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Development of a decision support system for managing *Heterodera schahtii* in sugar beet production

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Abstract

A decision support system, SBN-Watch, was developed to demonstrate the influence of crop rotation and the choice of sugar beets *(Beta vulgaris)* varieties on the sugar beet cyst nematode *Heterodera schachtii* Schmidt (SBN) population and sugar beets yield. The database in SBN-Watch consists of a varietal unit with five sugar beet varieties representing the three categories “Standard,” “Tolerant,” and “semi-tolerant.” Data of minimal yield (m), tolerance limit (T), and population dynamic parameters were obtained from published commercial field trials conducted in Sweden and Denmark in 2011. Additionally, a sanitation intercrop unit with different resistant classes of white mustard (*Sinapsis arvensis*) and oil seed radish (*Raphanus sativus*) was included. The relationship between initial population (Pi) and sugar yield as well as SBN final population in soil (Pf) was calculated by two Seinhorst equations. Few data inputs are required to be entered by the user in SBN-Watch, mainly the initial population (Pi), expected sugar price and exchange rate of € to SEK. The calculated reproduction factor (Rf) values using SBN-Watch corresponded well with varietal characteristics, where the standard variety Mixer had the highest (Rf) values. The influence of the initial SBN population on the calculated sugar yield (tonnes ha^{-1}) was generally small at Pi < 2.

Key words

Beta vulgaris, Decision support system, *Heterodera schachtii*, Management.

The incidence of SBN has increased in Swedish sugar beets production in recent years, partially due to warmer summers, increased acreages of winter oil seed rape (WOSR) and the transition to a three-year crop rotation (Andersson, 1999). Cultivation of sugar beet in Sweden follows the environmental management system MBO (Environmental Management for Beet Production), guidelines including recommendations on cropping intensity of sugar beets in the crop rotation. The MBO system principle is rather similar to the ISO 9001system, and it is compulsory for all sugar beet growers (Olsson and Nordstrom, 2002). According to the MBO system, the frequency of sugar beets crops in the crop rotation is limited to once every three years or once every four years if WOSR is included in the crop rotation. Chemical control of nematodes is not allowed, instead, an integrated pest management (IPM) strategy based on cultivation of tolerant sugar beets varieties, crop rotation, and to some extent cultivation of nematode resistant intercrops is adopted by the growers. In fact, this strategy is largely in agreement with the EU-directive 2009/128/EC (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02009L0128-20091125&from=EN), which obligates the implementation of IPM in the EU-member states. In this directive, crop rotation is indicated as one of the important control measures to suppress pests, weeds, and soil-borne pathogens. Information on susceptibility of different sugar beets varieties and the ability of resistant intercrops to reduce SBN population is provided by annual testing in commercial field trials conducted by the Nordic Beet Research (Olsson, 2011). However, assembling the information into a practical tool for planning sustainable crop rotations to avoid risk of infestation by SBN can be a difficult task for both sugar beet growers and crop advisors.

Decision support systems (DSS) are tools that help the user makes a decision based on relevant information and accurate analysis, easily accessible to the user (browser-based), have generally low operation costs and are easy to update. DSS became popular and widely used in crop rotation planning (Dogliotti et al., 2003), choice of pesticide methods to control weeds (Newe et al., 2003), and risk assessment of plant diseases (Raatjes et al., 2004). Such systems were also developed as a tool for managing certain plant parasitic nematodes. dev "NemaDecide" a DSS was developed by Been et al. (2006), for managing the potato cyst nematodes (*Globodera rostochiensis* and *G. pallida*). This system enables the growers to estimate risks of yield loss, follow the population development of the nematodes and gives recommendation for chemical control. Another DSS for managing parasitic nematodes is "Nemaplot" (http://www.nemaplot.de/Applet/plotnema_eng.html), and the model used simulates the whole life cycle of sugar beet nematode (*H. schachtii*), taking in consideration the number of generations in a growing season (Schmidt et al., 1993). Furthermore, crop rotations are planned by integrating cultivation of non-host crops and intercrops with sugar beets to keep the SBN population below tolerance limit. However, "Nemaplot" does not give a possibility to choose between different sugar beet varieties. A key issue in planning crop rotation is estimating the time it takes for a SBN population to reach the tolerance level when non-hosts are grown after the sugar beet crop. "Nemaplex" is a DSS based on the models of Burt and Ferris (1996) to manage plant parasitic nematodes (http://nemaplex.ucdavis.edu/Uppermnus/MangmntUtilities.htm). The SeqOpt application in "Nemaplex" estimates the optimum rotation length under non-host conditions. However, as in "Nemaplot," the SeqOpt does not offer the choice of a specific sugar beets variety. The aim of this study was to develop a user-friendly DSS for planning sustainable and economically feasible crop rotations for sugar beets in Sweden. "SBN-Watch" was developed in close collaboration with the Sugar Beets Growers Association and crop advisors in Sweden. In general, sugar beet varieties are grouped into four categories: (i) "Standard" varieties, susceptible to SBN; (ii) "Tolerant" varieties, which produce high yield despite the occurrence of SBN; (iii) "Semi-tolerant" varieties, which maintain normal yield in soils with low SBN densities; and (iv) resistant varieties (Reuther et al., 2017). Based on differences in multiplication factors of four sugar beets varieties, one "Standard," one "Tolerant" and two "Semi-tolerant," the decline rates under non-host crops, the SBN population dynamics and corresponding sugar yields were estimated by SBN-Watch using published models (Seinhorst, 1965; Seinhorst, 1967; Burt and Ferris, 1996).

