Comprehensive Disease Survey of U.S. Sunflower: Disease Trends, Research Priorities and Unanticipated Impacts

Thomas Gulya,¹ Robert Harveson,^{2,†} Febina Mathew,³ Charles Block,⁴ Sue Thompson,⁵ Hans Kandel,⁶ Duane Berglund,⁷ John Sandbakken,⁸ Larry Kleingartner,⁹ and Samuel Markell^{10,†}

¹USDA-ARS (retired), Sunflower Research Unit, Fargo, ND, USA;

²Panhandle Research and Extension Center, University of Nebraska, Scottsbluff, NE, USA;

³Dept. of Plant Science, South Dakota State University, Brookings, SD, USA;

⁴Seed Science Center, Iowa State University, Ames, IA, USA;

⁵University of Southern Queensland, Toowoomba, Qld, Australia;

⁶Dept. of Plant Science, North Dakota State University, Fargo, ND, USA;

⁷Dept. of Plant Science (retired), North Dakota State University, Fargo, ND, USA;

⁸National Sunflower Association, Mandan, ND, USA;

⁹National Sunflower Association (retired), Mandan, ND, USA;

¹⁰Dept. of Plant Pathology, North Dakota State University, Fargo, ND, USA

Sunflower (*Helianthus annuus* L.) is an important food, fuel, and ornamental crop that is grown in dozens of countries on six continents. Sunflower is unique in that it is commercially produced as three different crops, all bred for different purposes. The majority of sunflower acreage in the U.S. is planted to oilseed sunflower. Oilseed hybrids are bred to have 40 to 50% oil content, and the oil is currently predominantly composed of oleic acid, in contrast to the high linoleic acid content of oilseed sunflowers of the last century. The second largest acreage of the U.S. sunflower is confection, bred for use in snack foods, breads, and candies. Lastly, sunflower is also a very important ornamental plant, widely used for both cut flowers and bedding plants. While the actual acreage of ornamental sunflowers is small, their value is very high.

Unlike many crops produced in the United States, the center of origin of sunflower is North America. Sunflower was initially domesticated and grown by Native Americans centuries ago (Heiser 1951; Smith 2014). However, commercial production of sunflower in the United States is a relatively recent development. Hybrid sunflowers have only been on the market since the mid-1970s, with open-pollinated varieties of foreign origin grown previously (Putt 1997). Oilseed and confectionary sunflower production expanded rapidly throughout the Great Plains until the acreage stabilized at approximately 0.8 M Ha annually in the 2000s.

[†]Corresponding authors: R. Harveson, E-mail: rharveson2@unl.edu; and S. Markell, E-mail: samuel.markell@ndsu.edu

Funding: We acknowledge the USDA National Institute of Food and Agriculture, North Central IPM Center project AG 2014-70006-22486 for supporting the Sunflower Pathology Working Group, without whom this manuscript would not have been created.

Accepted for publication 12 November 2018.

Sunflower is susceptible to many yield-limiting diseases, which are largely caused by pathogens that have coevolved with sunflower for thousands of years in North America and often infect and survive on other *Helianthus* spp. (wild sunflowers), which are ubiquitous throughout the Great Plains (Harveson et al. 2016b). In the early 2000s, the National Sunflower Association initiated a rigorous effort to better understand the importance of diseases and other factors limiting sunflower production in the United States. In this feature article, we report on the importance, implications, and impacts of one of the most comprehensive crop disease surveys ever done in modern agriculture, and five of the most important diseases: downy mildew, *Phomopsis* stem canker, rust, *Rhizopus* head rot, and *Sclerotinia* head rot.

Historical Background of Sunflower Surveys in Europe and North America

Surveys of crop production are commonly conducted by governmental agencies, commodity groups, and university researchers. Often, surveys have a narrow geographic focus, a short time frame, and/or may be limited to examining yield or few production factors. In Europe, where a long history of modern sunflower production exists, multicountry disease surveys started in the late 1970s (Sackston 1978) and continued intermittently through the 1980s (Acimovic 1979, 1989). The input for these broad disease surveys was the subjective observations of pathologists in their respective countries, but no numerical data were recorded. In the 1980s and 1990s, plant pathologists in several countries published more rigorously disease surveys in their specific countries (Bhutta et al. 1993; Mirza and Beg 1983; Vicente and Zazzerini 1997; Zazzerini 1981; Zazzerini et al. 1987). These surveys were also conducted intermittently, and assessment of region-wide impact of diseases was difficult because a standardized format was not used.

Sunflower disease surveys in Canada also predate work done in the United States. The first Canadian disease survey was initiated by W. E. Sackston, often referred to as the “Father of Sunflower Pathology” (Harveson et al. 2016b). His first published survey

documented the status of diseases in the Manitoba sunflower crop (Sackston 1949) and provided a framework for subsequent surveys (Hoes and Huang 1976; Hoes and Putt 1963; Sackston 1954, 1957). These surveys examined the incidence of all sunflower diseases observed in the fields. Between 1989 and 2017, a robust annual sunflower disease survey was conducted in the province of Manitoba, where the majority of Canadian acreage is produced (Rashid 1989; Rashid et al. 2017). Approximately 40 to 60 sunflower fields were scouted annually in late September as the sunflower crop was maturing. Generally, prevalence and severity (using severity scales) of five to six major diseases were recorded. These surveys produced consistently collected and rigorous data in the province.

In the U.S., the first extensive sunflower disease survey was done in 1984 and concentrated on North Dakota, South Dakota, and Minnesota, where the majority of the U.S. production was located. Surveyors examined over 160 fields in 2 weeks and documented the prevalence and severity of 10 major diseases. The survey was very labor- and coordination-intensive and was not repeated until 1991 and 1995 (Gulya 1996).

Fig. 1. Location and year of sunflower fields surveyed from 2002 to 2015 in the United States.

In response to growing acreage nationally and the laborious nature of conducting a physical survey of sunflower fields across the U.S. Great Plains, the next widespread sunflower survey efforts were based on questionnaires and grower responses (Lamey et al. 1992, 1999). Between 4,000 and 8,000 questionnaires were distributed to sunflower growers using the *Sunflower* magazine mailing list (published by the National Sunflower Association, Mandan, ND). In the first year, only growers in North Dakota were contacted, but in later years, the surveys were sent to growers in North Dakota, South Dakota, Minnesota, and Kansas (Lamey et al. 1992, 1999). The questionnaires were broad in scope, and were designed to collect data about insect, weed and disease problems, and pesticide use. Growers were specifically asked to list the worst disease problem (out of nine choices), estimate the percent lodging due to *Sclerotinia* diseases, and estimate the incidence of *Sclerotinia* head rot. Approximately 7 and 15% of those questionnaires were returned annually and detailed reports were distributed (Lamey et al. 1999).

