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Technologies for Smart Chemical Control of Broomrape (*Orobanche* spp. and *Phelipanche* spp.)

Hanan Eizenberg, Radi Aly, and Yafit Cohen*

Broomrapes (*Orobanche* and *Phelipanche* spp.) are obligate root parasites that spend most of their life cycle in the soil subsurface, making them hard to detect. In these underground developmental stages, broomrapes are highly sensitive to herbicides, and therefore knowledge of the dynamics of their parasitism is essential to precisely apply herbicide for their control. To address these complexities, two approaches have been proposed: (1) estimating the temporal variation in parasitism dynamics and predicting broomrape parasitism on its host by thermal time; (2) characterizing the spatial variation in infestation within and between fields by using a geographical information system and a global positioning system. In addition, the use of molecular markers to identify broomrape infestation (species and amount) in the field can contribute to determining its spatial distribution, which can then be used for site-specific weed management. In this paper, we discuss how technology can be optimized for control of the root-parasitic broomrapes. Special attention is given to the development of integrative approaches. An example of a decision support system for the rational management of Egyptian broomrape in processing tomato is given.

Nomenclature: Egyptian broomrape, *Phelipanche aegyptiaca* Pers. (syn. *Orobanche aegyptiaca*) ORAAE; tomato, *Solanum lycopersicon* L.

Key words: Broomrape, geographical information system, growing degree day, remote sensing.

The Problem: Complexity of Chemical Control of the Parasitic Weed Broomrape

The broomrapes (*Orobanche* and *Phelipanche* spp.) are obligate root parasites that spend most of their life cycle under the soil surface. Key growth phases of the root parasites include dormancy, seed germination, attachment to the host root, connecting to the host tissues, and tubercle production (Joel et al. 2007; Parker and Riches 1993). After shoot emergence the broomrapes produce inflorescences bearing hundreds of thousands of dustlike seeds that are hard to be detect in the soil (Joel et al. 2007; Parker and Riches 1993). Potential herbicides must be selective for the host plant but phytotoxic to the parasite. The parasite is directly connected to the host, and this must be taken into account when exploring potential herbicides for root-parasite control. The host should be tolerant or resistant to the herbicide without reducing its phytotoxicity, if the herbicide is to be applied against the parasite via the host's conductive tissues. In addition, chlorophyll inhibitors cannot be used because of the lack of a target enzyme (Joel et al. 2007; Parker and Riches 1993).

Broomrapes are highly sensitive to herbicides when growing in the soil subsurface, as reported for several parasite–crop systems (Colquhoun et al. 2006; Eizenberg et al. 2006; Foy et al. 1989; Jacobsohn and Kelman 1980; Plakhine et al. 2001; Figure 1). Therefore, to accurately apply herbicide for broomrape control the parasite's development stage should be known. With weeds that are not root parasites, herbicides can be applied on weed foliage and rates can be calibrated to weed sensitivity, phenological stage, or infestation level. However, the infestation level of broomrape in the field varies and cannot be easily detected (Figure 1). In the case of a root parasite, herbicide must be delivered to the soil subsurface and activated in the root zone where the broomrape is attached. Moreover, the time required for parasitic weed emergence is much longer than for nonparasitic weeds (Eizenberg et al. 2004b), making it even more difficult to be detected early enough for optimized control.

Another aspect to be considered when developing a control strategy for root-parasitic weeds is that host roots continue to grow and induce parasite seed germination throughout the growing season, and therefore herbicide must be delivered to the root repeatedly throughout the season.

To address these complexities, two approaches have been proposed: (1) estimating the temporal variation in parasitism dynamics and predicting broomrape parasitism on its host by thermal time; (2) characterizing the spatial variation in infestation within and between fields by using a geographical information system (GIS) and a global positioning system (GPS). Said mapping can aid in considering the use of site-specific weed management (SSWM).

When the cost of technology decreases (or its availability increases), and at the same time the cost of agricultural investment increases, precision agriculture, specifically SSWM, becomes a cost-effective approach. Several recently introduced technologies can advance the search for a solution to root-parasite control above and below the soil surface. Several of those technologies have been adopted by farmers for precision control of parasitic weeds. In this paper, we discuss how this technology can be optimized for the control of the root parasite broomrape.

Biotechnological approaches, such as the use of genetically modified crops with induced resistance to herbicides, will not be discussed in this paper.