Materials and methods

Database construction

The database consisted of two units, (i) a sugar beets unit with a list of "Standard," "Semi-tolerant" and "Tolerant" varieties, and (ii) an intercrop unit. The varietal unit included values of parameters for calculating sugar yield and SBN population dynamics. These values were obtained from Swedish and Danish commercial field trials (Olsson, 2011). The intercrop unit included Rf values of resistant class 1 and 2 of mustard and oil seed radish cultivars (Olsson, 2009).

Data input

To start using the SBN-Watch, certain data are required to be entered by the user. The most important input is the average initial population density in the soil Pi (eggs g^{-1} soil). Field soil has to be sampled according to, guidelines from the Nematode Laboratory (NL) laboratory, which provides services for growers for analyzing plant parasitic nematodes in soil. Other data inputs are financial information regarding the expected sugar beets price (€ $tonne^{-1}$) and exchange rate (€ to SEK). Using a drop-down list, sugar beet varieties and crop sequence can be selected. Additionally, another option concerning tolerance (T) can be made by the user through entering a specific (T) value for the selected sugar beet variety.

Modeling population dynamics of SBN

Changes in the population of SBN in the soil under presence of the host (sugar beet) or non-host crop plants have been described by different equations in the literature. A modified equation by Burt and Ferris (1996) was used to describe SBN population dynamics when a non-host crop was selected to be cultivated in the crop rotation:

$$P_{(m)} = S^{m} \times P_{i}, \tag{1}$$

where s = proportion of the population survived (s = 0.35); Pi (eggs g^{-1} soil) = initial population of SBN at sowing expressed as number of eggs g^{-1} soil; and m = number of years the non-crop was grown in succession. If WOSR was selected to be cultivated in the rotation, a multiplication factor of 1.5 was used instead (Olsson and Olsson, 2006).

When a sugar beets variety was selected for cultivation, the final population Pf was calculated by the equation of Seinhorst (1967):

$$Pf = a(-\ln q) - 1(1 - qPi) + sPi, \tag{2}$$

where a = Reproduction factor at very low Pi values; s = proportion of the population survived (s = 0.35); q = constant < 1.

The reproduction factor (Rf) of a sugar beet variety was then calculated as Rf = Pf/Pi. To estimate the number of years required for (Pi) to reach (T) for specific sugar beets variety, the equation of Burt and Ferris (1996), Equation (1), was used modification:

$$m = \frac{\log(T_{sort}) - \log(P_i \times RF)}{\log(S)} \tag{3}$$

where Tv = tolerance limit for specific sugar beets variety was used instead of population P; Rfv = reproduction factor (Rf = Pf/Pi) of a given sugar beets variety; s = survived proportion of SBN = 0.35.

Estimating sugar yield

To estimate yield loss of sugar beets due to infestation by SBN, the equation of Seinhorst (1965), which relates sugar beet yield to SBN population density at sowing was used:

$$Y = m + (1-m)Z^{(Pi-T)}, \tag{4}$$

where Y = relative yield; m = minimum yield at the highest SBN population; Z = constant; Pi = initial SBN population at sowing (eggs g^{-1} soil); and T = tolerance limit. When $Y \times Z^{(Pi-T)}$ is $< m \times Y$ the value of $m \times Y$ is used to express yield. When $Y \times Z^{(Pi-T)} > m \times Y$ the yield is estimated by the equation $Y \times Z^{(Pi-T)}$.

Demonstration of the influence of crop rotation on SBN population dynamics and sugar beet yield by SBN-Watch

Different crop rotation scenarios were chosen to illustrate the influence of sugar beet varieties, non-host crops, WOSR and intercrops on the SBN population and sugar yield as shown in Table 2. Pi value of 2 eggs g^{-1} soil was assumed in the initial year of sugar beet cropping.

Estimation of the number of years required for economically feasible cultivation of sugar beet

In this demonstration example, the sugar beet variety “Rosalinda” was selected to be grown in year zero followed by non-host crops. Pi value of 4 eggs g^{-1} soil was assumed in the initial year of sugar beet cropping.

