55 The beet cyst nematode (*Heterodera schachtii*): An ancient threat to sugar beet crops in Central Europe has become an invisible actor

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Introduction

The beet cyst nematode (BCN) was one of the first discovered plant parasitic nematodes. *Heterodera schachtii* was observed in 1859 in Halle in Central Germany by the botanist Herman Schacht and described later by Adolf Schmidt in 1871, who named this cyst nematode species after its original discoverer. At about the same time, Julius Kühn provided proof that BCN reduced plant growth and suppressed yield of sugar beet, symptoms that were previously called 'beet weariness'. Partly due to the lack of knowledge about the effect of sugar beet monocultures on the population build-up of BCN, this nematode had a devastating impact on sugar production in 1876 that led to the shutdown of 24 sugar factories in Germany (Hallmann *et al.*, 2009).

Economic importance

In Europe where awareness of BCN problems has a long history, estimates of the percentage of infested sugar beet growing area is largely based on personal experience of experts and rarely on systematic surveys that are mostly conducted on national scopes. Combining both information sources, about 10–20% of the European sugar beet growing area representing more than 164,000 ha (Eurostat, 2020) on average, can be assumed as BCN infested. In the core production areas of Europe (France, Germany, Netherlands and Belgium) with intensive cultivation of sugar beet, local BCN infestations have a long history and might locally exceed 50% of the regional sugar beet areas. Over the period 2010–2020, sugar beet production experienced a significant change and high-yielding tolerant cultivars became available to growers. Thus older approximations on economic impact of BCN are probably not up to date, though in 1999 economic damage of BCN in Europe was estimated to be up to €90 million annually (Müller, 1999).

Traditionally used standard sugar beet cultivars were susceptible and sensitive to BCN. To control population build-up of BCN, resistant sugar beet cultivars were available but unattractive for growers due to their low yield potential. Both cultivar types were gradually replaced by a high-yielding sugar beet cultivar with tolerance to BCN that was introduced in 2004. Cultivation of

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tolerant cultivars gradually increased primarily in regions with well-known BCN infestation levels, reaching over 80% in some regions. Between 2004 and 2020, sugar yield per hectare in Germany approximately increased by 25% and is currently at an average of 13.4 t/ha (VDZ/VWZ, 2020).

Host range and distribution

Heterodera schachtii is globally distributed and occurs mainly in temperate but also in Mediterranean and sub-tropical climates. Its presence is confirmed in 87 countries across all continents (CABI, 2020). While BCN is associated with 218 plant species, it is mainly reported to reproduce on brassica crops (*Brassica napus, B. rapa, B. oleracea, Raphanus sativus, Sinapis alba*), chenopodium crops (*Spinacia oleracea*) and economically it is most important on beets (*Beta vulgaris*), where it causes significant damage to sugar beet (Turner and Subbotin, 2013; Hemayati *et al.*, 2017).

Symptoms of damage

Damage results from water and nutrition deficiency in plants, as a response to disturbed root growth that is caused by nematodes penetrating the roots. As a result, affected sensitive cultivars show wilting and stunting of plants. In heavy BCN infestations, older leaves show yellowing as a consequence of manganese deficiency. As BCN penetrate roots, plants try to compensate for the damage caused by the development of lateral roots. In sensitive genotypes, this appears as root bearding (Fig. 55.1). Damage is most severe for seedlings up to 2 months after sowing. The presence of BCN at later growing stages is largely tolerated by sugar beet. Thus the extent of damage is mainly determined by the initial population density (*Pi*) of BCN and the sowing conditions in spring, specifically sowing time, water availability and temperature. Sugar beet can tolerate a BCN population pressure below a certain damage threshold. A succession of field trials (2007–2011, unpublished data) conducted at the Julius Kühn Institute field station in Elsdorf (Germany) showed the relation between *Pi* densities and relative damage for a susceptible, a resistant and a tolerant sugar beet cultivar (Table 55.1).

Fig. 55.1. Heavy beet cyst nematode damage and root symptoms (bearding) of a susceptible sugar beet cultivar sampled 90–100 days after sowing. Photograph courtesy of D. Daub, Julius Kühn Institute.

At a *Pi* class over 1500 eggs and juveniles/100 ml tolerant and resistant cultivars still showed 16% yield damage. Irrespective of *Pi* densities, sugar yield achieved with tolerant cultivars was always one to two tonnes per hectare above the susceptible cultivar. Hauer (2016) found a similar yield reduction in tolerant cultivars.