Chemical Control of Broomrape

Approaches for the selective control of broomrape using systemic herbicides are based on the aromatic amino acid synthesis inhibitor glyphosate, or the branched-chain amino acid synthesis, acetolactate synthase (ALS) inhibitors, imidazolinones and sulfonylureas (Schloss 1995). Sulfonylurea herbicides are applied to the host plant, and are rapidly

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Figure 1. Tomato fields infested with different levels of Egyptian broomrape: (a) none; (b) 1–5 shoots m^{-2}; (c) 5–100 shoots m^{-2}; (d) 100–500 shoots m^{-2}.

translocated to the roots and the parasite (when attached) via acropetal and basipetal translocation. Imidazolinone herbicides are absorbed and translocated through the host to the meristematic tissues where the ALS enzyme is highly active.

Chemical control of broomrape has been investigated since the 1970s (Aly et al. 2001; Eizenberg et al. 2004a, 2006, 2009a; Foy et al. 1989; Garcia-Torres and Lopez-Granados 1991; Goldwasser et al. 2001, 2003; Hershenhorn et al. 1998a, 1998b, 1998c, 2009; Jacobsohn and Kelman 1980; Lins et al. 2005). Herbicide effectiveness and timing of application vary depending on the crop species (host) and herbicide. To achieve successful control, the developmental stage of the parasite must be known. Before the introduction of technologies for broomrape detection in the soil subsurface or the use of modeling approaches, an empirical approach to broomrape control was used. This approach included two or three repeated applications (at 2- or 3-wk intervals) of herbicides belonging to the sulfonylurea or imidazolinone families, or of glyphosate.

Glyphosate at low rates of 72 to 144 g ai ha^{-1} applied one to three times was effective at controlling crenate broomrape or Egyptian broomrape in carrot (*Daucus carota* L.), parsley (*Petroselinum crispum* J. Hill), faba bean (*Vicia faba* L.), and pea (*Pisum sativum* L.) (Foy et al. 1989; Jacobsohn and Kelman 1980; Kasasian 1973). Foliar application of 4.8 to 9.6 ai ha^{-1} imazapic controlled sunflower broomrape on sunflower (*Helianthus annuus* L.) (Aly et al. 2001; Eizenberg et al. 2009a), carrot (2.4 to 4.8 ai ha^{-1}) (Jacobsohn et al., 1996), and parsley (2.4 to 4.8 ai ha^{-1}) (Goldwasser et al. 2003). Crenate broomrape was controlled in faba bean with imazethapyr at rates of 75 to 100 g ai ha^{-1} when applied before broomrape emergence (Garcia-Torres and Lopez Granados 1991). Host's seed drenching for crenate broomrape control in faba bean was proposed using the herbicide pronamid (Jurado-Expósito et al. 1996, 1997). Small broomrape was controlled in red clover (*Trifolium pretense* L.) when 10 to 40 g ai ha^{-1} imazamox was sequentially applied to the foliage (Colquhoun et al. 2006; Eizenberg et al. 2006; Lins et al. 2005).

Application of sulfonylurea herbicides sulfosulfuron and rimsulfuron directly to the soil, prebroomrape attachment, controlled Egyptian broomrape in tomato (*Solanum lycopersicum* L.) at rates of 37.5 to 75 g ai ha^{-1} and potato (*Solanum tuberosum* L.) at rimsulfuron rates of 25 to 50 ai ha^{-1} (Eizenberg et al. 2004a, 2006; Goldwasser et al. 2001; Hershenhorn et al. 1998a, 1998b, 2009; Kleifeld et al. 1998) by controlling most of the preconditioned and germinating seeds or even small (1 to 4 mm) and young attachments. When sulfonylurea herbicides are applied, they must be incorporated into the soil by overhead irrigation.

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Available Technologies to Improve Chemical Control of Broomrape

