans and Fischer 1999; Fischer *et al.* 2014; Tack *et al.* 2015). PY is the yield possible by growing the best available cultivar in the absence of manageable stresses (such as diseases, weeds, pests, nutrients). Water supply must be adequate or else "water limited potential yield" (PY_w) can be defined (Fischer *et al.* 2014). YG is defined as the difference between PY and farm-realised yield. Gains in potential yields are usually attributed solely or mainly to genetic improvement in yield. Given data on PY and farm-realised yield over time, changes in YG can then also be estimated. Improvements (decreases) in YG over time usually are indicative of improved agronomy and farm management.

Studies providing estimates of potential yield gains and yield gaps in the major crops were comprehensively reviewed by Fischer *et al.* (2014) and their estimates for major crops are shown in Table 1. For most crops contributions by breeding were estimated to be greater than 50% of total farm-realised gains.

Table 1. Estimates of rates of yield improvement (between approximately 1990-2012), determined by Fischer *et al.* (2014). Definitions of potential yield and yield gap are provided in the text.

Crop	Rate of improvement in potential yield (%/annum)	Current yield gap (expressed as % of farm yield), and rate of change (%/annum)	Example studies documenting past potential yield change
Wheat	0.6	48, -0.2	Dixon et al. (2006); Underdahl *et al.* (2008)
Rice	0.8	76, -0.4	Peng *et al.* (2010); Silva *et al.* (2017)
Maize	1.1	Wide range from 36 (Iowa) – 400 (Africa), -0.6	Duvick (2005); Duvick *et al.* (2004)
Soybean	0.7	30, -1.0	De Bruin and Pedersen (2009);

YIELD GAINS IN SUGAR BEET AND SUGARCANE

Average worldwide farm-realised yield of sugar beet has increased by approximately 250% since 1961 (Figure 2). By contrast, average farm-realised yield of sugarcane increased less than 50% in the same period (Figure 2). The yield increase of sugar beet is within the range of other major crops, while that for sugarcane is much less. The sugar content of both sugar beet and sugarcane increased less than yield (only 15-20%) in the last 50 years (http://www.fao.org/faostat).

One factor possibly contributing to increased sugar beet yields is a decline in area planted (from approximately 9 million hectares in 1980 to 4.5 Mha in 2017; http://www.fao.org/faostat) that may have caused production to retract to more favourable areas. However, yields in France, where area planted has remained roughly constant, showed a similar total increase as the world on average (i.e. 250%; Figure 2) indicating yield increases have also arisen from other factors to a large degree.

Several studies have provided clear evidence of major contributions by both breeding and improved agronomy to farm-realised yield improvements in sugar beet. Mackay *et al.* (2011) analysed data from historical sugar-beet trials in the UK and reported a linear increase in yield of 1.6% per annum. They attributed about half of this increase to improved cultivars. Jaggard *et al.* (2012) analysed cultivar trials in Europe and also reported a 1.6% per annum increase in PY. In Germany, Loel *et al.* (2014) reported a 0.6-0.9% per annum gain in yield due to breeding. Loel *et al.* (2014) also emphasised better timing of operations by farmers and better cultivar choices by farmers. Hanse *et al.* (2018) examined progress in beet yields in the Netherlands and estimated a 3.4% per annum improvement after 2000 and attributed a 1% per annum increase from 2006 to 2016 to genetic improvement.

Biancardi (2005) provided a detailed account of technical developments in sugar-beet breeding programs. A series of major historical innovations were emphasised as contributing to progress, including development of systems to breed hybrid cultivars and improvements in breeding for resistance to a range of diseases and beet cyst nematodes. Hoffmann and Kenter (2018) argued that further yield improvements are likely in sugar beet but improvements in sucrose content are less likely.

