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REVIEW ARTICLE

Sustainability of the Sugar Beet Crop

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Abstract The sustainability of modern sugar beet growing has been proved considerably high. Its improvement has been gradual, streamlined with relevant progresses in crop breeding and husbandry. However, opportunities still exist for a much better required sustainable intensification of sugar beet production. For this purpose, one of the most important prerequisites definitely is the availability of sugar beet varieties characterized by a high and stable yielding attributes, but also endowed with key sustainability traits, such as resistance to biotic and abiotic stresses,and resilience and adaptability to lower input practices. It is expected that now-a-days by employing powerful novel molecular techniques, new sugar beet varieties will be developed which would improve potentially the sugar production from beets.

Keywords Sugar beet · Sustainability · Yield · Cropping inputs · Genetic resistance

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Introduction

World sugar production presently reached about 175 Mt. Based on projections of per capita sugar consumption and population increase (Glower et al. 2007), one million additional tons per year would be required in order to meet the demands of 230 Mt in 2050. Currently, around 20% of the world's sugar production comes from sugar beet (*Beta vulgaris* L. subsp. *vulgaris*) (Figs. 1, 2), the rest almost entirely from sugar cane (*Saccharum* hybrids L.). Increased demand for both the crops might be anticipated for biofuel production (Jordan et al. 2007) (Fig. 1).

Sugar beet plays a key role in the agriculture scenario of 52 countries, thriving in zones of temperate climate (i.e., central and south Europe, USA, etc.). The cost of cane sugar is lower due to crop's perennial habit and to free energy for processing provided by its bagasse, whereas 15–20 Mw/h power, entirely generated from non-renewable energy sources, is at least required in a beet processing plant of 10,000 tons per day. Perenniality further results in fewer losses through nitrogen percolation, higher nutrient and water uptake efficiency due to a deeper root system which also supports soil microbial activity, reduced soil surface loss to water and wind erosion, lower nitrogen leaching and also decreased herbicide use due to considerably smaller weed populations (Glower et al. 2007; Jordan et al. 2007). On the other hand, sugar beet requires around five times less water quantity than sugar cane.

Since the onset of the green revolution era, "conventional" cropping systems of most important plant species enormously increased their productivity because of extensive mechanization, plant breeding advances and synthetic agrochemicals' use (Brummer et al. 2011). However, this has been achieved by irreversibly modifying millions of hectares of natural ecosystems and releasing huge amounts

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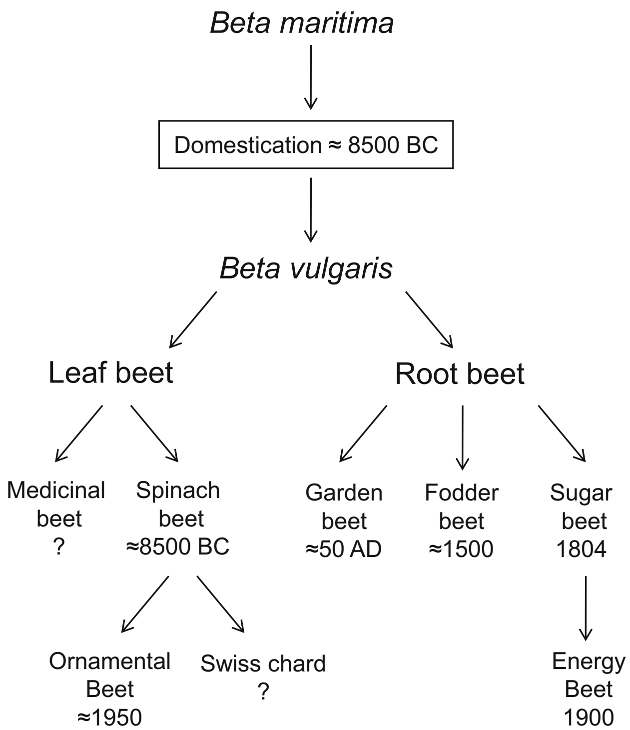

Fig. 1 Chronology of *Beta vulgaris* after domestication (Biancardi et al. 2005)

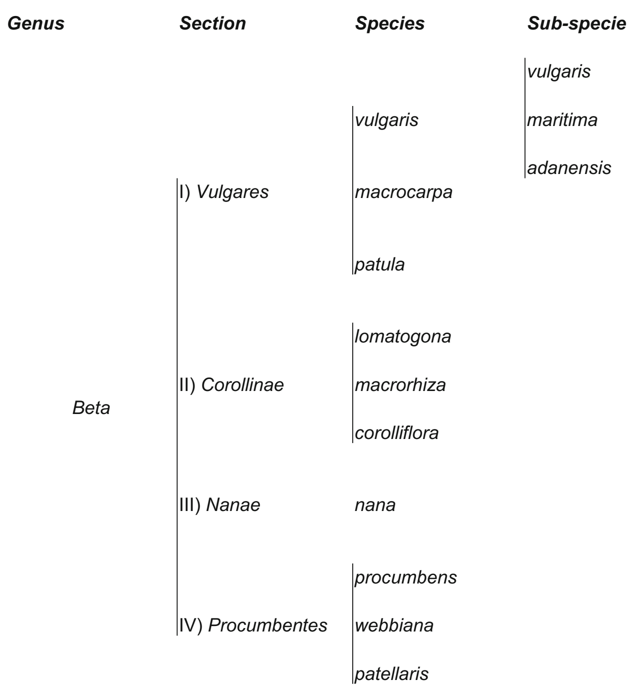

Fig. 2 Taxonomy of genus *Beta* (Ulbrich 1934)

of nitrogen, phosphorus, pesticides, carbon dioxide, methane, etc., into the environment. Furthermore, disease and weed control based on extensive chemical treatments has increased costs and resulted in the occurrence of several resistant pathogens and weeds. To relax the negative effects accompanying modern cropping methods on the environment and human health, and also to preserve future soil productivity, various alternatives and more "sustainable" farming systems have been suggested (Fig. 3).