Table 1. Crop rotations planned by SBN-Watch.

Rotation	Cro	> p sequence				
1	Mixer[1]	Cereals	Cereals	Mixer		
2	Mixer	Cereals	WOSR	Cereals	Mixer	
3	Mixer	Cereals	WOSR	Cereals	Oil radish	Mixer
4	Julietta[2]	Cereals	cereals	Julietta		
5	Julietta	Cereals	WOSR	Cereals	Julietta	
6	Julietta	Cereals	WOSR	Cereals	Oil radish	Julietta

[1]Standard Syngenta sugar beets variety; [2]Tolerant KWS sugar beets variety.

Table 2. Chemical properties of field soil collected from Hagestad.

pH	P–AL[1]	K–AL[2]	Clay	OM[3]	Sand
	mg 100 g jord^{-1}			%	
7,1	12	6,4	1	8	73

[1]P-AL (Soluble phosphor; AL-soil analysis method of ammonium lactate); [2]K-AL (Soluble potassium; AL-soil analysis method of ammonium lactate); [3]OM (Organic Matter).

Demonstration of the correlation between the initial population density (Pi) and reproduction factor (Rf)

A demonstration example was used to illustrate the relationship between the initial population of SBN and the reproduction factor. Three sugar beet varieties "Mixer," "Rosalinda" and "Julietta" were selected to be tested at six different Pi (2; 4; 7; 9; 13; 17 eggs g^{-1} soil) similar to the levels used in microplot experiments described below. The final SBN populations (Pf) were estimated by SBN-Watch and the corresponding reproduction factors were calculated as Rf = Pf/Pi.

Microplot experiments

Two experiments were conducted according to Fatemy et al. (2007), but with the following modification. The field soil was not sterilized in order not to affect the biological and physical soil characteristics, instead different inoculum levels of SBN were generated by mixing different proportions of a naturally infested soil with a nematode free soil collected from the same commercial field in 2013 and 2014. The selection criteria of the field soils were a conducive light soil with high sand content (73%). Soil chemical characteristics were analyzed at Eurofins Food and Agro Testing Sweden AB, Kristianstad, Sweden (Table 2). The infestation levels were analyzed in the inoculum soil and the nematode free soil before soil collection and transportation to experimental site. Soil inocula and the nematode free soil were mixed by a cement blender to generate different Pi (eggs g^{-1} soil) levels confirmed by analysis of subsamples from each level (Table 3). The experiments were set up as microplots consisting of 12 l plastic buckets (28 cm diameter; height 24.5 cm) filled with 12 kg soil each (n = 4). The Each microplot was fertilized with 3.6 g NPK 15-4-8 mineral fertilizer, which corresponds to a standard level of 130 N ha^{-1} used in the commercial sugar beet fields, then sown with three seeds. Three sugar beets cultivars (Table 3) were grown each year in the microplots, arranged randomly in four blocks in a net house under natural conditions. The buckets were buried into the soil to give similar soil temperature as in the field. Watering was done directly after sowing and then when it is needed during the growing season. After germination the plants were thinned to one sugar beets plant per microplot. All experiments were conducted at the Swedish University of Agricultural Sciences (SLU), Alnarp. The initial densities and final SBN populations in the microplots were analyzed at the HS Nematology laboratory, Alnarp using Seinhorst elutriation method (Seinhorst, 1964).

Table 3. Sugar beets varieties tested at different Pi (eggs g^{-1} soil) levels in microplot experiments.

	Varietal category			Pi (eggs g^{-1} soil)		
Year	Standard	Semi-tolerant	Tolerant			
2013	Mixer[1]	Rosalinda[2]	Alexina[3]	7	13	17
2014	Mixer	Rosalinda	Elora	2	4	9

[1]Standard Syngenta sugar beets variety; [2]Semi-tolerant KWS variety; 3Tolerant KWS variety.

Results

Features of SBN-Watch

The SBN-Watch starts with information about the SBN biology and description of models used for calculation of population dynamic and sugar yield followed by three user interfaces: in the first interface soil analysis of the initial SBN population Pi (eggs g^{-1} soil), sugar beets price and exchange rate (€ to SEK) must be entered. The second interface comprises the choice of crop rotation (Fig. 1) and the third interface shows population dynamic of SBN upon choice of certain variety at a given Pi and