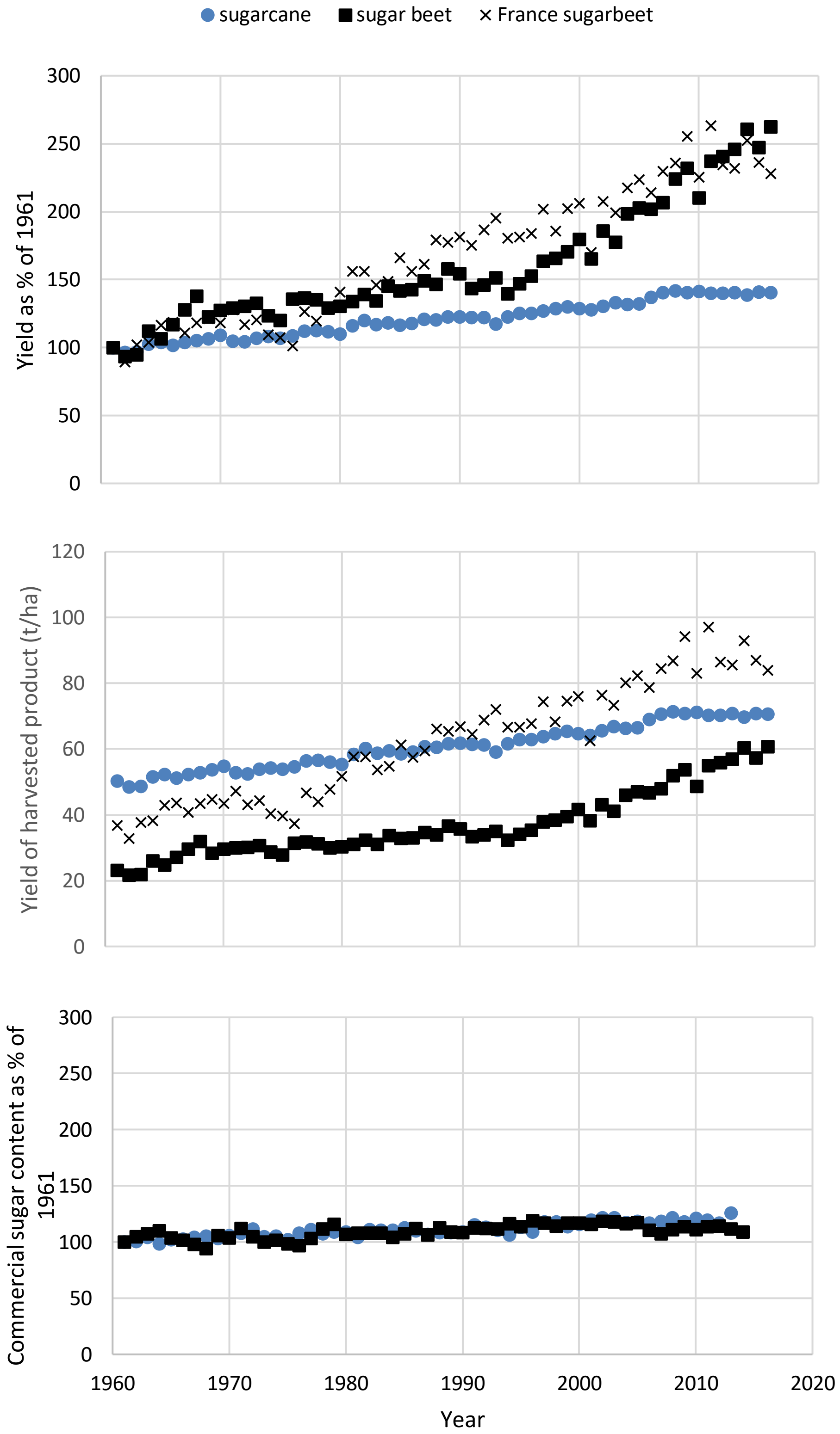

Figure 2. Farm-realised yield of harvested product (cane or beet) expressed as percentage of 1961 (top), absolute yield of cane or beet (middle), and commercial sugar content (sugar produced per weight of harvested product) (bottom), for sugarcane averaged worldwide, sugarbeet averaged worldwide, and sugarbeet for France only.

In sugarcane, possible reasons for slow rates of yield improvement have been discussed, especially problems with continual sugarcane monoculture (e.g. Garside *et al.* 2005; Pankhurst *et al.* 2003; Pankhurst *et al.* 2005). Many studies showed large gains in yield (30-50%) after long duration fallows or fumigation with methyl bromide (e.g. Garside and Bell 2011; Muchow *et al.* 1994), suggesting a major constraint to high yield is build-up of harmful soil biota. Another detrimental impact arises when mechanised harvesting is introduced, which causes stool damage and soil compaction (Braunack *et al.* 1993; Wood 1985). However, although these effects are important there is no evidence the impacts progressively increase over time. For example, in Australia yield responses from fumigation with methyl bromide were as large in the 1980s as 30 years later (Croft *et al.* 1984; Garside and Bell 2011). Therefore, it seems unlikely that these problems would be cancelling out genetic or agronomic improvements that may otherwise be expressed as gains in farm-realised yields.