This article reviews the sustainability components of current sugar beet production methodology and identifies potential future improvements.

The Evolution of Sugar Beet Cultivation

The nineteenth century witnessed the continuous increase in sugar yield by sugar beet, with the help of effective breeding methods first developed in France and by a rapid and precise system of sugar analysis for selection procedures (McFarlane 1971; Biancardi et al. 2005). Since long rotation periods (at least 3–4 years) were required by the beet crop in order to reduce soil-borne diseases (Schacht 1859; Briem 1895), sugar beet was recognized as a very suitable component of rotations including cereals. However, traditional sugar beet cultivation required around 700 h of manual labor per hectare (Martindale 2013). The advances in mechanization, high-yielding varieties and chemical inputs led to a gradual transition to a conventional cropping system, almost everywhere employed at present.

Conventional System

The twentieth century witnessed an outstanding progress in sugar beet breeding and farming practices, resulting in impressive sugar yield production, enhanced industrial extraction rates and reductions of production costs (Robertson-Scott 1911; Winner 1993; Draycott 2006).The introduction of genetic monogermity and apposite drilling machines (Fig. 4) (Savitsky 1950, 1953) rendered early

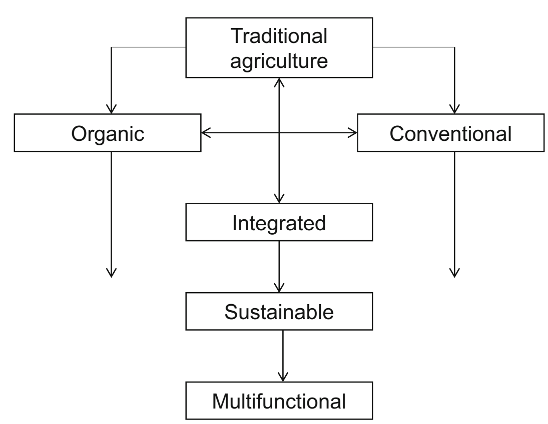

Fig. 3 Evolution of agricultural systems (Biancardi et al. 2005)

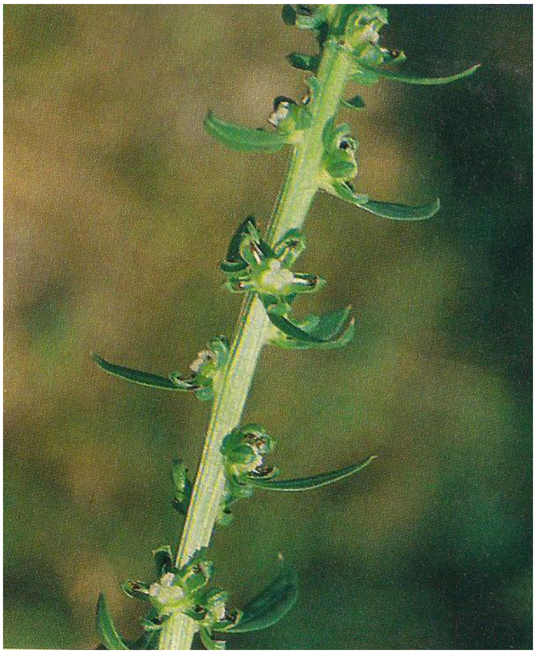

Fig. 4 Monogerm and male sterile sugar beet flowers producing monogerm seeds

days hand thinning of seedlings obsolete. Sugar beet was one of the first crops protected with chemical products (Winner 1993). Also, seed pelleting improved the sowing precision (Leach and Bainer 1942; Winner 1993). The exploitation of genetic resistance to diseases, primarily for curly top, cercospora leaf spot and later to rhizomania, significantly increased sugar yield and reduced the use of pesticides. Integration with chemical treatemnst are also suggested when protection by genetic resistances is incomplete, as in the case of cercospora leaf spot (CLS) (Skaracis et al. 1996).

Breeding methodology has substantially been empowered by advances in molecular biology and biotechnology in the last 20 years, allowing for a significant improvement of selection efficiency. Despite high national averages, sugar yield per hectare still increases about 1.4% annually in European countries (Bosemark 2006). About half of this rate seems to be associated with integrated breeding, and the remaining to the cropping practices (Sneep and Hendriksen 1979). In Germany, Loel et al. (2014) observed a yearly increment of sugar production of 0.6–0.9% as a result of breeding improvements.

Weed control is important in order to eliminate competition with weeds and avoid difficulties during mechanical harvesting (Demont and Dillen 2008). Depending on crop stage and composition of weed populations, multiple treatments are needed to achieve the best control. In case of failed chemical control, mechanical weeding and, more rarely, manual hoeing might be required.

Before lifting, beets are mechanically defoliated and topped because of the low sugar content of leaves, petioles and crowns. Also, these parts have a high concentration of impurities reducing sugar extractability. Beet roots are transported to the factory as soon as possible in order to avoid sugar losses of different origin. The topped parts remain on the field are rarely used as cattle feed.

Due to increasing sugar demands and the need for improving competitiveness of the sugar beet sector, more sustainably intensive crop management systems are needed to improve productivity (sugar yield per unit area). To this end, however, much remains to be done, since current mean sugar yields in the more productive countries reach only half of an estimated potential of about 24 tons per hectare (Loel et al. 2014). Several alternative crop management systems have been proposed (Fig. 3) (Martindale 2013). Beet processing plants needs similar improvements in order to save energy and increase sugar extractability.

Organic System

Organic farming aims at food safety and maintenance of current production levels and biodiversity, using only natural, certified inputs. The system prohibits the use of synthetic fertilizers and pesticides and also sowing genetically modified varieties, resembling thus traditional agriculture, along with a closed cycle of fertility, and possibly of energy, on the farm. This is attainable by proper crop rotation including perennial pulses and shifting (or "set aside") cultivation, using manures, harvest residues, etc. (Martindale 2013). It's products are labeled and identified by legally protected terms, such as "Bio" or "Organic," issued by official controllers according to national regulations.