While information was collected in all disciplines, the disease data were considered the least useful and reliable. Few fungicides were labeled in sunflower and the identification of diseases tends to be more challenging than the identification of other pests, such as weeds. Accurate disease identification was further compromised because many sunflower growers were relatively unfamiliar with the “newer” crop and there was a near total absence of extension material on sunflower diseases in most sunflower-growing states. However, data from previous questionnaire-based surveys by Lamey et al. (1992, 1999) made it clear that diseases had an impact on yield, although it was not always clear which diseases.

Development of a Comprehensive Survey

In 2001, the National Sunflower Association (NSA) made more robust identification and quantification of yield-limiting factors a national priority. The strategy was to develop a comprehensive survey where in-field assessments were made by qualified “experts,” and on a national scale. To accomplish this, several obstacles needed to be overcome. First, the vast tract of land in the United States cultivated with sunflowers presented a logistical challenge. Sunflower was, and continues to be, a field crop with relatively limited acreage (<1 M Ha) that is spread across the U.S. Plains states over 2,000 km from southern Texas to northern North Dakota. Second, very few agriculture professionals in either the public or private sectors were dedicated specifically to sunflower. Historically, three midwestern land grant universities (North Dakota State University, South Dakota State University, and the University of Minnesota) had pathologists assigned part-time to sunflower in the early 1980s, but each of those positions was soon lost or reassigned. Similarly, only one seed company employed a pathologist to work on sunflower, and that position was later eliminated. By the 1990s, there was only one full-time publicly employed sunflower pathologist in the U.S., located at the United States Department of Agriculture – Agriculture Research Service (USDA-ARS) in Fargo, ND. Consequently, the majority of sunflower pathology work was done by a small group of professionals (largely extension plant pathologists) who have split responsibilities with crops of higher acreage in their respective states such as wheat (*Triticum aestivum* L. emend. Thell), soybean (*Glycine max* L. Merr.), corn (*Zea mays* L.), dry edible bean (*Phaseolus vulgaris* L.), canola (*Brassica napus* L.), etc. This combination of factors created a void of expertise and educational resources from which to draw on; a further obstacle to realizing the new vision for the survey.

In response, a concerted effort to recruit and educate numerous agricultural professionals from seed, chemical, and oil crushing companies, USDA-ARS researchers, university research and extension personnel, and other agronomists to volunteer in the survey. Volunteers were divided into teams of two to four individuals, based on both expertise and geography. For example, to fill a sunflower survey team in northwest Minnesota, a botanist from the USDA in Fargo (with weed experience), an agronomist from a seed company located in northwest Minnesota with insect experience, and a pathologist from southeast North Dakota might be teamed together. Despite this,

expertise in one or more needed disciplines was often limited on teams and the development of robust training for surveyors was critical.

In the early years of the survey, volunteers were personally trained by a team of instructors, generally consisting of an agronomist, weed scientist, entomologist, and plant pathologist. The instructor teams traveled to selected sites in North Dakota, South Dakota, Kansas, and Texas to conduct one-day short courses, which included both lectures and in-field hands-on demonstrations. Extension materials designed for disease diagnosis and academic reference materials (including photographs) supplemented the short courses, but were severely limited in the early years of the survey and did not include all diseases (Berglund 2007, Cholik 1999). In subsequent years, the need for short courses was less critical and done less frequently as experienced volunteers often surveyed for many years. Additionally, short courses were later complimented by webinars on multiple topics, such as yield measurements, disease diagnostics, and insect identification. In the later years of the survey, extension publications were distributed at short courses and made available online (Friskop et al. 2009, 2011a; Harveson 2010b, 2011a, b, 2013; Harveson et al. 2012b, c).

In 2001, the new survey was conducted for the first time, but limited to North and South Dakota. One field for every 2,023 ha (5,000 acres) of sunflower planted was surveyed across the two states. Division of fields was made by county, and if less than 2,023 ha were planted in a single county, the effort to combine two low-acreage counties together and survey one field among them was made. For example, if county A planted 8,100 ha of sunflowers and counties B and C planted 1,000 ha each, surveyors would arbitrarily select and survey four sunflower fields in county A and one field in either

county B or C. As the survey was primarily designed to identify yield-limiting factors and estimate yield loss, the timing of the survey was in the latter half of September or early October when the sunflower crop was near harvest. In the first year, 406 fields were examined by trained surveyors.

Once a field was selected to be surveyed, surveyors would select two sites within the field. Sites were determined by each survey team and selected as most representative of the entire field. When fields were variable, surveyors attempted to capture that variability by representative site selection, such as a “good and bad” site, or a “wet and dry” site. The identification of diseases, weed species, insects, bird damage, and estimates of yield were all recorded by consistent and rigorous evaluations in each site.

The diseases included in the 2001 survey were *Sclerotinia sclerotiorum* diseases (wilt, midstalk rot, and head rot), *Phomopsis* stem canker, “premature ripening,” *Verticillium* wilt, charcoal rot, *Rhizopus* head rot, rust, and downy mildew. Premature ripening was a general term of nonspecific causal agent until *Phoma macdonaldii* was implicated (Donald et al. 1987). Root rots were not included in this survey largely due to the timing of the survey was conducted. Except for rust, foliar diseases were not included as they are rarely economically important in the United States and are difficult to identify at later growth stages and after frost.

To determine disease pressure at each site, surveyors marked out two specific areas that included 50 sunflower plants (25 in each of two adjacent rows). For all diseases except rust, incidence was recorded by calculating the number of sunflower plants infected with each disease. Data were recorded primarily by visual examination of the plants, but destructive sampling was commonly done for confirmation of disease presence, such as charcoal rot. While the severity of damage by each of

Fig. 2. Location and year of sunflower fields surveyed from 2002 to 2015 in North Dakota and Minnesota.

these was not specifically recorded, surveyors would make notes if severity of any disease was high enough to cause meaningful yield loss. For rust, severity was recorded by visually estimating the severity on the upper four fully expanded leaves on each plant, with the aid of disease assessment diagrams (Friskop et al. 2015b).

In 2001, the data generated from the survey provided much better identification and quantification of the disease pressure than either questionnaire-based or the localized efforts that had been done in the past. Building on this success, the NSA made the survey a national event beginning in 2002.