In contrast to other major crops there have been no published studies using controlled experiments comparing potential yield (i.e. where biocides are used to control pests and diseases) of historically important sugarcane cultivars released at different times and including recently released cultivars. Therefore, it is difficult to quantitatively assess genetic gains in PY in sugarcane. However, the persistence of cultivars widely used by farmers for 30 or more years after first being grown as seedlings are apparent in a range of countries (www.sugarcanevarietynotes.com). This raises concerns among industry stakeholders about rates of progress arising from breeding, particularly when coupled with data in Figures 1-2.

In most countries, replacement of dominant sugarcane cultivars occasionally occurs due to new diseases or strains of disease (e.g. Croft *et al.* 2008; Magarey *et al.* 2001; Viswanathan and Rao 2011). Minimising impact of diseases through cultivar release is clearly a critically important contribution by breeding programs, but this contribution is different to improvement of yield or sugar content. It should also be acknowledged that individual cultivars offering clear yield gains over all other cultivars have, occasionally, been released in some countries in recent decades. An example is recent adoption of Co0238 providing large gains in northern India (https://sugarcane.icar.gov.in/images/sbi/article). However, such cultivars appear rarely and not able to be systematically repeated by breeders.

Edmé *et al.* (2005) documented a 15% increase in cane yield and a 27% increase in sugar content over 33 years up to 2000 in Florida, USA, and attributed 69% of the resulting increase in sugar yield to breeding. The increase in yield was roughly similar to that observed on an average worldwide basis (Figure 2), while the increase for sugar content was much greater than the worldwide average. Interestingly, in the past the Florida (Canal Point) breeding program has had a reputation among sugarcane breeders worldwide for producing high sugar-content clones and parents (Jackson 2018), suggestive of favourable methodology at that program for improvement of sugar content.

Partly in response to industry concerns about progress from breeding programs, Cox *et al*. (2005), Cox and Stringer (2007) and Burnquist *et al.* (2010) analysed productivity data in Australia and Brazil. These studies portrayed large and positive genetic gains. Those authors argued that plateaued farm-realised yields could be explained by concurrent declining environmental effects such as soil degradation due to sugarcane monoculture. However, criticisms of the statistical model used in these studies have been raised. These criticisms arise because at any point in time, new cultivars, on average, would have fewer old ratoon crops, and perhaps be adopted more by better growers. Thus, non-random distribution of the residual (non-modelled) effects associated with crop-cycle effects and individual farm effects, may cause upward bias in estimating genetic gains.

EVIDENCE AND REASONS FOR SLOW GENETIC GAINS IN SUGARCANE BREEDING

To provide commentary on progress in sugarcane-breeding programs it is important to consider the basic structure of existing sugarcane-breeding programs. While individual sugarcane-breeding programs differ in specific aspects, the general system in Figure 3 has been followed by most programs worldwide for >60 years (Heinz 1987; Jackson 2018). From annual crosses among a collection of "active" parent clones, large populations of seedling clones are produced and entered into the first stage of a multi-stage selection pipeline that typically takes eight or more years. At each stage of selection, clones are evaluated in field trials for commercially important traits. A subset of clones with best apparent performance transferred to the next stage for further and progressively more accurate evaluation. The best performing clones from the final stage of selection may be released to growers. Importantly, in terms of considering genetic gain over time, the best performing clones are also used as parents for further generations of crossing (Figure 3). Long-term genetic gain occurs if some new parents selected from the advanced stage trials have higher breeding values than older parents, where the breeding value of a parent is defined as average performance of its progeny.