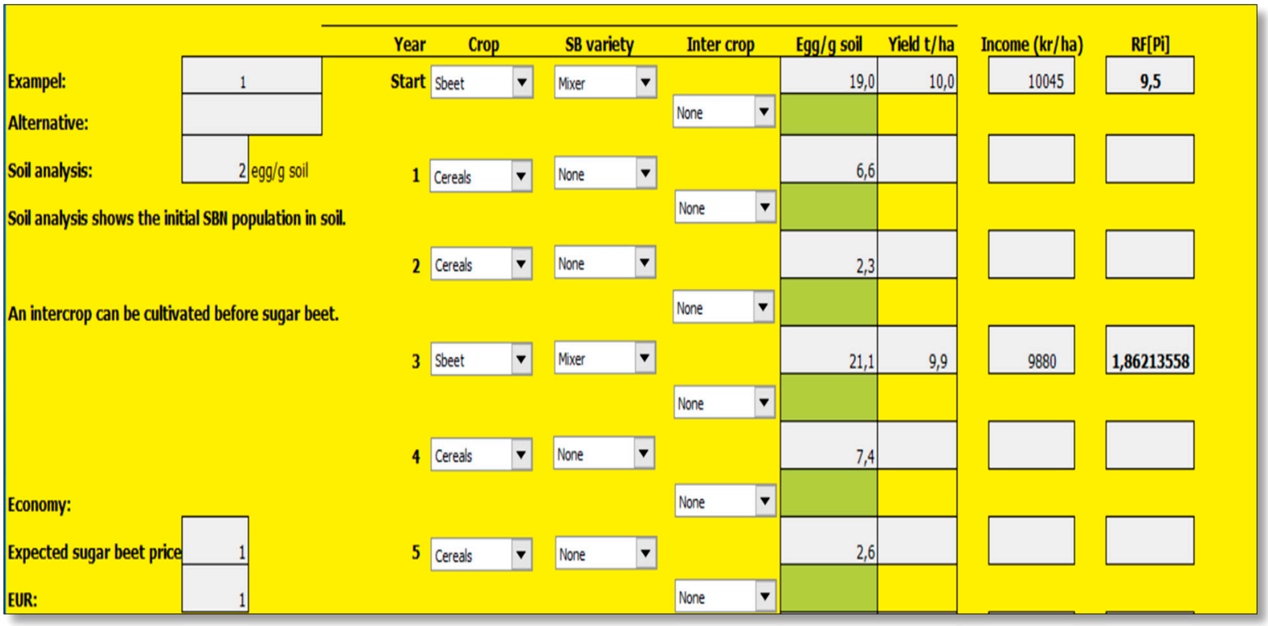

Figure 1: A screenshot of the user interface showing a selected crop rotation and the estimated final SBN population (Pf) values, sugar yield (tonnes/ha), income (SEK/ha) and the reproduction factor (Rf) values.

T value, which can optionally be changed by the user. SBN-Watch delivers results in a form of report, including information on the selected crop rotation, sugar yield, economical value, SBN population dynamics within the selected crop rotation and finally the number of years to wait for the next sugar beet crop to be grown when specific variety was selected followed by non-host crops.

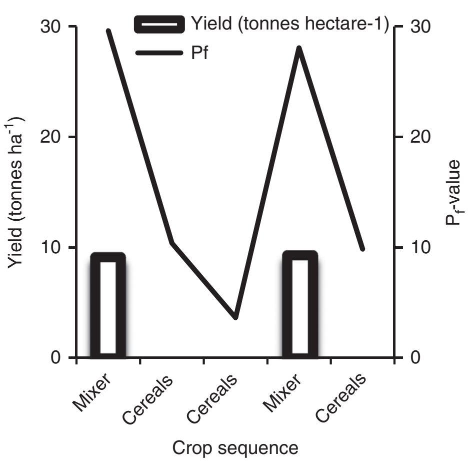

Figure 2: Crop sequence in rotation 1: standard sugar beets variety “Mixer”; Cereals; Cereals; “Mixer.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

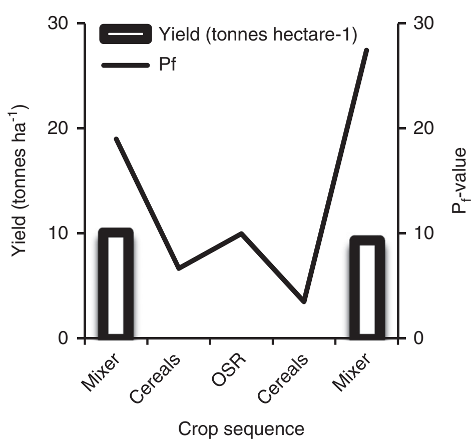

Figure 3: Crop sequence in rotation 2: standard sugar beets variety “Mixer”; Cereals; WOSR; Cereals; “Mixer.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

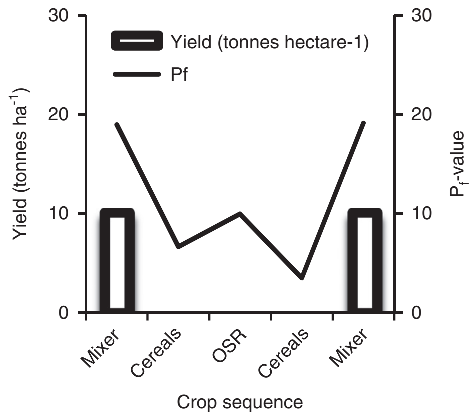

Figure 4: Crop sequence in rotation 3: standard sugar beets variety “Mixer”; Cereals; WOSRWWOSR; Cereals; Oil radish; “Mixer.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