Organically produced sugar from beets requires further adaptations in root delivery and processing: The operating chain must be completely clean before receiving the organic roots to avoid admixtures with conventionally grown beets. Synthetic additives, such as antifoam, flocculants, are not allowed (Sørensen et al. 2005). For these reasons, attempts for commercial production of organic beet sugar barely survive in Europe. Given the absence of effective natural means to combat some diseases and weeds, the future of organic sugar beet is the future of organic sugar beet is shrouded by uncertainty.

Integrated System

During the growing period, conventional farming can be improved by applying more appropriate and/or integrated methods in order to minimize the aforementioned negative effects (Bonny 1997). The most important ones are as follows: (i) introduction of environmentally friendly pesticides, (ii) rational integration of chemical treatment with genetic resistance to pests and diseases, when the latter is not sufficient by itself, (iii) wider rotations to reduce the inoculum of soil-borne diseases and prevent, or delay, the occurrence of resistant pathogen strains and more aggressive and/or resistant to chemical treatments weeds, (iv) modern soil sampling techniques for a more precise identification of nutrient needs, (v) timely weed surveys to reduce herbicide use and costs, and (vi) improved collaboration among farmers and extension services for a better organization of all actions throughout the growing period. It also is important to aim at reducing the distance between beet producers and sugar factories and processing plants (see Sect. 2.1).

Multifunctional System

Agricultural multifunctionality is defined as the joint production of standard commodities (food, fiber, etc.) and ecological services (Banaszak 1992; Jordan et al. 2007). Abiding to it, sugar beet can be well characterized as a "biorefinery" crop, given that all by-products and co-products are, and can potentially be, used for a variety of purposes (i.e., molasses as fermentation raw material toward various high added value products, remnant tops and pulp as feed, factory lime for soil improvement, etc.).

Precision Farming

Precision farming became possible because the use of GPS devices, which allow a precise localization of the tractor on the field. The delivery of agrochemicals is based on maps, previously established by remote sensing systems, indicating the spatial differences (Bongiovanni and Lowenberg-Deboer 2004). Also, sensors mounted on the tractor instantly evaluate nitrogen levels through canopy color differences, as well as soil moisture, soil compaction, the presence of diseases, weeds and stresses. Based on data collected, the distribution devices optimize the flow of agrochemicals applied. However, the expansion of precision farming has been slower than foreseen. With accuracy improvement, precision farming could provide a significant reduction in environmental damage and production costs required for sustainable agriculture (McBratney et al. 2005).

Sustainable Sugar Beet Cultivation

To fulfill all sustainability prerequisites, agriculture has to find the right compromises between current and future levels of production, so as not to jeopardize long-term potentials. To this end, fertilizers must be used more efficiently to avoid releases in groundwater and the atmosphere. The search for effective and environmentally friendly pesticides and herbicides will also be necessary. Exploitation of available and new genetic sources for usable variation controlling resistance and/or tolerance to biotic and abiotic stresses definitely needs to be enhanced. Advances in molecular genetics and biotechnology are expected to significantly contribute to this purpose.

Annual crops are often associated with strong monoculture, a totally unnatural and costly approach which greatly compromises the ability of natural ecosystems to provide all needed services to farmers, to the public and to the environment (Tilman et al. 2002). In fact, this ability is proportional to the biodiversity of the ecosystem. The negative effects of monoculture can be attenuated by organizing proper crop rotations, which are also useful for reducing soil-borne diseases and prevent or delay weed resistance to herbicides (Martindale 2013).

Sustainability also entails reduction in greenhouse gas emissions as nowadays is mandated at the European and the global level. Sugar beet crop's emissions are mainly the result of fuel energy needed during cultivation, estimated at 25 GJ per hectare (Hulsbergen et al. 2001). This includes both fuel consumed on the farm and the indirect energy incorporated in fertilizers, pesticides, machinery, etc. Around 34% of total energy is required for harvesting, 25% for fertilizers, and 18% for plowing to 0.25 m. The outputs are evaluated as 250 GJ per hectare considering sugar alone, and as 350 GJ per hectare if by-products are included. Thus, sugar incorporates roughly 10 times more CO_2 than the amount released (Martindale 2013). The rate improves if by-products are included and further by exploiting new uses for waste co-products, as exhausted cossettes and carbonation sludge for paper production, vinasse for compost fermentation, etc. (Vaccari et al. 2005).

Carbon footprint is an index describing the impact of agricultural products on the environment (Glower et al. 2007). The footprint of white sugar produced by British Sugar factories is 0.6, i.e., 1 g of sugar requires the release of 0.6 g of CO_2 considering all direct and indirect emissions from sowing to the consumer (Anon 2010). The amounts emitted in the different steps of the production chain are shown in Fig. 5 and adequately correspond to the quantity of not renewable fuel or energy required.

The main stages of sugar beet production directly related to sustainability, along with indications for possible further improvements, are described below.

Soil Tillage and Drilling

Primary tillage is usually performed in autumn, when soil moisture is at optimum. Plowing depth for sugar beet varies