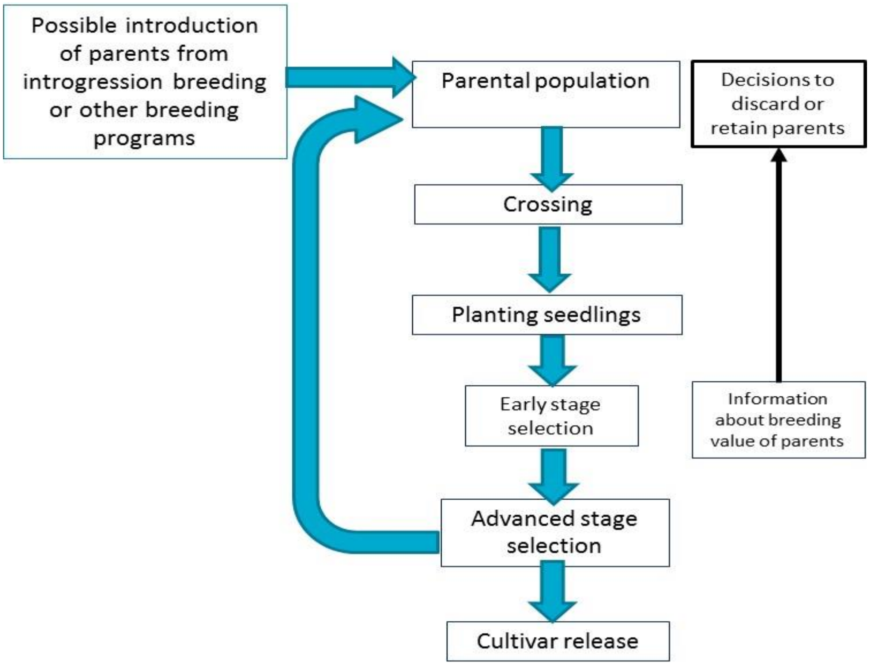

Figure 3. Schematic diagram of generalised sugarcane-breeding program system, which has prevailed worldwide for >60 years. The main components are: (i) Maintenance of a collection of parent clones (typically 100-1000 clones); (ii) Annual crossing among some of these clones to produce seedlings; (iii) Planting of seedlings into a pipeline of successive stages (typically 3 to 6 stages) of selection trials, taking about 8-12 years in total where during each stage, clones are evaluated in field trials for economically important traits (eg. yield, sugar content, disease resistance, etc) and those with apparent best performance are transferred to a successive stage of selection for more accurate evaluation; (iv) From the final stage of selection any clones with apparent better economic value than existing cultivars may be released to growers; (v) The best performing clones are tested as parents for further generations of seedlings, alongside other parents retained from previous cycles; (vi) Decisions to discard or retain parent clones are based on performance of progeny in the selection trials; (vii) New parents and genetic diversity may be introduced from outside the program, occasionally from introgression breeding using wild relatives of sugarcane or elite clones from other (typically foreign) breeding programs.

Evidence of a problem with this breeding system has arisen in that in many countries some widely grown cultivars are derived from old parents (http://sugarcanevariety.org/default.aspx). This occurs despite breeders extensively using newer clones as parents. For example, in Australia in 2016 the top six cultivars were derived from parents with an average age of 50 years (Wei and Jackson 2016). In a study by Rattey *et al.* (2004), very slow rate of progress in breeding value of parents was also clear when breeding values of the best old (pre-1975) parents were compared with the youngest parents. This suggests that generation-wise gains in breeding values of parents are small.

The major reason for slow rates of genetic gain in the system depicted in Figure 3 is the low narrow-sense heritability in modern sugarcane parents for key traits, particularly cane yield (Wei *et al.* 2017). Narrow-sense heritability represents the proportion of phenotypic variation observed in a trait that is passed from parents to progeny (Falconer and Mackay 1995), and studies in sugarcane indicate consistently low (<0.2) narrow-sense heritability for cane yield (see summary of published reports in Wei and Jackson 2016). Low narrow-sense heritability arises if allelic interactions are important (Falconer and Mackay 1995). Allelic interaction effects are termed "non-additive" genetic effects and are common in heterozygous species, especially in improved genetic populations. Allelic interactions may be particularly important in sugarcane considering its high heterozygosity and polyploidy (Chen 2010). Whatever the underlying genetic cause, the practical implication of low narrow-sense heritability is that selection of parents based on phenotype (as in the breeding system in Figure 3) is ineffective for improving breeding value. Thus, the breeding cycle depicted in Figure 3 is not only slow (taking >8 years per cycle) but is also relatively ineffective in modern programs.