The National Sunflower Survey: 2002 to 2015

With the exceptions of 2004, 2014, and 2016, the survey was conducted annually from 2002 to 2017 (2017 data not presented). The number of states surveyed increased from two in 2001 (North Dakota and South Dakota) to seven (North Dakota, South Dakota, Minnesota, Kansas, Nebraska, Colorado, Texas) plus the adjacent Canadian province of Manitoba. These seven U.S. states annually plant 95 to 98% of the total U.S. sunflower acreage (Sandbakken 2017). Survey techniques, methods, and the data collected were essentially the same as described in 2001, but with several important modifications. In 2003, the number of fields surveyed was reduced from one field per 2,023 ha planted to one field per 4,046 ha (10,000 acres) planted. Also in 2003, new agronomic data were added to the survey, including irrigation (yes/no), row width, tillage practices, previous crop, and sunflower type (oil versus confection). In 2006, surveyors began recording data on *Phoma* black stem. Additional assessments in other disciplines were added as well (for example, regionally important or emerging pests of concern).

After the 2013 survey was complete, the decision was made to continue the survey every odd year. The decision to conduct the survey every other year was made for several reasons, one being the high intensity of labor and time involved in an annual survey. An important second reason was that sunflower pathologists were responding to outbreaks of the most economically important diseases. Beginning in 2011, intense disease-specific surveys that examined *P. helianthi* (causal agent of rust) races (Friskop et al. 2015a), *Diaporthe* species prevalence (causal agents of *Phomopsis* stem canker) (Mathew et al.

2015), and both races and fungicide sensitivity of *Plasmopara halstedii* (causal agent of downy mildew) (Gilley et al. 2016, 2017) were conducted.

From 2002 to 2015, a total of 2,267 fields were surveyed across seven states (Fig. 1). While this number of fields surveyed is very high, fields from some states (Nebraska and Texas) were not surveyed every year, due to the varying number of acres planted and the availability of trained surveyors to conduct the survey. Since disease occurrence is more a factor of geography and climate than political borders, the data from adjacent states were combined to better illustrate the regional differences, namely North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP), and Texas (TX) (Figs. 2, 3, 4, and 5). North Dakota and the sunflower growing area of Minnesota (extending roughly less than 150 km east of the North Dakota border) have consistently led the U.S. in sunflower production and experience cooler mean summer temperatures and a shorter growing season than the other regions. It is notable that a west (drier) to east (wetter) rainfall gradient occurs across the roughly 700 km wide region and nearly all sunflowers are in rain-fed production (nonirrigated). Of the 1,117 fields surveyed where data on dry land or irrigation was recorded in the ND/MN region (Fig. 2), only 1.2% of the surveyed fields were irrigated throughout the period of this survey. Sunflower production and surveyed fields in SD are heavily concentrated in the center part of the state (Fig. 3). Daily high temperatures in SD are higher than in ND/MN, although the vast majority of sunflowers surveyed in SD were still produced without any irrigation (98.9% of surveyed fields). Sunflower production and surveyed fields in the CHP are concentrated in eastern Colorado, western Nebraska, and western Kansas (Fig. 4). The summer temperatures of the region are higher than in the two northern regions and sunflowers are grown under both rain-fed and irrigated conditions. Of the 225 surveyed fields in the CHP with dry land or irrigation data recorded, 42% were irrigated. In TX, sunflower production and surveyed fields are concentrated in the northwest part of the state (Panhandle), but a notable number of fields in east and far southeastern TX were surveyed in the latter years of the survey (Fig. 5). Summer temperatures in TX are higher than all the other regions, and the majority (63%) of sunflower fields were irrigated.

Fig. 3. Location and year of sunflower fields surveyed from 2002 to 2015 in South Dakota.

In this manuscript, data are presented as prevalence, incidence, and severity (rust only). We define prevalence as the percent of fields where a specific disease occurs. For example, the prevalence of downy mildew in SD in 2011 is 17% because downy mildew is present in 17% of the fields in SD in that year. We define incidence as the percent of plants in a field that are infected by a pathogen. For example, incidence of downy mildew in SD in 2011 is 5%, because in fields where downy mildew occurred in SD in that year, 5% of the plants surveyed in those fields were infected. For rust only, we define severity as the amount of pustule coverage on the upper four leaves, which are those leaves primarily responsible for seed fill, and thus most critical to any potential disease-induced yield loss. For example, rust severity in 2010 in the CHP is 4.3%, because in fields where rust occurred in that region in that year, the damage to the upper four fully expanded leaves in sunflower fields was estimated to have a severity value of 4.3% using disease assessment diagrams (Friskop et al. 2011a).

The prevalence, incidence, and potential economic damage of all 10 diseases surveyed are widely variable by region and year. However, five diseases, downy mildew, *Phomopsis* stem cankers, *Rhizopus* head rot, rust, and *Sclerotinia* head rot, are considered to be the most impactful diseases surveyed in this time period. Thus, we focus the interpretation, findings, and auxiliary benefits of the survey on these five diseases.

Downy Mildew

Downy mildew of sunflower is caused by the obligate, soilborne, oomycete pathogen *Plasmopara halstedii* (Farl.) Berl. and de Toni. It is an economically important seedling disease that occurs on sunflower and many other genera in the family Compositae. Cool (10–15°C), wet

soil conditions after planting are optimum for infection. However, yield losses vary from year to year depending upon several factors, including incidence and distribution of the pathogen, percentage of plants infected in the field, and weather conditions. When downy mildew occurs in patches, yield losses in those areas may approach 100%, but when downy mildew occurs sporadically, surviving plants often compensate for those that die prematurely after early infection (Harveson 2011a; Humann et al. 2016c).

Signs and symptoms of downy mildew can be broadly categorized into two major groups based on symptoms and time of infection. Systemic infection occurs when the roots of young seedlings are infected by *P. halstedii* zoospores, often resulting in plant death (Friskop et al. 2009; Harveson et al. 2012a; Humann et al. 2016c). If seedlings survive, they are severely stunted (Fig. 6) and chlorosis is associated with leaf veins but can also cover entire leaf surfaces (Fig. 7). Extended periods of high humidity and cool temperatures (<18°C) enhance the development of white cottony growth (zoosporangia) on the underside of infected leaves. Secondary foliar lesions may occur when windblown zoosporangia from other infected leaves land on dew-covered sunflower foliage, but these localized foliar lesions are rarely economically important (Friskop et al. 2009; Harveson 2011a).

Throughout the 12 years the survey was conducted, the prevalence of downy mildew was consistently as high or higher in ND/MN than in any other region (Fig. 8). The prevalence in ND/MN was approximately 40% in 2005 and 2011 and 20% in 2007, 2008, 2009, and 2015. While prevalence varied greatly in ND/MN, incidence in fields was relatively consistent, with a range of approximately 3 to 12% (Fig. 9). Prevalence never exceeded 13% in any other region in

Fig. 4. Location and year of sunflower fields surveyed from 2002 to 2015 in the Central High Plains of Colorado, Kansas, and Nebraska.

any year, except for TX in 2007. It is notable that this was the only year downy mildew was identified in TX.