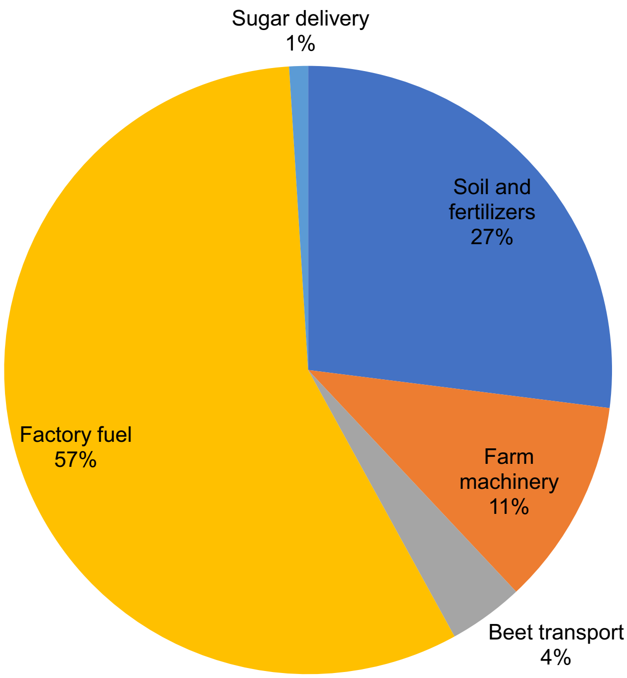

Fig. 5 Carbon dioxide emissions in the sugar production cycle

depending on soil's clay content. Heavy soils require a depth of up to 0.5 m, whereas sandy soils require usually 0.2–0.4 m (Koch et al. 2009). The subsequent shallower tillage operations aim to gradually obtain better soil conditions for seedling emergence. Heavy and powerful tractors, equipped with multiple-blade plows, recently have simplified soil preparation procedures. In addition, the increased awareness of ecological issues led to techniques such as minimum or conservation tillage, where the soil surface is always left covered by crop residues. In this case, tillage is shallower and does not bury the surface layer. Thus, organic matter content slowly increases, as does the amount of carbon fixed in the soil (Martindale 2013).

Drilling machines are modified in order to sow seeds in more compact soil that is covered by a more or less thick and uniform layer of plant residues, also due to the compulsory pre-sowing treatment against weeds. Contrary to other crops, field trials performed in different parts of the world showed a decrease in sugar yield of beets cropped using minimum or reduced tillage (Koch et al. 2009). The reduction in plowing depth gives similar results.

Crop Rotation

Sugar beet usually is included in a 3–5- or more-year rotation, according to local practices, soil conditions, climate, diseases, weeds, etc. Preceding winter wheat, one or more years of other crops (corn, potato, soybean, alfalfa, barley, etc.) frequently are included. Where there is a risk of wind or water erosion, winter or cover crops need to be used together with appropriate conservation tillage, also helping to prevent nitrogen leaching during winter. To reduce the population of nematode cysts in the soil, winter catch crops, such as *Sinapis alba,* also are frequently used (Märländer et al. 2003). Repeatedly growing sugar beet on the same field causes a rapid yield drop, mainly due to increased disease inoculants. Consequently, this practice must be carefully avoided.

Fertilization

Fertilizers influence sugar yield and quality of beets which determines the processing efficiency. Processing quality is estimated on the basis of certain root constituents that hinder crystallization and lower the amount of extractable (white) sugar (Van der Poel 1998).

Pre-sowing fertilization includes the necessary elements for the incoming crop, taking into account future losses through water movement, etc. Due to their limited mobility in the soil, when phosphorus, potassium and magnesium fertilization is required, they are normally applied before plowing in autumn in order to loosen the fertilizers in the processed soil layer (Martindale 2013). The most critical element is nitrogen (N), which has different forms, each with complex dynamics and interactions strongly influencing sugar yield and quality. Due to insufficient depth of the usual sampling and to small number of samples per area, N availability in the soil often is underestimated and leads to excessive fertilization. Nitrogen dynamics may differ depending on weather, with low soil temperature frequently causing poor mineralization of organic matter, reduced crop development and enhanced leaching of nitrates through groundwater (De Koeijer et al. 2003; Stevanato et al. 2010). Owing to the difficulty in predicting N requirements, farmers tend to provide higher than needed amounts, and such excess harms the crop more as compared to a moderate shortage. As the range between nitrogen shortage and excess is very narrow, the crop should preferably be supplied with less rather than more nitrogen (Stevanato et al. 2010). Improvements in precisely determining the appropriate amount of N fertilizers will definitely limit the damage due to loss of sugar production, and also the damage caused by N leaching via water movement.

Only 30–50% of the amount of N and P fertilizers applied is utilized by the crop (Glower et al. 2007). The remaining amounts of N and to a lesser extent of P are transported by ground and surface water, causing eutrophication and consequently hypoxia in river and lake waters and also in widespread ocean areas (Diaz and Rosenburg 2008; Brummer et al. 2011). These damages can be reduced by improving fertilizer use efficiency, which in turn implies investments in upgrading farmers' skills and efficiency of extension and assistance services (Martindale 2013).

Exploiting genetic diversity for various morphological and physiological traits related to nitrogen use efficiency (NUE), as found in other crops (Ortiz-Monasterio et al. 1997; Foulkes et al. 2009), will definitely prove very useful for selection purposes in sugar beet. Root length, root density and ability to develop a deep root system are among the important traits for sugar beet, as hypothesized by Stevanato et al. (2010). The development of varieties with high NUE would be of great interest in reducing production costs and nitrate leaching.

Sowing

Seed germination ability and emergence acquired great importance following the discovery (Savitsky 1950) and adoption of genetic monogermity, as it decisively influences final sugar yield (Desprez 1993; Märländer et al. 2003; Biancardi et al. 2005; Stevanato et al. 2011). Field germination is continuously increasing due to improvements related to (i) targeted selection of parental lines with satisfactory seed yield and ability to transmit high germinability to the hybrid, (ii) improved techniques in seed production to safeguard seed quality and (iii) advanced seed processing to eliminate abnormal seeds, priming to enhance a faster and uniform seedling emergence even under adverse conditions (Bourgne et al. 2000), pelleting to facilitate precision sowing and protection of young plantlets by incorporating systemic pesticides (Lexander 1993; Durr 1994) and, (iv) better seed bed preparation. The target of a 100% field germination almost attained, and is already realized in the greenhouse (Prince and Durrant 1990; Desprez 1993).