Successful broomrape control (which refers to both control efficacy and prevention of yield reduction) is achieved during the parasite's subsurface developmental stage. However, acquiring precise and robust data on its underground developmental stages is a great challenge. To address this, a modeling approach to predict the initial stages of parasitism was proposed in several crops (Eizenberg 2011; Eizenberg et al. 2005a, 2006, 2009b; Ephrath and Eizenberg 2010). The introduction of the minirhizotron video camera and its adaptation for nondestructive in situ monitoring of broomrape development in the soil subsurface allowed the development of a robust thermal time model and its validation under field conditions (Figure 2). Furthermore, this technology enabled the defining of stages at which broomrape is most sensitive to herbicides (Eizenberg et al. 2009b). This new technology considerably enhanced and optimized the efficacy of chemical control of parasitic weeds (Figure 3). However, the minirhizotron technology only allows the development of a temporal model for parasitism prediction and timing of herbicide applications. For optimal chemical control with minimal herbicide use, additional spatial information is needed. Such information can be acquired by means of common precision agriculture techniques like GIS, GPS, and remote sensing. Although detecting and mapping techniques exist for nonparasitic weeds, the development of a detection technique of root-parasitic weeds in the soil subsurface is a challenge since they cannot be detected in the soil subsurface in the field scale. Few studies have shown that there is a correlation between the number of broomrape shoots and the seed bank in the soil (González-Andújar et al. 2001). Under this assumption the spatial distribution of the root-parasitic broomrape can be mapped by intensive survey on the basis of visual inspection. With the incorporation of field history the spatial patterns can then be studied by spatial analysis techniques in a GIS environment (discussed further on). Obviously intensive surveys that are based on walking in the field toward the end of the season are not practical and can only be used for research purposes. Yet, studying the spatial patterns of the broomrape and tracking their factors may yield, using geostatistical analysis, a decision-supportive tool for optimal sampling strategies with minimum samples (Jurado-Expósito et al. 2003). When a small number of samples is sufficient, more reliable sampling techniques become cost effective and practical. One of the alternatives is extracting broomrape seeds from the soil, and using molecular markers for the detection and diagnosis of broomrape species and population levels in the soil. This procedure is rapidly becoming feasible thanks to the parasitic plant genome project, which provides genomic information for use in the public domain (Westwood et al. 2012).

Modeling Approach for Prediction of Subsurface Growth of Broomrape

Models facilitate the prediction of host–parasitic weed interactions and weed population dynamics by describing a particular phenological event for the individual stages of parasitism such as seed germination, attachment, tubercle production, or parasitic shoot emergence. Several models

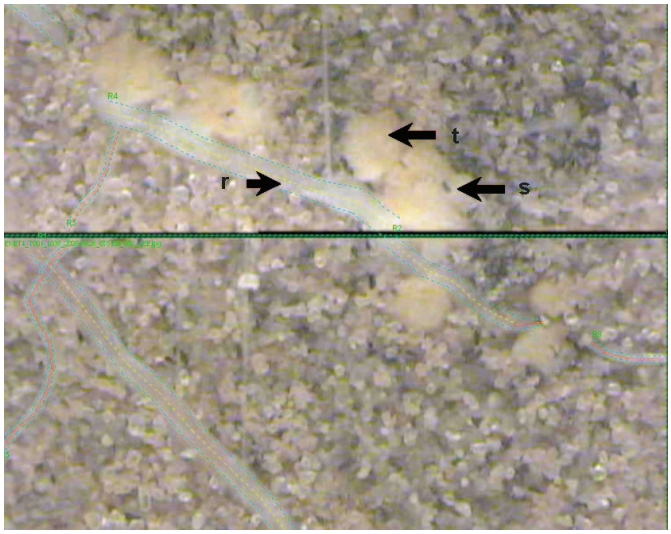

Figure 2. Nondestructive in situ observations using the minirhizotron for the detection of soil subsurface development of Egyptian broomrape on tomato roots under field conditions. r = tomato root; s = Egyptian broomrape seed; t = Egyptian broomrape tubercles.

based on thermal time (heat units or growing degree days [GDDs]) robustly estimate the parasitism dynamics of broomrape (Eizenberg et al. 2004b, 2005a, 2009a; Ephrath and Eizenberg 2010; Kebreab and Murdoch 1999). The use of thermal time as a parameter for predicting the parasitism is effective when phenology is highly dependent on temperature. The rationale behind this concept is to develop means for predicting parasitic stages at which the broomrape is sensitive to herbicide for precise chemical application at those stages. The parameters obtained from the mathematical equations describing the parasitism dynamics are all nonlinear, characterized by lag, log, and maximal phases. The use of mathematical equations enables estimating parameters of specific events during the life cycle of broomrape. A nonlinear, three-parameter sigmoid curve described the parasitism of small broomrape in red clover (Eizenberg et al. 2004b, 2005a,b), sunflower broomrape in sunflower (Eizenberg et al. 2009a; Ephrath and Eizenberg 2010), and Egyptian broomrape in processing tomato (Eizenberg et al. 2009b; Hershenhorn et al. 2009). This three-parameter sigmoid equation estimates: (1) the time when only few broomrapes are attached; (2) the time (in GDD) required to reach 50% of maximal attachments; (3) the maximal number of broomrapes that are attached. The lag phase can be estimated by a modification of the four-parameter Weibull equation. This modified equation was the first to estimate the precise time of the first attachment of sunflower broomrape on sunflower (Eizenberg 2011). Such models predict by thermal time the number of parasites and the average of their developmental stage, and estimate their susceptibility to herbicide at those stages. For example, imidazolinone herbicides control parasites via the plants to which they are attached, and therefore, a prediction of the attachment size and density during the growing season can give an indication of the optimal timing for herbicide application. If the herbicide is applied before the broomrape has attached to the roots, or when the size of the attachment is too large, control efficacy will be reduced. On the basis of this information, optimal timing for herbicide application will be at the estimated inflection point. When the herbicide has been designed to prevent parasitism, such as