While water (rain or irrigation) after planting is critical for infection, soil temperature at planting may more likely explain the differences in downy mildew prevalence among regions. Downy mildew rarely occurred in TX and was consistently low in the CHP despite most surveyed fields in TX and a large minority of fields in the CHP regions being irrigated. This is likely due to soils in this region being warmer than those in ND/MN at planting. In fungicide field trials conducted from 2011 to 2015 in ND, where adequate moisture was provided through drip irrigation, downy mildew failed to develop only when high temperatures occurred immediately after planting and inoculating (Humann et al. 2016a). Similarly, Gulya et al. (2013) found no correlation between ND rainfall totals between 15 May and 15 June (approximate sunflower planting time) and downy mildew prevalence from 2001 to 2011.

The prevalence and incidence of downy mildew in this survey is likely an underestimate of actual disease pressure in all regions. Previously, Gulya et al. (2013) compared downy mildew prevalence

data generated from two different surveys conducted at different times in the growing season in ND from 2001 to 2011: this current survey (which was conducted at the end of the season) and the NDSU-Integrated Pest Management (IPM) Mid-Season Survey (conducted from emergence to early reproductive stages of sunflower growth). Gulya et al. (2013) found prevalence to be approximately twice as high in the midseason survey, because many infected plants that were visible during the growing season were dead and no longer present/visible when the current survey was conducted later in the season. Consequently, the impact of downy mildew on sunflower yield was also thought to be underestimated in the late season survey between 2001 and 2011. Considering this information, it is likely that actual downy mildew prevalence and incidence in all regions in this current survey is proportionately higher.

Sunflower Rust

Sunflower rust, caused by *Puccinia helianthi* Schwein., occurs worldwide on cultivated sunflowers (oil and non-oil types), ornamentals, and wild *Helianthus* species. When conditions are favorable

Fig. 5. Location and year of sunflower fields surveyed from 2002 to 2015 in Texas.

for disease development (8+ hours of free moisture and temperatures of 15 to 25°C), significant losses (up to 80%) in both yield and seed quality (size, test weight, and oil content) can occur (Markell et al. 2009, 2015a). *P. helianthi* is an autoecious rust with five distinct spore stages in its life cycle, which enhances the opportunity for

Fig. 6. Severe stunting of sunflower plants due to systemic infection from the downy mildew pathogen.

Fig. 7. Large chlorotic areas of leaves of a systemically infected sunflower plant.

frequent sexual recombination events and earlier disease onsets (Friskop et al. 2011a; Harveson 2010b; Harveson et al. 2012b).

Four out of the five spore stages are macroscopically visible on the sunflower host (Friskop and Markell 2016). The earliest visible sign of this pathogen are flask-shaped pycnia, yellow-orange spots (approximately 6 mm or less) on the upper side of the cotyledons or leaves and may be surrounded by a chlorotic halo. Aecia will appear directly opposite the pycnia on the underside of the leaf (Harveson 2010a, b). Aecia are collections of small orange to yellow cups producing aeciospores and are approximately the same size as the pycnia. One to two weeks after aeciospore infection, the rust-colored uredinial pustules are formed (Fig. 10), giving the disease its name. The uredinia are the most recognizable sign of the pathogen and can occur on leaves or other plant organs (bracts, petioles, and stems). Urediniospores are also called “repeating spores” since they are the only spore state which can reinfect sunflowers that same growing season. The repeated infection can quickly result in an epidemic. Suboptimal low temperatures and host maturity will initiate the change from uredinia to telia. Telia are coal-black (Fig. 11), producing teliospores that overwinter in plant residues and serve as an inoculum source the next season (Friskop et al. 2011a; Humann et al. 2016c).

Of the five surveyed diseases discussed, rust had the highest prevalence over the entire survey (Fig. 12). Prevalence in each region commonly exceeded 50%, and in some years, it occurred at a far higher level. The lowest levels of rust nationally occurred in two periods; 2002–2003 and 2011–2012. Both periods were characterized by droughts. While variation occurred, rust prevalence in ND/MN, SD, and the CHP trended similarly from 2006 to 2015, except for low levels in SD in 2008 and 2009.

Rust severity only exceeded 4% four times; in TX and ND/MN in one year each and in the CHP in two years (Fig. 13). The highest rust severity recorded in the survey was in the CHP in 2015. This is largely a result of three surveyed fields in NE experiencing a very severe epidemic (severity of approximately 20%), while the remaining fields had severity levels less than 2%. Rust severity was relatively high in ND/MN from 2007 to 2009 and in 2009 in SD and the CHP. The high levels of rust severity followed a remarkable increase in overwintering of the pathogen in 2008. Markell et al. (2009) reported that of fields where rust occurred in 2008, by mid-July in ND and MN, aecia were observed in 56% of those fields. In NE, both pycnia and aecia (Fig. 14) were observed in 85% of fields that were surveyed (Harveson 2010a). Prior to this, these early spore stages were rarely observed and never reported widespread in either region.

Fig. 8. Prevalence of downy mildew from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

In fields where rust overwintered, a rust epidemic could begin much earlier as the inoculum source was local and did not have to blow in from other fields. In some cases, rust infection occurred early enough to infect cotyledons. The early onset of infection exacerbates end of season severity and helps explain the high severity observed in those regions in 2009.

The relatively high rust severity and high prevalence likely caused widespread, but unclear levels of yield loss in 2009. Friskop et al. (2015b) examined the impact of rust severity on yield in a series of sunflower rust fungicide trials in ND. Of eight trials where rust reached or exceeded 5% at growth stage R7 (the approximate time of survey), a statistically significant reduction in yield due solely to rust occurred in four of them. Notably, yield loss occurred in others but other limiting factors contributed to that yield loss. Similarly, in those same data sets, they found that for every 1% increase in rust severity, yield at R7 was reduced by 6.6%. While mean rust severity in the survey rarely reached 5% in any region, severity exceeded 5% in many individual fields, and it is possible yield loss occurred at severity levels less than 5%. The relationship between rust and yield was similar in 2009 when a severe natural epidemic occurred in hybrid performance trials in Carrington, ND (Friskop et al. 2011b). In an oilseed performance trial with 75 hybrids, yields of hybrids with zero rust were approximately 1,600 kg/ha, but rust severities of 5, 10, and 20% correlated to yields of 1,300, 1,000, and 450 kg/ha ($r = -0.639$, $P < 0.0001$). It is notable that the same methods to estimate severity used in both studies are used in this survey.