Breeding systems that target non-additive genetic effects, such as production of heterotic groups of parents for F1 hybrid cultivars and reciprocal recurrent selection (RRS) (Allard 1999; Biancardi 2005; Eberhart *et al.* 1973), have been used in crops such as maize, sugar beet and others. RRS was originally developed in maize and designed to simultaneously improve two groups of parents, where parents of one group are selected for their breeding value based on crosses made with parents from the other group. Adaptations of RRS may be appropriate in sugarcane (Wei and Jackson 2016). Genomic selection for breeding value (Hayes *et al.* 2009; Meuwissen *et al.* 2001; Wei and Jackson 2016) is another approach that may be of value. Although genomic selection applications to date do not generally select for non-additive genetic effects genetic gains may be fast because of accurate prediction of breeding values in combination with rapid (1-3 year) breeding cycles.

MANAGEMENT OF SUGARCANE BREEDING AND SUPPORTING RESEARCH

Sugarcane-breeding programs worldwide have followed a similar overall breeding system for many decades. Unlike other crops, there has been few if any serious attempts to explore more sophisticated breeding systems including those that may better capture non-additive genetic effects. In addition to concerns about progress in sugarcane-breeding programs, in some sugarcane industries basic agronomic interventions probably offer even greater opportunity for rapid yield improvement in the short term. While published evidence is difficult to obtain, anecdotal observations and communications by many sugarcane scientists suggest that in many countries, large gains in productivity could be achieved easily (at least from a technical perspective) through basic interventions such as control of ratoon stunting disease and fertilizer management.

These issues raise a question: are there features of sugarcane breeding and research institutes that may limit major innovation and progress compared with other major crops? Three related factors that may have contributed are:

(i) Scale and capacity of individual programs - Investment in major or risky innovation is easier to finance, and therefore normally greater, if the target market is large (Dasgupta and Stiglitz 1980). Improvement of some major crops has been led by some companies targeting large multi-national seed markets, and additionally supported in some cases by institutes with a global mandate (e.g. CIMMYT and IRRI) (Reeves and Cassaday 2002). This has facilitated development of some large programs with deep specialist expertise. By contrast, sugarcane research and development has been done mainly by nationally focused institutions and developing scale and capacity in individual programs is more difficult.

Private investment in sugarcane breeding has not occurred largely because protecting intellectual property (IP) rights to new sugarcane cultivars remains difficult. Sugarcane growers easily replant any new cultivar from their own farm (in contrast for example to F1 hybrid seed). This is coupled with relatively weak legal IP protection customs in most sugarcane industries or countries. While sugarcane growers worldwide enjoy no direct IP costs for the cane they plant, the associated lack of private investment in developing better cultivars has probably been detrimental to longer-term rates of genetic gain.

(ii) Competition - Breeding programs in many crops, including sugar beet, has been driven by companies strongly competing for farmer market share of seed sales (Pray and Fuglie 2015). This contrasts with many sugarcane-breeding programs that are government or sugar-industry owned or subsidised, sometimes operating as near monopolies. Effective innovation is often driven by competition, while monopoly and government-funded organisations often fail to innovate effectively (e.g. Potts 2009; Tang 2006).

(iii) Links with world leading universities - Breeding programs of major crops in the USA and Europe have benefited greatly over a long period of time by proximity and close relationships with world class universities. For example, the development of much quantitative-genetics theory was and is still done in partnerships between active maize and wheat breeding programs and universities such as Iowa State University and North Carolina State University, among others. While this research provided benefits to the field of plant breeding generally it disproportionally impacted favourably on the programs and crop species in which the research was directly conducted.

CONCLUSION

Sugarcane improvement is not keeping pace with other major crops including sugar beet. Sugarcane-breeding programs are not making significant generation-wise genetic gains. This is at least partly due to persistence of a general breeding system worldwide that does not effectively deal with non-additive genetic effects that are important in modern sugarcane programs. Conditions that could better stimulate more effective innovation, including larger-scale private investment by specialist breeding companies targeting multi-national markets, seem unlikely to arise. Given the current trends of yield increases in sugar beet compared with sugarcane, and associated reductions in production costs of sugar from beet, it seems likely that a progressively greater proportion of sugar from 2030 onwards will come from beet rather than cane.