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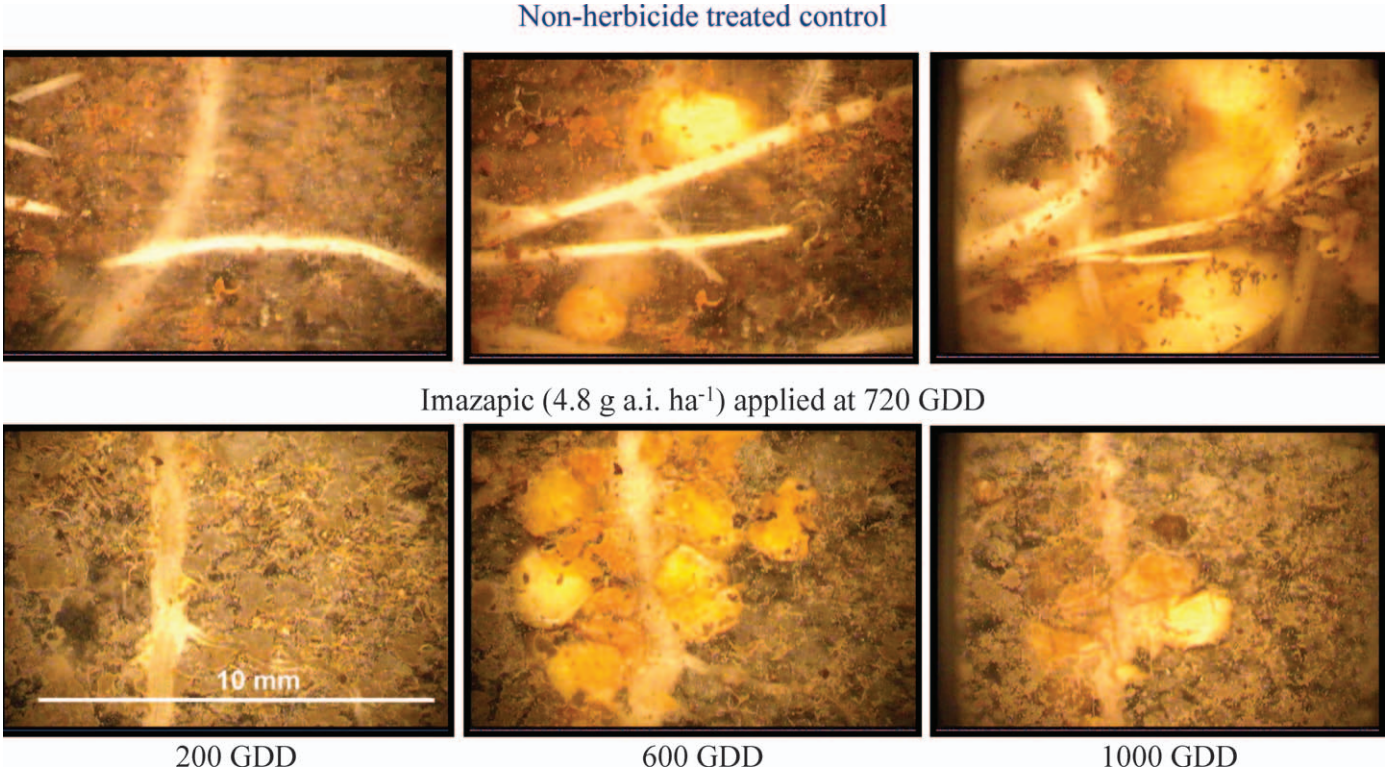