After the 2009 epidemic, the widespread use of tools to manage rust likely had a major impact on the reduced rust severity in years that followed. Pesticide use data are surveyed every 4 years in ND. In 2004, data on foliar fungicide use was not recorded in ND on sunflower and thought to be very low (Zollinger et al. 2006). In 2008, a foliar fungicide was applied on 24.7% of ND sunflower hectares (Zollinger et al. 2009), largely because of an emergency pesticide exemption (Section 18) being granted for rust control in response to the epidemic. In 2012, a foliar fungicide was applied on 35.3% of sunflower hectares (Zollinger et al. 2014). Although data are not available, it is widely believed that growers also planted more rust-resistant hybrids following the 2009 epidemic.

Sclerotinia Head Rot

Sclerotinia sclerotiorum (Lib.) de Bary is a common soilborne fungus that is considered the most serious sunflower pathogen in temperate regions worldwide. It is capable of infecting roots, stems, buds, and heads; it survives in soil for many years while also

possessing a large host range of more than 360 plant species, belonging to 225 genera in 64 families (Gulya et al. 1997; Harveson 2011b; Harveson et al. 2012c). The pathogen's impact on yield is determined by the type of disease observed, and the plant growth stage at the time of infection. It can cause three different diseases: 1) wilt and basal

Fig. 10. Reddish-brown colored uredinial pustules.

Fig. 11. Black colored telial pustules on an infected leaf.

Fig. 9. Incidence of downy mildew from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

stalk rot; 2) midstalk rot; and the most damaging and important 3) head rot (Harveson 2011b, Rashid et al. 2016).

The pathogen overwinters in soil as sclerotia, surviving for 3 to 7 years, and their viability is controlled by several factors including soil moisture, temperature, and soil type. Wet soil conditions and high temperatures $>27^{\circ}\text{C}$ are detrimental to survival, while dry soils at 5°C are favorable for sclerotia survival and viability. Infection occurs in two distinct disease phases depending on the method of germination of the overwintering sclerotia. Mycelial germination produces mycelia that can directly infect the roots causing root rot, basal stem rot, and wilt of the sunflower plant (Fig. 15). Germinating sclerotia can also produce apothecia (Fig. 16) and ascospores that become airborne, infecting sunflower heads and stems, which results in head rot and midstem infection and breakage (Gulya et al. 1997; Rashid et al. 2016).

Sclerotinia head rot may cause partial or total yield losses when infection occurs during early flowering. Yield losses of 10 to 20%

are commonly reported in most years; however, incidences of head rot epidemics of up to 80% have been observed (Rashid et al. 2016). Head rot also affects the seed quality by reducing the seed oil content by 10 to 15% and increasing free fatty acid content, leading to rancidity. Disease incidence and severity vary from year to year and region to region based on soil moisture levels and environmental conditions that promote apothecial formation and ascospore production that coincides with the different stages of the crop growth.

Initial symptoms of head rot consist of dark, water-soaked spots on the back of the head or white mycelial growth appearing on the developing seeds on the floral side. As disease progresses, a rot occurs on the interior of the head filled with irregularly shaped sclerotia. Infections eventually result in complete disintegration of heads, leaving nothing but frayed vascular elements resembling a broom head (Fig. 17). Severely infected heads will fall to the ground.

Prevalence of Sclerotinia head rot was much higher in the ND/MN region than any other region, with a mean prevalence of approximately

Fig. 12. Prevalence of rust from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

Fig. 13. Severity of rust from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

29% over the course of this survey (Fig. 18). Remarkably, while prevalence exceeded 10% in ND/MN every year, it exceeded 10% in SD and TX in only two years and the CHP once. Incidence was highest in ND/MN and SD, and never exceeded 5% in TX and the CHP regions (Fig. 19).

The stark contrast in prevalence and incidence among regions is heavily related to midsummer temperatures. While high temperatures in July and August are commonly below 30°C in ND, they consistently exceed that in the CHP and TX, and frequently exceed that in SD, making infection less likely in those regions as temperatures commonly exceed the optimum for ascospore germination.

As a result of a wide infection window and sensitivity to climatic conditions, a dramatic range of infection severity can occur with *Sclerotinia* head rot, ranging from localized damage to completely shredded heads. Consequently, with only prevalence and incidence data, it is difficult to estimate yield loss from data acquired in this survey.

Rhizopus Head Rot

Rhizopus head rot is caused by several species in the genus *Rhizopus*, including *R. stolonifer* (Ehrenb.) Vuill and *R. oryzae* (syn. *R. arrhizus*) Went and Prisen Geerlins. These species may occur singly or in a complex, and all are found naturally occurring in soil or as a common airborne contaminant. It is a sporadic, but often destructive disease, commonly posing a serious threat to production in the CHP of the U.S. Under the right environmental conditions, it can cause up to 100% losses in severely affected fields (Harveson 2013, 2016a).

Economic losses and yield damage are not well understood, but recent studies in NE, SD, and ND have estimated yield losses as high

as 40% in inoculated plots (Harveson et al. 2018b). Losses are additionally highly dependent upon several primary factors including the number and severity of wounds, a humid environment, and the age of the plants at time of infection. Mechanical injury of some form (damage from hail, birds, or insects) is required to open wounds on the backs of ripening heads. After infection takes place, the disease will become more severe in warm, humid environments, particularly under irrigation.

Symptoms of disease first appear on the backs of heads as dark spots of varying sizes as a result of some type of wound, followed by a watery, soft rot that later dries and turns dark brown. As disease progresses, heads dry prematurely, shrivel, and tissues become shredded (Fig. 20). *Rhizopus* head rot is distinguished from *Sclerotinia* head rot by the grayish fuzzy mycelial growth on the flower side of the head (Fig. 21) (Harveson 2016a; Harveson et al. 2012c).

Fig. 14. Early rust spore stages – pycnial (left), aecial (right).

Fig. 16. Apothecia emerging from buried sclerotia.

Fig. 15. Wilting sunflower plant due to the basal stem rot phase of *Sclerotinia* infection.

Fig. 17. Shredding and decapitation of a sunflower head due to *Sclerotinia* head rot.

In all but three years of the survey, prevalence of *Rhizopus* head rot in TX was higher than all other regions (Fig. 22). In nine of the 12 years surveyed, the prevalence in TX was 50% or greater. Conversely, the prevalence of *Rhizopus* head rot in ND/MN was less than 25% in all but two years, and never exceeded 40%. Prevalence levels in SD and the CHP generally fell between levels in ND/MN and TX. Like *Sclerotinia* head rot, the dramatic differences in prevalence are due to a summertime temperature gradient among the regions. However, whereas *Sclerotinia* head rot is favored by low summer temperatures, *Rhizopus* head rot is favored by high summer temperatures, although some differences among causal species exist.