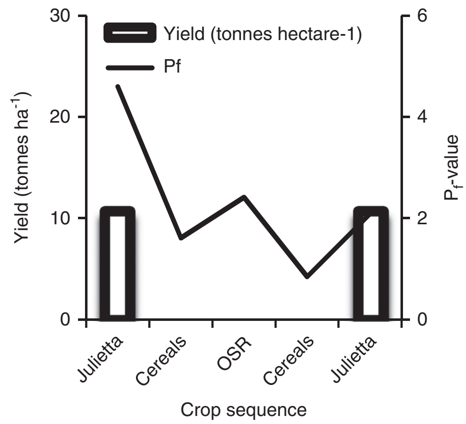

Figure 6: Crop sequence in rotation 5: tolerant sugar beets variety “Julietta”; Cereals; WOSR; Cereals; “Julietta.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

Demonstration of the influence of crop rotation on SBN population dynamics and sugar beet yield by SBN-Watch

The first two crop rotations illustrates the guidelines that give recommendations to growers for cultivating sugar beet every three years together with non-host crops or every four years upon cultivation of WOSR in the same crop rotation. In the first crop rotation, the standard variety “Mixer” was selected to be cultivated in a three years rotation in sequence with cereals. In this case, the calculated Pf values were as follows: 19, 6.6, 2.3 and 21.1 eggs g $soil^{-1}$ (Fig. 2). The Rf values were 9.5 and 1.9. The calculated sugar yields were 10.0 and 9.9 tonnes $hectare^{-1}$, respectively. In crop rotation 2 “Mixer” was selected followed by a cereal crop, WOSR and a second cereal crop before cultivating “Mixer” again in the crop rotation. The calculated Pf value increased to 10.0 after WOSR then declined to 3.5 after the second cereal crop and finally increased to 27.4 egg g $soil^{-1}$ after “Mixer” (Fig. 3). The Rf values were 9.5 and 1.2 and the calculated sugar yields were 10.0 and 9.3 tonnes $hectare^{-1}$, respectively (Fig. 3). Selecting a resistant oil radish intercrop before the second sugar beets crop in crop rotation 3, decreased the Pf value to 2.0 and the sugar yield 10.0 tonnes $hectare^{-1}$, was 700 kg higher than the corresponding

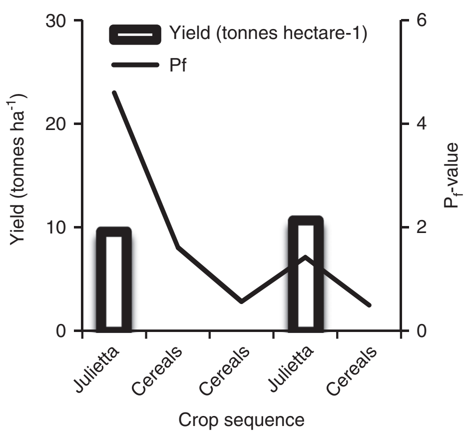

Figure 5: Crop sequence in rotation 4: tolerant sugar beets variety “Julietta”; Cereals; Cereals; “Julietta.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

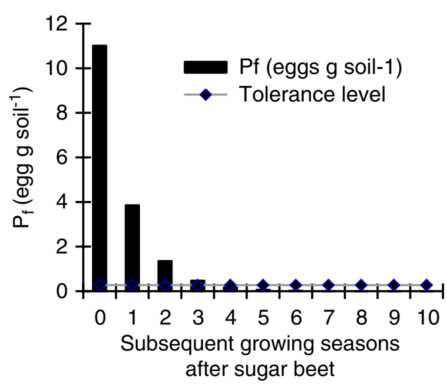

Figure 7: Crop sequence in rotation 6: tolerant sugar beets variety “Julietta”; Cereals; WOSR; Cereals; Oil radish; “Julietta.” The SBN initial population (Pi eggs g^{-1} soil) = 2.

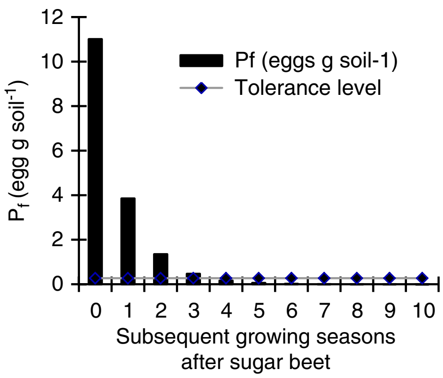

Figure 8: SBN population dynamic under the semi-tolerant variety "Rosalinda" followed by non-host crops at The SBN initial population Pi (eggs g^{-1} soil) = 4, Tolerance (T) = 0.273, proportion of the population survived (s) = 0.35 and reproduction factor (Rf) = 3.8. The suggested number of waiting years by SBN-Watch to the next "Rosalinda" crop is four years (Pf < T).