Biology and life cycle

Population dynamics of BCN is mainly affected by crop rotation. Under Central European conditions two to three generations of BCN can develop per year. *Pi* density increases with concentration of susceptible hosts in a crop rotation. Critical for control is a minimum 2 years non-host break in the rotation. For Central European conditions it can be assumed that control of BCN in 4-year crop rotations usually is not necessary. In addition, alternative hosts like cabbage, spinach, Swiss chard, beetroot or oilseed rape, that are cultivated in the same rotation with sugar beet, have to be considered too.

Like many other plant parasitic nematodes, BCN populations are distributed in coherent foci of varying dimensions. Foci of older BCN populations in the field extend ellipse-like in the direction of the soil preparation (Fig. 55.2). Different soil types alter the abundance of BCN; for example, higher numbers of BCN may occur in sandy

Table 55.1. Relative damage[a] (%) of different beet cultivars at different *Pi* density classes of *Heterodera schachtii*.

Cultivar type	*Pi* class in eggs and juveniles/100 ml soil 500–1000	1001–1500	>1500
Susceptible	16.2	19.7	28.3
Resistant	7	13.9	15.7
Tolerant	2.7	4.5	15.9

[a]Per cent of yield detected at *Pi* class <500 eggs and juveniles/100 ml soil

Fig. 55.2. Two *Heterodera schachtii* foci in the direction of soil preparation in a sugar beet field. The *Pi* levels inside foci exceeded 2000 eggs and juveniles per 100 ml soil. Photograph courtesy of D. Daub, Julius Kühn Institute.

patches (Hbirkou *et al.*, 2011). Higher numbers of BCN cysts also may occur at the edges of fields where beets are piled up at harvest before they are loaded onto trucks.

The root depth of sugar beet determines the vertical distribution of BCN. Cysts can be extracted from soil sampled as deep as 1.2 m. The vertical distribution of BCN is variable, and they may be concentrated either in the top or subsoil, or equally distributed over both soil layers. Although it has been known for a long time that BCN occurs in deeper soil layers, this was not considered relevant for damage caused to sugar beet.

Interactions with other nematodes and pathogens

It is possible that tolerance against BCN disappears if other diseases (e.g. viruses, leaf spot, soil pathogens) simultaneously damage sugar beet. On the other hand, penetration of sugar beet roots by BCN juveniles and reproduction may give access to other pathogens or suppress infections by other pathogens (Heijbroek *et al.*, 2002; Hol *et al.*, 2013).

Recommended integrated nematode management

Before tolerant sugar beet cultivars were available, cultivars with HS1^{pro1} resistance against BCN were used specifically in cases where other control measure against BCN were restricted or growers favoured a dual use strategy of production and control. The resistance mechanism in this genotype is based on a hypersensitive reaction in tissues, which implies a high grade of intolerance towards penetration by BCN juveniles. Therefore, the management value of this resistance type is possibly limited to the reduction of BCN populations over crop rotation (Roberts, 1992). Although efforts have been made, the yield potential of resistant cultivars have not met grower's expectations and therefore they are no longer available for cultivation. Instead, the cultivation of nematode tolerant cultivars increased in sugar beet growing regions where BCN infestation traditionally was expected.

Presumably, the majority of sugar beet genotypes that were used for breeding tolerant cultivars derive from partially resistant *B. maritima* accessions (Blok *et al.*, 2018). Growers use tolerant cultivars primarily due to their significant yield benefit, thus partial resistance traits in tolerant cultivars are not used on purpose. Partial resistance in tolerant cultivars allows some reproduction of BCN below a specific equilibrium density. Therefore, reproduction of BCN in these tolerant cultivars at very low *Pi* densities (<500 eggs and juveniles/100 ml soil) usually results in higher reproduction rates, which decreases with increasing *Pi* densities. Tolerant cultivars show differences in partial resistance. Testing partial resistance requires a definition of quantitative resistance. Such a definition strictly would require a calibration to a standard *Pi* density and a standard susceptible reference to determine relative susceptibility.

Sufficient weed control in sugar beet rotations is crucial as some weeds are suitable hosts for BCN. Information on host range among weeds is not readily available and is often disjointed in relation to specific weed species. A recent survey of 27 plant species only confirmed *Thlaspi arvensis* and *Stellaria media* as being hosts with evident reproduction potential for BCN, but only if higher plant densities occur (Meinecke and Westphal, 2014).