While prevalence of *Rhizopus* head rot is very high in TX, incidence is generally lower than in other regions (Fig. 23). Over the 12 years of the survey, incidence in the CHP region was much higher than any other region. This may be in part due to the frequency of

hail-producing thunderstorms that are common during the summer in the CHP (Harveson 2013). Considering both prevalence and incidence across the regions, it is likely the greatest amount of yield loss occurs in the CHP.

Phomopsis Stem Canker

Phomopsis stem canker is a major yield limiting fungal disease worldwide. It was initially thought to be caused exclusively by *Phomopsis helianthi*, Munt.-Cvetk., Mihaljc. and M. Petrov. (syn *Diaporthe helianthi*). With new diagnostic methodologies, however, the disease has recently been shown to also be induced by a complex of *Diaporthe* spp., including more than 10 species recently identified in Australia (Thompson et al. 2011). In the U.S., *D. helianthi* and *D. gulyae* (R. G. Shivas; S. M. Thomps. and A. J. Young) are the most prevalent species (Mathew et al. 2015). Yield losses approaching 40% have been reported from

Fig. 18. Prevalence of *Sclerotinia* head rot from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

Fig. 19. Incidence of *Sclerotinia* head rot from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

commercial sunflower fields as a result of early *Diaporthe* infection (Masirevic and Gulya 1992; Thompson et al. 2011).

Symptoms may first be recognized as small, brown spots with yellow chlorotic margins at the edge of older leaves of the

Fig. 20. Sunflower head tissues rotted and shredded due to *Rhizopus* head rot.

Fig. 21. Grayish mycelial growth of the *Rhizopus* pathogen emerging on the flower side of an infected sunflower head.

sunflower plants during the early reproductive stage. The infection spreads from leaves through the petioles, eventually reaching the main stalk of the sunflower plant. Lesions on the stem develop on the stalks centered on the axils, appearing wet with a tan to brown color (Fig. 24). Lesions will increase in length often reaching 15 to 20 cm, and eventually girdle the stalk, whereupon plants wilt and lodge (Fig. 25). Infection causes the pith to degrade severely enough that stalk lesions are easily crushed with pressure (Markell et al. 2014).

Prevalence of *Phomopsis* stem canker has increased in all regions since the survey began in 2002 (Fig. 26). In the first six years of the survey (2002 to 2008), the mean prevalence of *Phomopsis* stem canker in TX, the CHP, SD, and ND/MN was 5, 15, 16, and 25%, respectively. However, the mean prevalence in the second half of the survey (2009 to 2015) was 7, 35, 50, and 56% in those same regions. In all regions but TX, mean incidence was approximately 20% throughout the course of the survey (Fig. 27).

Phomopsis stem canker has historically been considered one the most important diseases of sunflower in Europe, but until 2009, it was not considered a significant problem in the U.S. In 2009, localized areas of severe yield loss to *Phomopsis* stem canker occurred in the Dakotas and MN. Yield loss to the disease was not documented, but reports of entire seed company nurseries being destroyed or commercial fields being decimated occurred in northern MN. Given that *Phomopsis* stem canker was relatively uncommon prior to 2009 and stem diseases are often considered the hardest to identify on sunflowers, it is possible that disease prevalence and incidence were actually underestimated.

In response, the NSA made research efforts directed at understanding and managing *Phomopsis* stem canker a priority. As a result, a significant emphasis was placed on fungicide efficacy and timing and genetic management of the disease. However, one of the most important findings was that the disease was caused not only by *D. helianthi*, but also by *D. gulyae*, a pathogen not previously identified in the U.S. (Mathew et al. 2015). While it is likely that high levels of rainfall and persistent cool July temperatures in the Northern Great Plains exacerbated the disease in 2009, the existence of two species that appear to be managed by different genetics also contributed to the rise of *Phomopsis* stem canker in the U.S. (Mathew et al. 2018c).

Novelty of the Survey

This survey is unique and different from standard disease surveys in that it also assesses multiple aspects of sunflower

Fig. 22. Prevalence of *Rhizopus* head rot from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

production, not just disease evaluations. Data are also collected at each site includes insect damage, weed issues, estimates of plant populations, and yield potential of fields, based on agronomic characteristics and measurements. Novel impacts of the survey include educating graduate students and postdoctoral scholars, identifying research priorities, discovering new diseases, and assisting in the creation of new federal funding programs.

Impacts: Increasing and Distributing Sunflower Knowledge

First and perhaps most important was the discovery of the paucity of educational literature on sunflower diseases available. This also demonstrated the need for training consultants and field scouts to recognize and distinguish prominent diseases of sunflowers. Correct diagnoses are critical to making sound management decisions. The surveys have also served as a training tool for personnel associated with the sunflower business to better understand IPM strategies and recognize multiple production problems. Increasing the number of people trained for the surveys reduces the number of fields scouted by each team, increases the efficiency of the survey, and results in a better educated cadre of sunflower personnel, whether their initial job was research, production, marketing, or extension. It is difficult to estimate the number of non-pathologists trained for disease identification, but that number is likely well into the hundreds when considering the 12 years, broad geography, and many in-person short courses and webinars of the survey.

The lack of educational materials available for those in the industry was the driving force behind the creation of the Sunflower Pathology Working Group (SPWG), funded through the North Central IPM Center Working Group Program (funding provided through the U.S. National Institute of Food and Agriculture) (Markell et al. 2015b). The primary mission of the SPWG was to produce and distribute, through multiple sources, both extension and research-related literature pertaining to diseases in the sunflower crop. It initially began with four pathologists from North Dakota, Nebraska, and Iowa. The core group soon expanded to include another pathologist from South Dakota and one from Australia, and recruited the efforts of dozens of other scientists for specific outputs. In the span of 4 years, this small group of scientists has produced the Compendium of Sunflower Diseases and Pests (Harveson et al. 2016b), book chapters (Gulya et al. 2017; Markell et al. 2015a), as well as numerous novel and traditional extension-oriented publications including playing cards and diagnostic cards (Markell et al. 2017). In addition to the current feature article, this

group has published and is planning and drafting additional articles for Plant Health Progress (Harveson et al. 2018a) and Plant Health Instructor (Mathew et al. 2018a), and an interactive eBook, all focusing on diagnostics and education.

Fig. 24. Light brown lesion characteristic of Phomopsis stem canker disease.

Fig. 23. Incidence of Rhizopus head rot from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

Impacts: Research Priorities, Advances, and Graduate Students

Presentation of the NSA survey results is a significant part of the NSA Annual Research Forum, the national reporting session and highest attended conference of the NSA held in Fargo, ND, each

Fig. 25. Severe lodging of *Phomopsis* stem canker-infected plants near harvest.