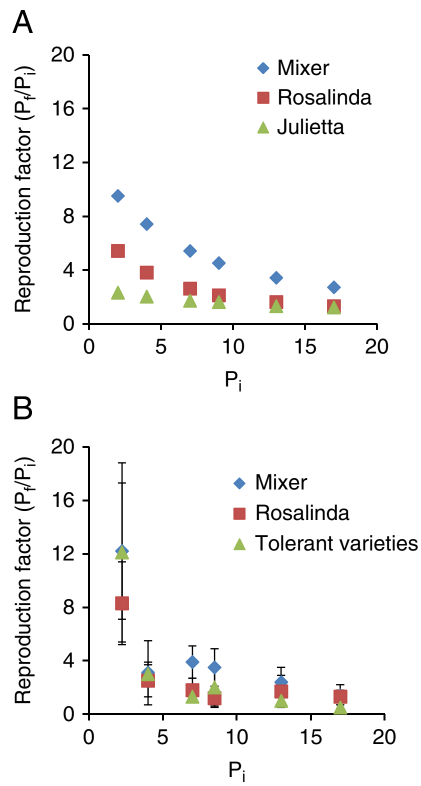

Figure 9: (A) relationship between initial SBN population (Pi eggs g^{-1} soil) and reproduction factors (Rf) of three sugar beets varieties estimated by SBN-Watch; (B) relationship between initial SBN population Pi (eggs g^{-1} soil) and reproduction factors (Rf) of four sugar beets varieties sown in microplots in 2013–2014 (*n* = 4). The bars represent means of Rf ± Sd.

yield in crop rotation 2 (Fig. 4). The Rf value of the second sugar beet crop was 2.0.

Choosing a tolerant sugar beet variety together with cereals in crop rotation 4, the Pf values were as follows: 4.6, 1.6, 0.6, and 1.4 (Fig. 5). Sugar yields were 9.6 and 10.7 tonnes hectare^{-1} and Rf values were 2.3 and 3.7 (Fig. 5). When Julietta and WOSR were grown together according as in crop rotation 5, the estimated Pf values were 4.6, 1.6, 2.4, 0.8, and 2.1 (Fig. 6). The sugar yield slightly increased from 9.6 to 10.7 tonnes hectare^{-1} as Pf after the second cereal crop decreased to 0.8 (Fig. 6). The Rf values of the first and second sugar beet crops were 2.3 and 3.6, respectively. Growing a resistant oil radish intercrop before "Julietta" in crop rotation 6, further decreased Pf value to 0.5 and the calculated sugar yield was 10.7 tonnes hectare^{-1} (Fig. 7).

Estimation of the number of years required for economically feasible cultivation of sugar beet

To answer the question of how many years it takes for a SBN population to decrease to the tolerance limit when a specific sugar beet variety was selected to be grown at a specific Pi (eggs g^{-1} soil) value, a demonstration example with the Semi-tolerant variety "Rosalinda" at Pi (eggs g^{-1} soil) = 4.0 is shown in Fig. 8.

In this example, SBN-Watch gives a recommendation for the user to wait four years before cultivating "Rosalinda" again in the crop rotation.

Demonstration of the correlation between the initial population density (P) and reproduction factor (Rf)

The predicted Rf values of three sugar beet varieties at different Pi values corresponded well with the varietal characteristics where the multiplication rates of the "Standard" variety "Mixer" and the "Semi-tolerant" variety "Rosalinda" were higher than in the "Tolerant" variety "Julietta" (Fig. 9A). Furthermore, the highest Rf values were estimated at the lowest Pi (eggs g^{-1} soil) values (Fig. 9A).

Microplot experiments

The means of reproduction factors from 2013 and 2014 were pooled together giving initial population densities from 2.24 to 17 (Fig. 9B). In general, the mean Rf values were higher at the lowest Pi (eggs g^{-1} soil) level (2.24) and the "Standard" variety "Mixer" had the highest Rf values. The Rf values of the "Tolerant" variety "Elora" and "Mixer" at the lowest Pi (eggs g^{-1} soil) were similar, but the variation was high at this particular level. The reproduction factors of all tested varieties were then decreased to Rf < 4 at Pi (eggs g^{-1} soil) > 4 (Fig. 9B). A similar trend was obtained by SBN-Watch, even two different "Tolerant" varieties were used, "Elora" in microplots and "Julietta" in SBN-Watch (Fig. 9A).