Figure 3. Nondestructive in situ observations using minirhizotron for smart control of sunflower with imazapic (4.8 g ai ha^{-1}) applied at 720 growing degree days (GDD). Top panels: nontreated controls. Left: sunflower roots presunflower broomrape attachment; center: sunflower broomrape tubercles; right: sunflower broomrape apex. Bottom panels: imazapic-treated sunflower. Left: sunflower roots preattachment; center: sunflower broomrape attachments preherbicide treatments; right: controlled attachments after imazapic application.

sulfonylurea herbicides, the correct timing for herbicide application should be before broomrape attachment, at the seedling or small attachment stages. In this case, the model is used to predict the germination or attachment stage (Ephrath and Eizenberg 2010, Kebreab and Murdoch 1999). Imazamox could be safely applied to red clover foliage at up to 40 g ha^{-1} at all herbicide application timings dictated by the model. Optimal control was achieved by first applying 20 g ha^{-1} imazamox at 1,000 GDD. This treatment was effective for an additional 800 GDD, thus providing small broomrape control for a period of 1,800 GDD that is about 90–100 d in a typical year (Eizenberg et al. 2006). On the basis of this modeling approach, a decision support system (DSS) was developed for Egyptian broomrape control in tomato (Eizenberg et al. 2009b.

Spatial Distribution of Broomrape

Precision agriculture and SSWM are new and modern agricultural concepts that are based on the detection of natural and human-made heterogeneity in the field, analyzing and defining the sources of the heterogeneity and as a result, applying chemicals at the optimal rate only in infested locations. This approach is based on current advances in modeling and on the cost effectiveness and availability of new technologies such as sensors, GPS hyperspectral and multispectral cameras, aerial and terrestrial photography, GIS software, image-processing software, and new algorithms. Introducing SSWM for the chemical control of parasitic weeds is not the same as for nonparasitic weeds where the weeds can be observed and detected after emergence. In the case of parasitic weeds, chemical control should be applied before shoot emergence, and therefore knowledge of their spatial distribution should be available in advance. Field history and the mapping of infection patches from previous years can provide the required data for herbicide applications in management zones. Field history documentation and GIS technology may be among the most promising means of increasing the precision of parasitic weed control under SSWM, as field history data from different growing seasons can be combined and an up-to-date map provided (Eizenberg et al. 2009b; Roei et al. 2011).

Hyperspectral and thermal imaging may aid in the detection, early in the season, of broomrape-infested patches in the field, on the basis of the hypothesis that host plants infected by broomrape may have water stress. Hosts plants that have water stress may be traced either by lower absorbance of the radiation in certain parts of the spectrum (hyperspectral imaging) or by higher leaf temperature (thermal imaging).

Spatial distribution and population dynamics of crenate broomrape parasitism on faba bean was investigated in a long-term study (Oveisi et al. 2010). Infection of crenate broomrape was seen to increase over time to a maximum 23 crenate broomrape shoots per square meter, as a results of thousands of seeds that are produced by individual shoots every year, enriching crenate broomrape seed bank in the soil. Thus, crenate broomrape locations in the field were predictable and could be used for site-specific herbicide application and control of the parasite. Another study was conducted in Israel to determine the spatial distribution pattern of Egyptian broomrape in several tomato fields, using

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mapping on a plot scale. Interpretation of the field maps is exemplified in Figure 4. The mapping was performed with a GPS-GIS system, with every sample point representing a square of 240 m^2 (40 samples ha^{-1}). On the basis of shoot emergence, each sampling point was classified into one of the four infestation levels shown in Figure 1: (a) none; (b) 1 to 5 shoots m^{-2}; (c) 5 to 100 shoots m^{-2}; (d) 100 to 500 shoots m^{-2}. The sample maps were interpolated by kriging to explore spatial patterns and influential factors (Figure 4). In this example, a clear pattern of small clusters (hot spots) can be observed. It can be hypothesized that this pattern is the result of infestation by specific human activities, for example reflecting the locations of collection containers or the site where a combine was washed.

The two above examples demonstrate mapping of broomrape after shoot emergence. These maps could serve to create a large database that could then be expanded into a regional database in a GIS environment. Such a database will enable comprehensive study of the spatial patterns of the broomrape and their influential factors. In addition, with the use of conventional spatial analysis and geostatistical analysis an optimized sampling strategy might be defined with minimum number of samples. However, mapping of broomrape after shoot emergence does not provide an up-to-date situation of spatial distribution before crop (host) planting. Spatial distribution might change as a result of cultivation or after crop harvest in the previous season, or because of environmental conditions such as wind, water flow, and the like.