Enhanced tolerance to frost during early development, combined with a strong genetic resistance to bolting, would allow autumn sowing in regions with relatively cold winters, where spring sowing is currently mandatory, and provide an early start in the spring that could lead to the production of at least 20% more sugar (Biancardi et al. 2005). Despite many attempts in this direction, no appreciable successes have been observed so far. Predicted increase in world temperatures could gradually allow autumn sowing at higher latitudes than the current limit for autumn beets of around 42 degrees North (Rosso et al. 1999). Autumn sowing could also offer other benefits, such as better protection of soil from wind and water erosion, reduced water and nitrogen losses, earlier harvesting, etc.

Weed Control

Sugar beet crop is very sensitive to weed competition, so herbicide treatments immediately manifest their beneficial effects on yield increase. Weed control requires continuous surveys by the farmer to detect any unforeseen weed growth (Demont and Dillen 2008). Selective herbicides provide successful weed control depending on weed composition, developmental stage, application time and other factors (Martindale 2013). Non-selective herbicides, with various modes of action, are able to control the common species of weeds and usually are distributed to clear the fields before sowing. The complexity of weed control necessitates more effective, easier to apply, less costly and environmentally friendly herbicidal methods.

Resistant to the non-selective herbicide glyphosate genetically modified (GM) sugar beet varieties, released about 20 years ago, constitute a novel approach for weed control. Their use has been permitted for some years in the USA, but in the European Union, the world's largest sugar beet producer, it is currently forbidden in most countries (De Francesco 2013). Weed control with glyphosate normally requires 2–3 broadcast applications, as with other herbicides, but is much easier because it is partially independent of the development of beets and weeds. In contrast to the low efficiency of selective herbicides, glyphosate also provides the possibility for late season applications (Demont and Dillen 2008) against mature weeds, while the cost is highly comparable to the conventional weed management.

As glyphosate-resistant varieties of several major crops (maize, soybean, cotton) have spread worldwide, the extensive use of glyphosate has led to the development of resistant weeds in several countries. A solution to the problem is envisioned by combining, in a single variety, two or more different mechanisms of resistance to the same herbicide. Also, alternating with selective herbicides should delay the development of resistant weeds (Waltz 2010; De Francesco 2013). Glyphosate releases fewer toxic residues and does not interfere with sugar beet development, as happens with conventional herbicides where selectivity is not complete and sometimes erratic due to weather conditions. In the presence of weed beets from bolters in the previous crop, the only valid control system is the use of glyphosate-resistant varieties (Desplanque et al. 2002). In a few years, almost all sugar beet varieties sown in the USA will bear this trait.

Irrigation

In semiarid and arid regions, drought is the main limiting factor for sugar yield, so water supply is absolutely necessary for crop survival. Sugar beet irrigation in the southernmost zones necessitates over 600 mm of water per growing season, in the Mediterranean countries 300–500 mm is often required, whereas 100–200 mm is occasionally needed in central Europe. Sugar beet growing is almost totally rainfed in the northern countries.

Irrigation efficiency normally is low, as around half of water provided is lost through percolation and evaporation. Given the diminishing availability of water for agriculture, better water supply methods should be developed. The extremely efficient system of drip-irrigation is not feasible due to its prohibitive cost. The widely applied sprinkler irrigation also is costly and the canopy can be damaged by drops from high-pressure pumps, a problem to overcome by pivot devices (Tilman et al. 2002). Humidity produced inside the canopy could also hasten the development of fungal diseases such as cercospora leaf spot and rhizoctonia. Furrow irrigation is relatively inexpensive but requires perfectly leveled fields and light soils, while part of water also is lost through evaporation and deep percolation.

Development of varieties endowed with higher water use efficiency (WUE) has been sought to reduce water needs, especially in sandy soils. Relatively recent studies have analyzed drought tolerance in different sugar beet genotypes (Ober et al. 2004). Although drought tolerance might be of interest in countries growing winter beet, only a few breeding programs appear to work on this purpose (Srivastava et al. 2000).

Crop Protection by Means of Genetic Resistance

Chemical treatments definitely will continue to be important for the protection against sugar beet pest and diseases. Given the need to minimize their negative side-effects, the availability of effective and affordable such products in the future is questionable. As a consequence, the development of sugar beet cultivars endowed with higher genetic resistance (and/or tolerance) against biotic and abiotic factors gains further significance.

Research in sugar beet for the exploitation of genetic resistance to most threatening diseases, as well as to various abiotic factors, has been ongoing for a long time. Although this effort has not fully achieved the expected success, positive results have safeguarded the competitiveness, and even the survival, of beet growing in most areas. A highly efficient genetic resistance or tolerance is the ideal tool to limit damages from a disease or a stress, since no therapy treatment should be required. As for its negative aspects, the initially lower sugar yield compared to that of susceptible varieties in the absence of a disease has now been corrected. The risk of pathogen's ability to compromise a resistance also appears limited for sugar beet, as evidenced by the very few reports of probable breakdown of resistance to rhizomania even after almost 20 years of growing resistant varieties.

Genetic variability present in the wild ancestors of modern crops is an important source to widen their genetic base, nowadays narrowed by continuous breeding activities (McGrath et al. 1999). This holds especially true for sugar beet germplasm whose narrow genetic base is due to a common origin as well as to cytoplasmic genetic male sterility (CMS) and monogermity transferred to cultivars. Advances in molecular biology and biotechnology currently provide very promising tools to dissect and exploit novel genetic resistances and to improve the efficiency of relevant selection methods (Zhang et al. 2008; Monteiro et al. 2018). Marker-assisted selection proves mostly useful, especially for complex traits, such as yield and resistances, under multigenic control (Bradford et al. 2005; Brummer et al. 2011). Apart from transgenesis, novel genome editing techniques, and specifically the CRISPR/Cas9 system (Belhaj et al. 2015), will revolutionize the way by which resistance breeding is practiced.

Biotic and abiotic limiting factors, for which resistance traits were identified and proved more or less effective for sugar beet protection, are presented below. More detailed information on diseases and their control are reported earlier (Biancardi et al. 2005, 2012; Draycott 2006).