If oilseed rape is cultivated in the same rotation with sugar beet, a specific point of concern is the appearance of volunteer oilseed rape post-harvest. Depending on weather conditions they can germinate in very high densities of several hundred plants per square metre. This takes place during summer months at soil temperatures above 20°C. The concurrent encounter of BCN, a very good host at high densities, optimum temperatures for the development of BCN and a period at cereal harvest where growers do not pay full attention to these fields, induce a high risk for an uncontrolled reproduction of BCN. The development of volunteers needs to be interrupted at a certain stage to prevent completion of the BCN lifecycle. A control method achieving this was developed based upon use of a degree-day model that provides a trap crop effect which enables the integration of oilseed rape and sugar beet in the same rotation (Daub, 2020).

In Central Europe, a standard method to control BCN is the cultivation of resistant white mustard (*Sinapis alba*) and oilseed radish (*Raphanus sativus*) as a catch crop prior to the cultivation of sugar beet. Breeding for resistance started over 30 years ago, and ongoing selection has achieved a very high grade of resistance in these cultivars today. In the field, catch crops achieve reduction rates of BCN population density of between 20% and 60%, depending on sowing time, plant density and crop performance. This, in turn, depends on water and nutrient availability. Due to the natural decrease of soil temperatures in autumn, sowing catch crops at the beginning of September does not show a sufficient effect on BCN reduction. Since new subsidy programmes to promote environmentally friendly cultivation have been established by many European countries, there has been a significant increase in growing mixed intercrops. The use of fertilizer is not allowed in these programmes. So far, this regulation does not meet requirements for the establishment of an effective catch crop against BCN. Growers have to check if seed mixtures contain registered cultivars with approved resistance as this is not regulated for seed mixtures.

Optimization of nematode management

The significant yield benefit of sugar beet cultivars with tolerance against BCN in infested and non-infested fields has been accompanied by disregard of traditional integrated control management strategies for BCN. Despite being tolerant, some cultivars can experience damage by BCN. There are three reasons for this: (i) tolerant cultivars primarily mask damage effects, like stunting, wilting, discoloration or root symptoms, due to their physiological adaptability; (ii) partial resistance in current cultivars with tolerance implies reliability towards sustainability of yield; and (iii) following an integrated approach to control BCN is more complex and time demanding than just using a tolerant cultivar as an all-inclusive solution. This trend ultimately results in a dramatic loss of information that prevents an overview of the real BCN situation in growing areas. Cultivation advice has to deal with this erosion of information as cultivation conditions in future possibly will foster the risk of BCN damage in sugar beet that will not appear visually.

Future research requirements

A major goal for future research on BCN and other plant parasitic nematodes will be to make direct and indirect damage impact visible on a plant and a crop scale in the field to provide data for multifactorial models. Future solutions have to cope with a more complex interaction between BCN and other biotic factors and the invisibility of damage in the field, due to the fact that breeding has focused on the selection of tolerance to many different pests and diseases. This specifically will be of some importance if the BCN population should adapt to the gene for partial resistance due to continuous field exposure, as was recently experienced with *Globodera pallida* in potato crops in north-west Germany. Due to the complexity of integrated nematode management and the fact that a huge data set on damage impact relation in the BCN–sugar beet pathosystem is already available, it would be very supportive for growers to develop an extension to established decision support systems like NemaDecide (see also Chapter 60 this volume), which is available for the potato cyst nematode.

Outlook: anticipating future developments

An average temperature increase and the occurrence of temporary droughts in spring are predicted in future climate scenarios for Central Europe (Ruosteenoja *et al.*, 2018). This might enhance the potential risk of increasing the number of generation cycles in a season and also increase the damage impact of BCN to sugar beet. In turn, this also enhances selection pressure of virulent pathotypes and overall reproduction of BCN.

Future solutions will be based on a multifactorial approach. Technical advances are being made and will deliver new techniques, for example detection algorithms that use remote sensing technologies in the field to delimit high-risk spots at early symptom development (see also Chapter 58, this volume) instead of sampling large areas. Future approaches like automatic detection and phenotyping of BCN in soil extracts using machine learning methods (Akintayo *et al.*, 2018; Chen *et al.*, 2020) will probably represent new key technologies for nematology that also potentially provide high throughput technologies. Technical development will enable faster and more complex calculation processing, which will be accompanied by the provision of complex models considering biotic, abiotic and technical patterns simultaneously for the provision of user-friendly decision support systems.

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