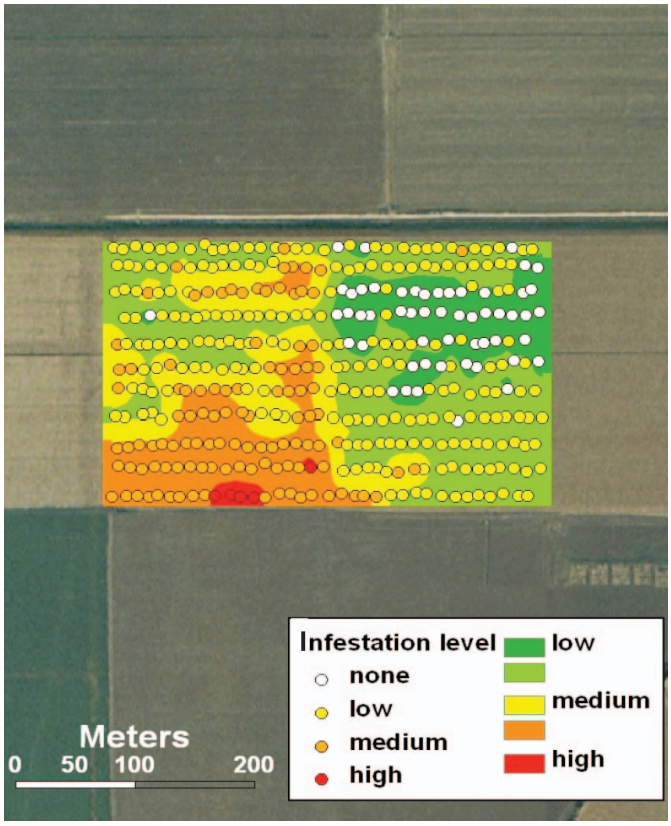

Figure 4. An example of the spatial distribution of Egyptian broomrape in a tomato field. The mapping was performed using a global positioning system–geographic information system (GPS–GIS) system. Every sample point represents a square of 240 m^2 (40 samples ha^{-1}). On the basis of shoot emergence, every sampling point was classified into one of the four infestation levels delineated in Figure 1. This distribution pattern is characterized by small clusters (hot spots) that were apparently caused by equipment-related infestation (representing, e.g., the location of a container or the spot where a combine was washed).

Molecular Markers for Identification of Broomrape Species in Soil

A new procedure has been proposed as a complementary methodology for mapping parasitic plants in the field. This procedure includes the development of a geostatistics model for soil sampling that will characterize the spatial variation in the field, and at the same time, the development of a technique for extracting DNA fractions from the soil. The latter technique will rely on the use of molecular markers to detect and identify broomrape species, and to assess their population levels in the soil. A molecular marker is defined as a DNA segment that is representative of differences at the genome level. Molecular markers offer numerous advantages over conventional phenotype-based alternatives as they are stable and detectable in all tissues regardless of growth, differentiation, or developmental stage. An ideal molecular marker technique should be simple, quick, and inexpensive, require only small amounts of tissue and DNA, consist of a marker that is polymorphic and distributed throughout the genome, provide adequate resolution of genetic differences, and require no prior genomic information on the organism under study (Agarwal et al. 2008). Genetic or DNA-based marker techniques such as restriction fragment length polymorphism, random amplification of polymorphic DNA, simple sequence repeats, amplified fragment length polymorphism, and internal transcribed spacers (ITS) are routinely used in evolutionary, taxonomic, phylogenetic, and diversity studies (Agarwal et al. 2008; Park et al. 2008; Schneeweiss et al. 2004).

Recently, a protocol that enables extraction of genomic DNA from a few tiny seeds of broomrape species in the soil was developed. Using this protocol, we were able to subject the sample DNA to a rapid polymerase chain reaction (PCR) assay. This protocol will be extended to the identification and distinction between soilborne and parasitic seed species collected from the field. We are currently developing a rapid and reliable PCR assay for diagnostic identification of the most damaging weedy root parasites, including Egyptian broomrape, crenate broomrape, sunflower broomrape, branched broomrape, and small broomrape (unpublished data). Our PCR assay will be based on the development of primers consisting of unique sequences in the ITS regions of nuclear ribosomal DNA (Schneeweiss et al. 2004), or primers consisting of unique sequences and expressed sequence tags of broomrape species to be selected from the Parasitic Plant Genome Project (http://ppgp.huck.psu.edu/) (Westwood et al. 2012). Extraction of broomrape species' genomic DNA directly from soil samples and subjecting it to real-time PCR is expected to enable quantitative diagnostics of broomrape species in the soil. These methods could be helpful in precision agriculture, which is gradually replacing traditional agricultural practices in developed countries.