Resistance to Biotic Stresses

Virus Yellows This disease is caused by a mixture of different viruses (BYV, BWYV, BMYV and BChV) vectored mainly by green peach aphid (*Myzus persicae*) and decrease sugar yield by about 30% (Stevens et al. 2004), being most severe in temperate climates such as California, Western Europe and Chile (Fig. 6). Systemic insecticides, also incorporated in the seed pellet, are quite effective against the spread of this disease. Conventional breeding for resistance has been moderately successful, owing to its quantitative nature. A locus controlling vein-clearing symptoms of BYV infection was mapped to chromosome

Fig. 6 Yellowing leaves inoculated with beet yellowing virus (courtesy Lewellen and Schrandt 2001)

IV, and three BYV resistance QTLs were identified and mapped to chromosomes III, V and VI (Grimmer et al. 2008).

Rhizomania Rhizomania is caused by *Beet necrotic yellow vein virus* (BNYVV), transmitted to roots by the fungus *Polymyxa betae,* is the most destructive and common pathogen in sugar beet cultivation worldwide (Figs. 7 and 8). Single gene resistance was first selected in Italy and variety Rizor proved considerably more productive than the varieties endowed with quantitative resistance cultivated at that time (De Biaggi 1987). A second type of resistance was found in California by Lewellen et al. (1987), named "type Holly" and later *Rz1*. Rizor and varieties with the *Rz1* gene present quite similar resistance (Biancardi et al. 2002).The origin of both quantitative and qualitative resistances seems attributable to crosses with B. *vulgaris* spp. *maritima* (Biancardi et al. 2002, 2012).

Besides resistance due to the *Rz1* gene which has been very successfully exploited worldwide, other resistance traits identified in various collections of *B. maritima* maintained by USDA-ARS include the powerful *Rz2* and the different in expression *Rz3*. The combination of *Rz1* or *Rz2* with *Rz3,* however, showed a lower virus concentration in beet roots than the *Rz1* alone (Gidner et al. 2005). *Rz3* maps to chromosome III, as well as *Rz1* and *Rz2*, to whom is linked (Gidner et al. 2005). Another *Rz4* source located on chromosome III, appearing different from the previous traits, also was identified (Grimmer et al. 2008) as further was by the same authors the potential resistance gene *Rz5*, found in a *B. maritima* accession sampled in Italy (Biancardi et al. 2012). Since both *Rz4* and *Rz5* map close to *Rz1*, there is the possibility that they may belong to an allelic series. Many possibilities of combating rhizomania through genetic engineering have also been investigated and suggested (Pavli et al. 2011).

Fig. 7 Plots of breeding lines differently resistant to rhizomania (courtesy Lewellen 2000)

Fig. 8 Beet showing the effects of severe rhizomania infection, including the yellowing spots on the leaves (courtesy Lewellen et al. 1987)

Beet Curly Top The curly top disease is caused by a mixture of at least three closely related viruses: beet curly top virus (BCTV), beet mild curly top virus (BMCTV) and beet severe curly top virus (BSCTV) (Strausbaugh et al. 2008), all transmitted by the beet leafhopper *Circulifer tenellus*. The insect attacks sugar beet and many other crops cultivated in semiarid areas (Western USA, Turkey and Iran) (Panella 2005). Since the virus often undergoes changes, it is necessary to continuously modify the structure of resistant varieties.

Powdery Mildew Damage from powdery mildew caused by *Erysiphe polygoni* is common in almost all cultivated areas with few exceptions. A quantitatively inherited resistance is known and widely used in commercial varieties (Whitney et al. 1983). More recently, other resistance traits to powdery mildew, conditioned by one dominant gene (Lewellen and Schrandt 2001), were transferred from *B. maritima* accessions and a series of germplasm releases were made (Lewellen 2000, 2004a, b). In the case of incomplete control of the disease, one or multiple treatments with sulfur or fungicides are required.

Root Rots Rhizoctonia root rot and crown rot caused by *Rhizoctonia solani* affect sugar beet worldwide (Windels and Harveson 2009). As crop rotations were shortened, the disease became an increasing problem. Rhizoctonia root rot is managed through an integrated program, based on resistant germplasm and appropriate cultural practices, wide crop rotations and repeated fungicide applications (Herr 1996). *B. maritima* is being screened through international collaborations for resistance to *Rhizoctonia solani* to be transferred to commercial germplasm.

Cercospora Leaf Spot Cercospora leaf spot caused by the fungus *Cercospora beticola* is the main fungal disease of beet-growing areas in temperate-humid environments (Skaracis and Biancardi 2000). The disease affects approximately one quarter of the cultivated acreage worldwide (Jacobsen and Franc 2009). Studies on genetic resistance to CLS began in the early 1900s, but the breeding efforts on lines derived from *Beta maritima* only gave the first results around 1930 (De Bock 1986). Until now, no other sources of resistance to CLS have been identified and released.

As a result of recent breeding advances, sugar yield of resistant varieties is today similar to that of the susceptible varieties (Panella and Lewellen 2007; Biancardi et al. 2012). Due to the intensive use of chemical treatments and the continuous development of pathogen's resistance to various fungicides, however, it is imperative that varieties with a higher level of resistance are developed. Eighty-two *B. maritima* accessions were recently evaluated in Europe, 10 of which proved strongly resistant to CLS (Frese 2004). Many of these have been incorporated into breeding programs to increase the genetic base of CLS-resistant varieties (Panella and Lewellen 2007). Many genetic engineering approaches also have been proposed as potentially powerful breeding tools (Skaracis and Biancardi 2000).

Nematodes *Sugar beet cyst nematode* (SBCN) (*Heterodera schachtii*) is among the most damaging pests of sugar beet in intensely cultivated areas. As soil fumigants were banned due to their high environmental impact (Zhang et al. 2008), a minimum of four-year crop rotation seems necessary to reducing cyst numbers in the soil. Also, varieties belonging to the genus *Raphanus* and *Synapis* are used as catch crops (Hartwig and Ammon 2002).