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Pourquoi le rendement de la canne à sucre n'augmente pas autant que celui de la betterave sucrière (ou d'autres cultures)?

Résumé. Depuis 1961, le rendement moyen mondial de la betterave sucrière a augmenté d’environ 250%, alors que celui de la canne à sucre a augmenté de moins de 50%. L'augmentation du rendement de la betterave sucrière est comparable à celle observée pour d'autres plantes de grandes cultures, tandis que celle de la canne à sucre est beaucoup plus faible. L’amélioration génétique apportée par la sélection a largement contribué aux gains observés dans les principales cultures depuis les années 1960. Pour la canne à sucre, il a été suggéré que les facteurs associés à la monoculture pourraient être au moins en partie responsables de la faible augmentation du rendement. Cependant, rien n'indique que de tels facteurs auraient augmenté, annulant par ailleurs les gains génétiques ou agronomiques qui auraient été générés. Il a été démontré clairement qu’il existe un manque de gain systématique sur le long terme du rendement ou de la teneur en sucre générés par les programmes d'amélioration de la canne à sucre. Ce manque de gain pourrait être dû à la persistance d'un mode sélection de la canne à sucre partout dans le monde qui ne gère pas efficacement les effets génétiques complexes de type non additifs, contrairement aux modes de sélection d’autres cultures qui ont évolués sur ce point. Les raisons d'un plus faible niveau d’innovation dans la sélection de la canne à sucre par rapport à d'autres grandes cultures sont peut-être liées à un plus faible niveau d’investissements et de concurrence entre des grands instituts multinationaux spécialisés dans la sélection et la génétique. Il est probable que les conditions à l'origine des tendances observées par le passé en matière d'amélioration du rendement de la betterave sucrière ou de la canne à sucre perdurent. Compte tenu des tendances récentes en matière d’amélioration des rendements, et même s’il est prévu que la production de betteraves sucrière soient légèrement réduites jusqu’en 2030, il semble probable qu’à long terme, la production mondiale de sucre provienne majoritairement de la betterave sucrière que de la canne à sucre.

Mots-clés: Sélection, canne à sucre, betteraves sucrières, amélioration du rendement

¿Por qué los rendimientos de la caña de azúcar no aumentan tanto como la remolacha azucarera (u otros cultivos)?

Resumen. El rendimiento promedio de remolacha azucarera en todo el mundo ha aumentado aproximadamente un 250% desde 1961, mientras que el de la caña de azúcar ha aumentado menos del 50% en el mismo período. El aumento del rendimiento de la remolacha azucarera está dentro del rango observado en otros cultivos importantes, mientras que el de la caña de azúcar es mucho menor. El mejoramiento genético ha contribuido de manera importante a las ganancias observadas en los principales cultivos desde la década del 60. En la caña de azúcar, se ha sugerido que los factores asociados con el monocultivo pueden ser, al menos en parte, responsables de los aumentos lentos del rendimiento. Sin embargo, no hay evidencia de que tales factores hayan estado aumentando con el tiempo, lo que anularía las ganancias genéticas o agronómicas que de otra manera estarían surgiendo. Existe clara evidencia de una falta de ganancia sistemática a largo plazo en el rendimiento de caña o el contenido de azúcar que se genera en los programas de mejoramiento genético de caña de azúcar. Esto se debe a la persistencia, en todo el mundo, de un sistema de mejoramiento genético que no trata de manera efectiva los efectos genéticos complejos no aditivos, a diferencia de los sistemas de mejoramiento genético que han evolucionado para algunos otros cultivos. Las razones para una innovación menos efectiva en el mejoramiento de la caña de azúcar, en comparación con otros cultivos importantes, quizás estén relacionadas con una menor inversión y competencia de los institutos multinacionales de gran escala especializados en genética y mejoramiento de cultivos. Parece probable que las condiciones que dan lugar a tendencias pasadas en la mejora del rendimiento de la remolacha azucarera o la caña de azúcar persistirán. Dadas las tendencias recientes de mejora del rendimiento, y aunque se espera que haya una ligera reducción en los niveles de producción de remolacha hasta 2030, parece probable que a largo plazo la producción de azúcar a nivel mundial se derive en una mayor proporción de la remolacha que de la caña.

Palabras clave: Mejoramiento de la caña de azúcar, mejoramiento de la remolacha azucarera