An Example of the Use of Today's Technology: Developing a DSS for Egyptian Broomrape Management in Processing Tomato

PICKIT, a DSS for the rational control of Egyptian broomrape in processing tomato, was introduced in 2009

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(Eizenberg et al. 2009a; Hershenhorn et al. 2009). This DSS is based on the integration of spatial and temporal models for precise chemical control of Egyptian broomrape in tomato. The chemical control is based on soil application of sulfosulfuron and postattachment applications of imazapic. Timing for herbicide applications is based on the thermal time model that has been developed for predicting the parasitism of Egyptian broomrape in tomato (Eizenberg et al. 2009a; Hershenhorn et al. 2009). The protocol proposed in PICKIT has been tested in Israel for the last 12 yr in about 50 field experiments, producing excellent results for the control of Egyptian broomrape in processing tomato. In these experiments, sulfosulfuron application was followed by an overhead irrigation (to incorporate the herbicide into the soil solution), and at later growth stages, imazapic was applied to the tomato foliage. A flow chart of the DSS PICKIT exemplifying the use of technology for optimization is presented in Figure 5. PICKIT consists of the following components:

(1) Risk assessment-use of all available databases to evaluate the risk of growing tomato in the face of Egyptian broomrape infection (Figure 5, step 1). The risk assessment is based on field history, e.g., crop rotation, cultivation, infection history, broomrape species, mapping the infection in previous seasons and on other crops, GIS database, model for seed dispersal, mapping before tomato season, and diagnostics (diagnostic and sampling tools are under development) (Figures 5a–d). These serve as input to create an up-to-date map of the spatial distribution of broomrape seeds in the field (Figure 5, step 2) before tomato planting (Figure 5, step 3).
(2) After tomato planting, soil temperature data are measured at a depth of 10 cm (Figure 5e). Data are converted to thermal time (GDD) using the GDD model (T_{base} = 10 C).
(3) Chemical treatments are applied according to the GDD model (Figure 5, step 4). Prophylactic chemical treatments with sulfosulfuron at 200, 400, and 600 GDD as required (one treatment at 200 GDD for low infestation level, two or three treatments for medium or high infestation levels at 400 GDD and 600 GDD, respectively).
(4) Post attachment imazapic treatments—this treatment may be phytotoxic to tomato, deforming young fruit if applied at the fruit-set stages. Therefore, imazapic can only be safely applied on tomato foliage from 45 d before harvesting (the time required for tomato to ripen from fruit set to full ripening) or later (Figure 5, steps 5, 6). After harvesting tomato, an evaluation of success of the control, which will be stored as field history and will be used next year, is required (Figure 5, step 8).

Additional information that might contribute to the detection of Egyptian broomrape infection during the growing season can be acquired by thermal imaging (Figure 5f). It may be hypothesized that the crop's response to parasitism is characterized by water stress, as a result of increasing leaf temperature. We propose that thermal imaging, conducted after Egyptian broomrape has parasitized tomato according to the thermal time model (Eizenberg et al. 2009a), will reflect the spatial distribution of Egyptian broomrape in the field. It would be a mistake to base the decision on where to apply herbicides only on this technology, but it can contribute essential information during the season. This approach is now under development and initial results looks promising (unpublished results).