Fairly high resistance was identified in the section *Procumbentes* (Schneider 1937). Commercial varieties with this source, however, proved rather ineffective for crop protection under severe attack (Lewellen and Pakish 2005). Similar resistance from *B. maritima* has since then been developed. Inheritance of resistance seems to depend on a dominant gene and provides a satisfying control (Lewellen and Pakish 2005). Varieties bearing the trait are currently marketed in the USA and Europe (Panella and Lewellen 2007).

Root knot nematode. Damage from root knot nematode (RKN), caused by numerous species of the genus *Meloidogyne,* is common in warm-temperate climates. The nematode causes root gall and reduces yield. Resistance from a *B. maritima* collection was transferred to sugar beet by Yu (2002). An isozyme marker was identified for RKN resistance, which may be essential in the development of sugar beet for subtropical areas where *Meloidogyne* spp. cause severe losses.

Insects *Aphids.* Green peach aphid (*Myzus persicae*) and black bean aphid (*Aphis fabae*) damage sugar beet by phloem feeding and, mainly, as vectors of a number of dangerous viruses. Both insects are common in every cultivation areas. Some degree of resistance to bean aphid colonization has been found in *B. maritima* (Dale et al. 1985) and to the multiplication rate of green peach aphid (Lehmann et al. 1983). According to Lowe and Russell (1969), the resistance to aphids seems to be under polygenic control (Gao et al. 2001). Some resistance traits were also found in *Beta corolliflora* and species of the section *Procombentes* (Fig. 2). The findings in the latter two sections have not led to any practical application (Van Geyt et al. 1990).

Root maggot. The pest affects sugar beet mainly in the USA and is caused by the larvae of *Tetanops myopaeformis,* which feed both on the surface and inside the taproot. Rot develops rapidly on the walls of the larva tunnels worsening the damage. Repeated pesticide treatments reduce the population, but these are becoming unavailable due to environmental concerns. Moreover, the insect seems to develop resistance to the chemicals commonly used. A promising method for crop protection is possible using transgenic traits that interfere with the digestive processes of the larvae.

Resistance Tolerance to Abiotic Stresses

The effects of climate on sugar beet production areas in Europe have been studied, and there is concern about the consequences that global climate change might have on sugar production, mainly due to rain shortages (Pidgeon et al. 2001, 2004). Surveys on commercial sugar beet varieties have shown the existence of genetic variability for tolerance to various abiotic stresses. Generally, these traits seem to be under multigenic control.

Drought Variability for drought tolerance has been investigated in the *Beta* germplasm, and several accessions of *B. maritima* were found interesting under drought conditions, as reported by Freese (2004) (Fig. 9) and also by Ober and Rajabi (2010). Discrete variability was also found in commercial varieties, likely caused by different

Fig. 9 Lines with different levels of drought resistance (courtesy Lewellen and Pakish 2005)

dynamics of the root system (Ober and Luterbacher 2002). Succulence index, wilting scan, green canopy and some water use parameters could be used as a first screening of genotypes to be further evaluated (Ober et al. 2005).

Cold Low temperatures frequently occur at early development (autumn sowing) or during emergence (spring sowing). Early studies showed differences in frost resistance among breeding lines. Cold resistance was apparently improved in two varieties (Dix et al. 1994). Increased sucrose content was observed in the progenies of plants surviving frost. Genetic variability also was observed for frost damage on mature plants close to harvest, with a high negative correlation between severity of frost damage and sucrose content (Wood 1952). Also, cold sensitivity and susceptibility to CLS were correlated, suggesting a common mechanism for resistance to both stresses (Wood et al. 1950).

Bolting Resistance Biennial sugar beet can revert to annualism under conditions of low temperatures and increasing photoperiod (Smit 1983). Flowering beets show fangy and fibrous root with reduced weight and sugar content, and stalks also cause harvesting difficulties. However, since the percentage of bolted beets is normally less than 0.1%, these problems are not significant. Nevertheless, close attention must be paid to the seed on bolted beets, as it is perfectly viable and produces weed beets that are very difficult to control.

Varieties differ in their response to vernalization, with the genetic base of bolting resistance still remaining unclear. Early studies by Marcum (1948) indicated that bolting resistance is under the control of several genes with different degrees of dominance. It was later shown that an additive-dominance model could explain the bolting response in the offspring of crosses between a susceptible and a resistant inbred line (Le Cochec and Soreau 1989). Other studies showed that genes with additive effects are of major importance with dominance and interaction effects also being significant in some crosses (Sadeghian et al. 1993). Mcgrath published the latest version of the sugar beet genome in 2018 (http://www.ncbi.nlm.nih.gov/assembly/GCA_002917755.1/), and a high polymorphism was found within the wild *Beta maritima*. On the contrary, no variation was found in five sugar beet lines, demonstrating that breeding caused the selection of favorable alleles and consequently increased bolting resistance.

Due to the complex genotype x environment interactions, progress on bolting resistance was initially obtained by selecting the variety in the climate where it would be grown (Smit 1983). Several bolting-resistant varieties, well adapted to areas with low spring temperatures, are commercially available. This has enabled a change in cropping practices toward earlier drilling, resulting in prolonged growth period and improved sugar yield (Westerdijk and Tick 1991). The use of molecular markers might further facilitate the selection of more bolting-resistant varieties.

Heat In countries with a subtropical climate, sugar beet is frequently subjected to thermal stress. High temperatures (35–45 °C), coupled with dry winds for long periods, create stress conditions resulting in subsequent sugar yield reduction. Srivastava (1996) demonstrated the existence of sufficient genetic variability in plant reactions to thermal stress. A test based on chlorophyll fluorescence measurement has been suggested to assist selection of tentatively resistant genotypes (Clarke et al. 1995).