January. Findings from the surveys have driven the priorities set by the NSA's research committee from the inception of the survey. These priorities then became the foci for research proposals addressing these issues funded by grower check-off dollars. These local dollars can then be leveraged to obtain federal and corporate funding.

While a direct result of the survey was the determination of future research priorities by the NSA, an indirect result was their investment in graduate student research projects, specifically designed to address epidemics observed in the survey. The first pathology graduate student project funded by the NSA was in direct response to the rust epidemics from 2008 to 2010. Results of those studies included the elucidation of most effective time period for making fungicide applications for optimal management and improved yields (Friskop et al. 2015b) and the registration of fungicides for use by producers (Friskop et al. 2018). Additional work conducted since then has included two additional graduate students working on fungicides to manage rust and genetics aimed at longer-term management of the disease (Berghuis et al. 2018; Friskop et al. 2015a; Humann et al. 2016b). A peripheral project that arose from the surveys was the finding of the early stages of rust (pycnial and aecial) in ND and NE in late spring (Fig. 14), suggesting overwintering of the pathogen from their locations of discovery (Harveson 2010a; Markell et al. 2009). This was a supposition not previously proven, and helped explained the sudden increase in rust epidemics.

Following the success of the first NSA-funded graduate students, the NSA has taken an active role in graduate student success. The general philosophy of the research committee has been to invest both in the research project and in the future sunflower researchers (i.e., graduate students and postdoctoral researchers). In response to the increase in *Phomopsis* stem canker documented in the survey, an NSA-supported Ph.D. student's work has documented multiple species causing the disease (Mathew et al. 2015). Work has begun to elucidate the complexity of the genetics involved in management of the disease (Mathew et al. 2018b, c). This initial work led to additional projects that examine host range, fungicide efficacy, the development of an application-timing model, and further examination of genetics. Similarly, the NSA funded multiple students to examine the race complexity and fungicide-sensitivity of the downy mildew pathogen, and continue to support additional rust work (Gilley et al. 2016, 2017; Humann et al. 2016a, b). Throughout the course of this survey, the NSA has supported and continues to support graduate students and postdocs.

The sunflower survey has played a crucial role in leveraging funding from other sources, which includes both private corporate partners and federal agencies. Additionally, the NSA has leveraged its

Fig. 26. Prevalence of *Phomopsis* stem canker from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

support to fund additional graduate students and postdoctoral researchers through federal and private corporate entities. Leveraged and direct funding for plant pathology research as a consequence (at least in part) of this survey is estimated to be in the millions of dollars.

The sunflower surveys have also served as a vehicle for the collection of soil and disease samples of interest to various researchers nationwide. Examples include the incidence and distribution of 1) *Macrophomina* and *Verticillium* in soil samples (Gulya et al. 2011); 2) new races of the sunflower rust pathogen (Friskop et al. 2015a); 3) additional fungicide-resistant and new races of the downy mildew pathogen (Gilley et al. 2016); and 4) *Phomopsis* stem canker samples for species identification (Olson et al. 2016). The surveys have been instrumental in the compilation of new disease knowledge and the collection of numerous pathogen isolates for study.

Participation in the surveys in Nebraska additionally spurred the interest of more comprehensive disease surveys, which had never been conducted before in the state (Harveson 2012a). As a result, new production problems were noted, including a never before described virus tentatively placed in the Tombusviridae (Harveson et al. 2017) (Fig. 28) and a first report in North America for the parasitic plant Louisiana broomrape (*Orobancha ludoviciana* Nutt.) on cultivated sunflower (Harveson et al. 2015) (Fig. 29).

The high incidence of *Sclerotinia* head rot noted from the early surveys was also an important factor in the initiation and continuation of the National *Sclerotinia* Initiative. This is a federal program that funds *Sclerotinia* research on five major crops, and annually holds a workshop and reporting session consisting of scientists and stakeholders with the goal of minimizing the deleterious effects of *Sclerotinia sclerotiorum* on numerous crops, including sunflower, soybean, canola, dry bean, and other pulse crops.

While sunflower is a relatively small acreage crop, the sunflower survey is unique and the data generated from it is uniquely powerful. While surveys of other field crops are frequently done, we are not familiar with a survey that (1) is conducted by in-field visits by trained professionals, (2) compiles all relevant abiotic and biotic stresses and estimates yield, (3) is done on a national scale, and (4) has been conducted annually. Similarly, it is rare that survey results would dictate research priorities of a national commodity across all subject areas, yet the sunflower survey does exactly that. Examples include engineering efforts, improved seed germination, avian habitat research aimed at reducing blackbird damage, and elucidation of a fungicide timing model for *Phomopsis* stem canker. When competing for federal funds or working with private partners to acquire

pesticide labels, the robust nature of the data has given researchers an advantage by documenting real need. Similarly, data from the sunflower survey has been used by private seed and chemical companies to help direct pest management priorities, whether that be incorporation of a disease resistance gene or pursuing a new fungicide label.

Fig. 28. Symptoms in the field from an unknown tombusvirus consisting of chlorotic ringspots and mottling.

Fig. 29. *Orobancha ludoviciana* (Louisiana broomrape) emerging from the soil at the base of a sunflower stalk.

Fig. 27. Incidence of *Phomopsis* stem canker from 2002 to 2015 in North Dakota and Minnesota (ND/MN), South Dakota (SD), the Central High Plains (CHP) states (Colorado, Kansas, and Nebraska), and Texas (TX).

It is not an overstatement to say that this sunflower survey has had both a direct and indirect role in the direction of all aspects of sunflower production in the past. With the integration of the sunflower survey results into research priorities of the NSA and the high value of the data to public and private partners, the sunflower survey will likely continue to have a role in all aspects of sunflower production into the future.

Acknowledgments

The authors acknowledge and express their sincere thanks to the hundreds of agricultural professionals that volunteered their time and expertise to make this survey possible. We thank the staff members and board of the NSA for contributing financially, logistically, and technically to this survey effort, and to the NDSU Cooperative Extension Service for leading and coordinating the survey. We thank the many public and private institutions involved for their direct and indirect technical and financial support of the effort. We thank Dr. Mal Ryley for contributions to the design of the manuscript and Michaela Halvorson for creation of the maps. We thank sunflower growers across the country for letting us survey and report on their fields.