Discussion

SBN-Watch is a risk assessment tool oriented to sugar beet growers and crop advisors in Sweden for managing the SBN population in individual fields. The main task was to enable sustainable and profitable sugar beet production, allowing the users to test and compare different scenarios to estimate risks in terms of yield loss and SBN population development through the entire crop rotation. In comparison with other DSS such as "NemaDecide" (Been et al., 2006), SBN-Watch does not give any recommendation for chemical control, as nematicides are not allowed to be used in Sweden. SBN-Watch rather depends on and emphasizes the role of crop rotation, cultivation of tolerant sugar beet varieties and sanitation with resistant intercrops for managing SBN. The concept of using tolerant sugar beet varieties for managing SBN is rather unique for SBN-Watch and is not considered in DSS like "Nemaplot" and "Nemaplex."

SBN-Watch was developed so that it gives relevant information to the growers with few data input. The two essential outputs of SBN-Watch are population dynamic of SBN and sugar yield in a specific crop rotation and at a given initial population density using published models. Regarding population dynamic, SBN can complete two generations per year depending on accumulated temperature during the growing season. The time point of when the second generation becomes fully developed is difficult to determine, but generally it occurs late in the growing season (Eriksson and Thorstensson, 2007). Therefore, we considered one SBN generation and used the model described by Seinhorst (1967) to estimate SBN population dynamic under the host crop (Olsson, 2011). This also simplifies the influence of climatic conditions, such as temperature, on the number of SBN generations under the growing season (Schmidt et al., 1993). In addition, since sugar beets is grown in a restricted region in south Sweden, thus regional differences in climatic conditions were not considered in SBN-Watch.

The model of Burt and Ferris (1996) describes changes in population densities of nematodes in the soil in relation to the presence of host or non-host crops, taking into account the number of years between the cultivation of the host crop. In the absence of sugar beets, the SBN population reduces each year under a non-host crop for example cereals, until sugar beet is grown again in the crop rotation. This ratio of a fixed rotation is used where a host crop is grown at regular intervals is described by the equation $P_M = S^M.g(P_M)$, where $g(P_M)$ describes the net growth of nematodes in crop rotation in which sugar beet is grown. Net growth reaches an equilibrium level during the growing season that cannot be exceeded due to environmental and biological factors. This model was implemented in SBN-Watch to describe SBN population dynamics under non-host crop cultivation. The proportion of the SBN population (s), which survives to the following year was, however, assigned to a relatively lower value compared to the values computed by Burt and Ferris (1996). This value was found to be relevant under Swedish conditions (Olsson, 2011). The accuracy of the (s) value is crucial for estimating the number of years (M) under the non-host crops and hence the length of the rotation given that the initial population is accurately quantified. Since SBN-Watch is based on data for individual sugar beet varieties, the number of years (M) is also influenced by the tolerance level of the selected variety, meaning that the more tolerant the variety is, the fewer number of years it takes for the SBN population under the non-host crop to reach the tolerance level. In general, the model of Burt and Ferris (1996) shows that the first crop rotation is usually shorter than the following cycles under sugar beet and the consecutive non-host crops, this was also shown by SBN-Watch (results not shown).

Several models that describe population dynamic of sedentary nematodes depend on the biological fact that the population dynamic is density dependent and the relationship between the initial population densities and the reproduction factors is non-linear (Nicholson, 1933; Seinhorst, 1967; Jones and Perry, 1978). In general, the predicted values of the final SBN populations and the reproduction factors of three sugar beet varieties representing different categories "Standard," "Semi-tolerant," and "Tolerant" were in agreement with their varietal characteristics. Both SBN-Watch and the microplot experiments had similar trends of density dependent Rf values. In the case of "Mixer" the corresponding Rf values in the microplots and SBN-Watch were 12 and 9.2, respectively. The variation was high at the lowest Pi (eggs g^{-1} soil) level in the microplots and the soil used was a sandy conducive soil, which might explain the difference in the Rf values. On the other hand, in Danish and Swedish field trials, the SBN population was found to increase 11 times after growing Mixer at Pi (eggs g^{-1} soil) = 1 (Olsson, 2011), equal to the estimated Rf value by SBN-Watch (Rf = 10.9) at Pi (eggs g^{-1} soil) = 1. In the same field trial, the average Rf value for three different semi-tolerant varieties was 5.9 and the estimated Rf value for the semi-tolerant variety "Rosalinda" by SBN-Watch was 6.6. The Rf value for the tolerant variety "Julietta" was 4.9 while the estimated Rf value by SBN-Watch was 2.4. This exceptionally high average value for "Julietta" was due to the high Rf value in Swedish field trials (Rf = 7.6) although in the corresponding Danish field trials the Rf value was 2.3 (Olsson, 2011). SBN population in the soil is known to be influenced by physical and biological factors such as soil type, temperature, rain, and antagonistic fungi (Westphal and Becker, 2001; D'addabbo et al., 2005). These factors were not considered in SBN-Watch, however, the model gave a satisfactory estimation of SBN population. Soil type and precipitation probably play more significant role on the extent of SBN damage to sugar beet. Microplot experiments conducted in an infested clay soil in 2012 showed a high increase in SBN population, but the plants compensated the damage due to the high precipitation during the summer (results not shown).