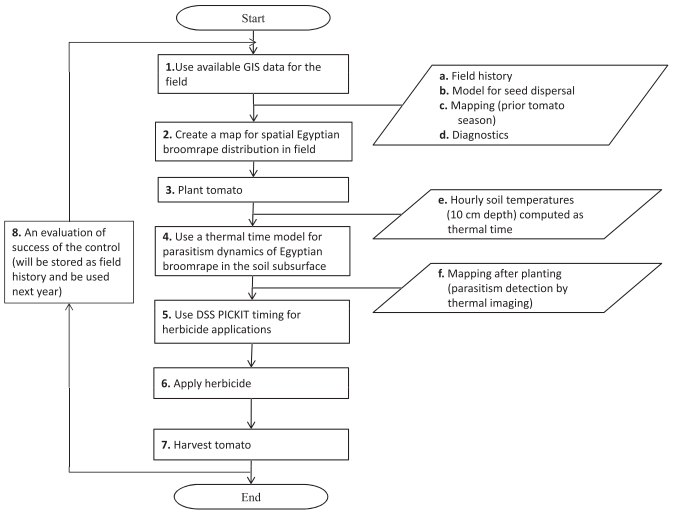

Figure 5. A flow chart of the use of technology for precision control of Egyptian broomrape in tomato in the fields. The protocol is based on the DSS PICKIT and the technology (a–f) is applied between key steps (1–8) to maximize the system's precision.

The DSS PICKIT was validated under field conditions using a minirhizotron camera (Figure 2) and yield measurements, and will be further evaluated and adjusted under commercial processing tomato field conditions in the coming years. All of the mentioned technology components will be integrated into PICKIT.

Further Research Using New Technologies

Many protocols and technologies have been introduced for nonparasitic weed detection. These should be adopted or modified for the detection and mapping of parasitic plants. Regional and field-scale GIS databases, including the field's history and other parameters as described above, should be logged and algorithms for DSS, seed dispersal, and weed patches, on the basis of those databases, should be developed.

Detecting PRE parasitism, when herbicide can be applied, is essential. As already noted, this can be achieved by the use of a thermal camera that can detect leaf temperature. The probability that parasitism will be detected by this methodology alone is low, but we hypothesize that it could be significantly increased when combined with the thermal time model. Both technologies can be used in a complementary way and contribute to the precision of the detection.

Three prediction models have been developed using thermal time for the parasitism of Egyptian broomrape in tomato, sunflower broomrape in sunflower, and small broomrape in red clover. The common factor in these examples is that none of the crops was exposed to water stress, either because the crops were irrigated or grew during the rainy season, enabling the use of thermal time as a robust parameter to predict parasitism dynamics (Eizenberg et al. 2005a, 2009a,b; Ephrath and Eizenberg 2010). However, with crops grown in dry soil, parasitism dynamics can be affected by water stress and soil moisture as reported under

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temperature- and moisture-controlled conditions (Kebreab and Murdoch 1999), and in the field in faba bean and common vetch (*Vicia sativa*) (Grenz et al. 2005; Perez-de-Luque et al. 2004), in chickpea (*Cicer arietinum*) (Rubiales et at al. 2003), and in tobacco (*Nicotiana tabacum* L.) (Karkanis et al. 2007). Therefore, the modeling approach should be extended to other crops and be adopted to dry conditions.

Although we did not discuss the induction of herbicide resistance in crops, it warrants mentioning here as a promising approach.

Conclusions

As the cost of technology drops (or its availability increases), and at the same time the cost of agricultural investment increases, precision agriculture, and specifically SSWM, becomes a cost-effective approach. Since broomrape is a root parasite, which is hard to control because it grows in the soil subsurface, the use of new technology has an added value for its detection. For instance, the minirhizotron camera enables the nondestructive observation of root parasites in situ, which can be useful for developing models of parasitism dynamics. As a result of introducing new technology, the efficacy of chemical control has increased over the last three decades. Using advanced technology has contributed to our understanding of the dynamics of parasitism and has allowed us to predict particular events that might be targets for control. Today, the use of chemical control for parasitic weeds should take into consideration precision agriculture techniques for herbicide application at the optimal timing and precise location. Other technologies include cameras (multispectral, hyperspectral, or thermal) that can serve in developing protocols for postattachment parasitic weed detection as a complementary means to the thermal time model. Later detection of shoots might also assist in controlling broomrape and preventing seed dispersal (but not the damage it has already caused). All protocols for broomrape detection include historical field data, and diagnoses should be stored and analyzed in a GIS; then a DSS can be applied for optimal herbicide applications.

Therefore, efforts in research should be concentrated in the development of an integrated approach on the basis of state-of-the-art technologies that were mentioned in this paper. These technologies include diagnosis, decision support system for smart chemical management, development of resistant varieties (both for herbicide resistant or broomrape–host resistant), modeling approaches, and GIS, as well as education and prevention, which will increase support for the chemical control approach. Recently, integrated projects have been initiated at the Rice Center and NARS of Benin and Tanzania, and in Israel. Those projects were presented at the 11th World Congress of Parasitic Plants in 2011 (Eizenberg et al. 2011; Rodenburg et al. 2011).

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