Salinity There is an increasing interest in halophytic crops as the world's supply of fresh water is shrinking (Koyro and Huchzermeyer 1999). There is also interest in using *Beta maritima* as a potential donor of salt tolerance genes, and even as a potential halophytic cash crop (Koyro et al. 2006). The physiological basis of salt resistance has been studied by Koyro (2000) and Bor et al. (2003) on *B. maritima*, since the habitat of this wild ancestor of sugar beet requires high levels of resistance to salinity (Shaw et al. 2002). Although sugar beet is well adapted to saline areas, it is sensitive to saline conditions at the germination stage. Romano et al. (2012, 2018) recently identified mechanisms of salt tolerance useful for future selection.

Multiple Resistance

Genotypes combining resistance to more than one disease are quite useful (McFarlane 1971), and many such varieties have been released over the years. For example, some CLS-resistant varieties have been crossed with genotypes bearing one or more monogenic resistances to rhizomania. Luterbacher et al. (2004, 2005), after a major survey involving 500 accessions evaluated in both field and greenhouse conditions, ascertained some cases of multiple resistance in *Beta maritima*. The rate of entries displaying more than one resistance was higher in the sections *Procumbentes* and *Corollinae*. Regarding the soil-borne diseases caused by *Aphanomyces cochlioides*, *Pythium ultimum*, *Rhizoctonia solani* and rhizomania, *B. maritima* showed the highest number of accessions endowed with multiple resistance.

The term multiple resistance (Scholten et al. 1999) also implies the accumulation of different types of resistance to a single disease in the same genotype. The combination of diverse sources of resistance increases the ability to lower the effects of the disease with complementary reaction mechanisms (Lewellen and Biancardi 1990). This synergistic effect (i.e., *Rz*1 and *Rz*2) is currently utilized successfully to reduce yield losses in severe rhizomania diseased fields. Varieties endowed with multiple resistance are also expected to provide better yield stability, a very important trait to ensure increased crop sustainability (Loel et al. 2014).

Length of Growing Season

The growing season length greatly influences sugar production, but early sowing and delayed harvest encounter difficulties mainly caused by climate factors and soil structure and difficulties during emergence. Appropriate sowing time depends on soil characteristics and on the bolting sensitivity of the cultivars. There is a tendency to plant early in some zones to lengthen the growing season and allow plants to develop in periods with good water availability. But this may increase the number of bolted beets and heighten the possibility of frost damage to plantlets (Draycott 2006). With better bolting and cold resistance, these risks could be reduced. As already mentioned, sufficient genetic variability for an effective selection for cold resistance has been verified and expected to be exploited.

High fiber content is an undesirable trait of beets left growing too long in the field, as woody roots hasten wearing factory machinery sugar extraction. Fiber content depends mainly on environmental factors. Woody roots can also be found in beet seeded in autumn, and especially in bolted plants.

Harvest and Processing

Besides advanced sowing, delayed harvest could be a target in order to lengthen the crop cycle. This practice mainly depends on soil structure and is possible only on permeable soils. Care must be taken especially with heavy soils, where rain might delay sowing for weeks or hinder harvest owing to limited trafficability (Thomasson 1982). Following harvest on overly wet soil, a considerable amount of sugar is lost due to root breakage and imperfect topping. Leaf material that remains attached to the roots after topping and excessive soil adhering to the taproot can cause significant problems in the processing plants.

Harvest losses partly depend on the taproot shape. If it is too long, there might be losses caused by cracks around the tail. Developed crowns make topping difficult. Excessive fanginess caused by the genotype or soil structure results in problems during lifting of the beets. Deep root grooves make cleaning difficult if not impossible, especially where soils are heavy (Mesken 1987a, b). Rounded and too short roots are not well anchored to the soil and may be susceptible to uprooting during topping, particularly when they protrude more than usual from the soil. Under these conditions, cutting the crown is difficult and the whole root often breaks up. Since harvesting is frequently done using a powerful and heavy 6-row harvester, there is the risk of soil compaction. In order to ease the movement and speed of these machines, sugar beet should be cultivated preferably on the plain and in large fields (Märländer et al. 2003).

There exist many possibilities to improve sugar extraction procedures usually adopted in the processing plants so as to contribute to the sustainability of the sugar beet crop (Van der Poel 1998). Given that 700 t of soil are left over when 10,000 t of beets are processed, beets should be delivered to the factory with as little soil adhering as possible. The water input needed for cleaning the beet roots also is impressive. Savings through condensation and water recycling are important in order to limit both the need for external sources and the waste water output (Anon 2010).

Power needs of sugar beet processing are very high and may be divided into external transport and factory energy. To limit the former, the cultivated fields should be within a short radius around the factory. A mean distance of 35–40 km is considered adequate for farm-factory transfers (Van der Poel 1998). The latter need is in the factory using fossil fuels to make steam for the evaporation and crystallization processes. Steam also drives the turbines for electricity generators. There are countless possibilities for improving the energy efficiency and limiting the release of greenhouse gasses from the processing chain.

Conclusions

Based on the principal criteria determining the sustainability of a crop, current sugar beet growing is adequately sustainable. In addition to the necessary improvement of crop's competitiveness, there are sound opportunities to further upgrade its sustainability. To this end, genetic resistance and tolerance to biotic and abiotic stresses can and will play the most important role.

Several potentially useful sources of such resistance have been verified. The molecular mechanisms of sugar beet–microbe interactions are being clarified, as is the function of specific genes involved and their expression. Sugar beet lines carrying additions or translocations of extra chromosomes, not only from *B. maritima* but also from *B. procumbens* and other species of the genus *Beta*, have been characterized. These lines will be very helpful for the cytological localization and molecular identification of disease resistance genes and their use in a more sustainable sugar beet crop.

Genetic, genomic and epigenomic tools now available are expected to considerably assist us in targeted screening of natural variation to further enrich cultivars with desirable sustainability traits. Specific emphasis will be given to resistance against abiotic factors where many more advances are necessary. Also, the novel genome editing techniques have the potential to exponentially increase the efficiency of sugar beet breeding and thus considerably contribute toward further advancing the sustainability and competitiveness of the crop.

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