In order to keep the SBN population at a low level and simultaneously obtain high sugar yield, the two main strategies for managing SBN in central Europe are crop rotation and growing tolerant sugar beets varieties (Hauer et al., 2016). Furthermore, a recent approach of managing SBN is through cultivation of resistant intercrops such as oil radish and mustard (Smith et al., 2004; Hauer et al., 2016). In general, both intercrops were divided into nine different resistance classes, however, it is only recommended to grow either class 1 or 2 for reducing SBN population (Heinrichs, 1998). In Swedish field trials oil radish and white mustard had a sanitation effect of 29–42% and 38–46%, respectively (Eriksson and Thorstensson, 2007).

Cruciferous plants such as WOSR and cabbage can increase the population of SBN in soil. While egg density increases by 1.5-fold under WOSR (Olsson and Olsson, 2006), winter cabbage is reported to increase SBN density threefold (Roberts et al., 1981). Selecting an intercrop after WOSR in crop rotation 3 and 6 reduced SBN population to 2.0 and 0.5, respectively. The Rf values of the intercrops were considered as fixed values in SBN-Watch, however, in practice the efficiency in sanitation is not constant and could vary depending on the pre-crop and soil tillage. Eriksson and Thorstensson (2007) found that growing peas as a pre-crop gave better root development and hence more efficient sanitation by the intercrops, compared to cereals. Considering the estimated reduction rate in SBN population due to sanitation by intercrops, the Pf values were, however, not over estimated by SBN-Watch, bearing in mind that the proportion that survives to the next growing season was assigned to 0.35. A very important aspect concerning Brassica intercrops is that growing these crops in the crop rotation can increase the risk of infection by certain soil-borne pathogens, e.g., *Plasmodiophora brassicae* and *Verticillium longisporum* in WOSR (Tzelepis et al., 2017). While *P. brassicae* is not a pathogen of sugar beet, *V. longisporum* can infect both WOSR and sugar beet plants in addition to white mustard and oil radish (Eastburn and Paul, 2007). It is therefore important to know if these pathogens are persistent by analyzing the field soils (Banno et al., 2011; Wallenhammar et al., 2012) before growing white mustard or oil radish.

The calculated sugar yields in crop rotation 1 and 4 showed that sugar beets can be cultivated sustainably every three years together with non-host crops, which is in accordance with the guidelines for cultivating sugar beets in Sweden. Other main crops which are known as hosts for SBN are spring oil seed rape and winter oil seed rape (WOSR) (Nielsen et al., 2003). Although the reproduction factor for WOSR was found to be low in both Swedish and German field trials (0.9–1.5) (Olsson, 2006), the guidelines by MBO recommend the Swedish growers to cultivate sugar beets in a crop rotation with WOSR not shorter than four years. Using SBN-Watch, this was also shown to be applicable for the tolerant variety "Julietta," however, the estimated sugar yield for the standard variety "Mixer" in crop rotation 2 decreased by 700 kg upon cultivation with WOSR. Selecting a sanitation intercrop in the crop sequence of rotation 3 maintained a sustainable sugar production in "Mixer." In general, SBN-Watch assumes that sugar yield will continue to decrease as the SBN population increases in the soil regardless of weather conditions and soil type. In fact, sugar beets can compensate for the damage by SBN in rainy summers (Olsson, 2011), something that we noticed in microplot experiments (results not shown).

Conclusion

SBN-Watch is an interactive tool, useful in discussions with farmers regarding the influence of crop rotation on pests and plant pathogens, especially in platforms such as "Greppa Naringen" (Catch the Nutrients) http://www.greppa.nu/om-greppa/om-projektet/in-english.html, focusing on reducing nutrients and pesticides losses to the environment as well as implementing IPM in Sweden. The illustrated examples by SBN-Watch showed that population dynamic of SBN could fairly be estimated through the entire crop rotation. When it comes to sugar yield, the model gives better estimation of yield at Pi (eggs g^{-1} soil) < 2. The accuracy of the model can further be fine-tuned by including other parameters as soil type and precipitation. Likewise, more experiments and data collection from commercial fields are required to verify the model and update the database with new sugar beets varieties. An MS Excel version of SBN-Watch is available to crop advisors and farmers, which will be continuously updated with new sugar beets varieties and corresponding data. http://hushallningssallskapet.se/tjanster-produkter/trycksaker-brev-2/ under "Verktyg forodling av sockerbetor" (Tools for growing sugar beets).

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