Literature Cited

- Acimovic, M. 1979. Evaluation procedures for the intensity of disease occurrence in sunflower. *Helia* 2:55-57.
- Acimovic, M. 1989. Sunflower disease mapping in Europe and some countries outside Europe in the period 1984-1986. *Helia* 11:41-49.
- Berghuis, B., Gilley, M., Halvorson, J., Hansen, B., Markell, S., Schatz, B., Halvorson, M., Fitterer, S., and Carruth, D. 2018. Evaluations of fungicides for management of sunflower rust on oilseed and confection hybrids. Proc. of the 40th Ann. Sunflower Res. Forum. Fargo, ND. January 10-11, 2018. Natl. Sunflower Assoc., Mandan, ND.
- Berglund, D. R. 2007. Sunflower Production. Publ. A-1331. North Dakota Coop. Ext. Serv. Fargo, ND.
- Bhutta, A. R., Bhatti, M. H. R., Ahmad, S. I., and Ahmad, I. 1993. Prevalence and incidence of sunflower diseases in Pakistan. *Helia* 16:93-98.
- Cholik, F. A. 1999. High Plains Sunflower Production Handbook. Publ. MF-2384. Kansas State Coop. Serv. Manhattan, KS.
- Donald, P. A., Venette, J. R., and Gulya, T. J. 1987. Relationship between *Phoma macdonaldii* and premature death of sunflower in North Dakota. *Plant Dis.* 71: 466-468.
- Friskop, A., Markell, S., and Gulya, T. 2009. Downy Mildew of Sunflower. Publ. PP-1402. North Dakota State Coop. Ext. Serv. Fargo, ND.
- Friskop, A., Markell, S., Gulya, T., Halley, S., Schatz, B., Schaefer, J., Wunsch, M., Meyer, S., Kandel, H., Acevedo, M., Venette, J., and Venette, R. 2011a. Sunflower rust. Publ. PP1557. North Dakota State Coop. Ext. Serv., Fargo, ND.
- Friskop, A., Markell, S., and Khan, M. 2018. 2018 North Dakota Field Crop Plant Disease Management Guide. Publ. PP-622. North Dakota State Coop. Ext. Serv. Fargo, ND.
- Friskop, A., Schatz, B., Mathew, F., Hendrickson, P., Gulya, T., and Markell, S. 2011b. Sunflower hybrid susceptibility and the impact on yield to sunflower rust in North Dakota. *Phytopathology* 101:S2.2-2.3.
- Friskop, A. J., Gulya, T. J., Halley, S. A., Schatz, B. G., Schaefer, J. P., Jordahl, J. G., Meyer, S. M., Misk, K. W., Hendrickson, P. A., and Markell, S. G. 2015a. Effect of fungicide and timing of application on management of sunflower rust. *Plant Dis.* 99:1210-1215.
- Friskop, A. J., Gulya, T. J., Harveson, R. M., Humann, R. M., Acevedo, M., and Markell, S. G. 2015b. Phenotypic Diversity of *Puccinia helianthi* (Sunflower Rust) in the United States from 2011 and 2012. *Plant Dis.* 99: 1604-1609.
- Friskop, A. J., and Markell, S. G. 2016. Rust. Pages 23-25 in: Compendium of Sunflower Diseases and Insects. R. M. Harveson, S. M. Markell, C. C. Block, and T. J. Gulya, eds. APS Press, St. Paul, MN.
- Gilley, M., Gulya, T. J., Misar, C., and Markell, S. M. 2016. Prevalence and Virulence of *Plasmopara halstedii* (Downy Mildew) in Sunflowers. Proc. of the 38th Annual Sunflower Res. Forum. Fargo, ND. January 12-13, 2016. Natl. Sunflower Assoc., Mandan, ND.
- Gilley, M., Markell, S., Halvorson, J., Pasche, J., Belles, D., Gulya, T., and Underwood, W. 2017. Downy mildew update: Determination of pathogen sensitivity to azoxystrobin (Dynasty). Proc. of the 39th Annual Sunflower Res. Forum. Fargo, ND. January 11-12, 2017. Natl. Sunflower Assoc., Mandan, ND.
- Gulya, T., Kandel, H., McMullen, M., Knodel, J., Berglund, D., Mathew, F., Lamey, H. A., Nowatzki, J., and Markell, S. 2013. Prevalence and incidence of sunflower downy mildew in North Dakota between 2001 and 2011. *Plant Health Prog.* 14:20.
- Gulya, T., Rashid, K. Y., and Masirevic, S. N. 1997. Sunflower diseases. Pages 263-379 in: Sunflower Technology and Production. Agronomy Monograph 35. A. A. Schneiter, ed. Agron. Soc. Amer., Madison, WI.
- Gulya, T. J. 1996. Changes in sunflower disease incidence in the United States during the last decade. Pages 651-657 in: Vol. 2, Proc. Int. Sunflower Assoc. 14th Sunflower Symp., June 12-20, 1996, Beijing.
- Gulya, T. J., Mathew, F. M., Harveson, R. M., Markell, S. G., and Block, C. C. 2017. Diseases of sunflower. Pages 787-838 in: Handbook of Florists' Crops Diseases, vol. 2. R. J. McGovern and W. H. Elmer, eds. Springer International, Switzerland.
- Gulya, T. J., Mengistu, A., Osborne, L., and Harveson, R. 2011. Distribution and Incidence of Verticillium and Charcoal Rot in six states as determined by soil bioassays. Proc. of the 33rd Annual Sunflower Research Forum. Fargo, ND. January 12-13, 2011. Natl. Sunflower Assoc., Mandan, ND.
- Harveson, R. 2012a. A summary of a three year disease survey of Nebraska sunflower production fields, including the appearance of an unknown virus disease. Proc. of the 34th Annual Sunflower Research Forum. Fargo, ND. January 11-12, 2012. Natl. Sunflower Assoc., Mandan, ND.
- Harveson, R. M. 2010a. First Report of the Early Spore Stages of Sunflower Rust, Caused by *Puccinia helianthi*, in Nebraska. *Plant Health Prog.* doi.org/10.1094/PHP-2010-0315-01-BR
- Harveson, R. M. 2010b. Rust of sunflower in Nebraska. NebGuide G1995, University of Nebraska Cooperative Extension. <http://extensionpublications.unl.edu/assets/pdf/g1995.pdf>
- Harveson, R. M. 2011a. Downy mildew of sunflower in Nebraska. NebGuide G2075, University of Nebraska Cooperative Extension. <http://extensionpublications.unl.edu/assets/pdf/g2075.pdf>
- Harveson, R. M. 2011b. Sclerotinia diseases of sunflower in Nebraska. NebGuide G2107, University of Nebraska Cooperative Extension. <http://extensionpublications.unl.edu/assets/pdf/g2107.pdf>
- Harveson, R. M. 2013. Rhizopus head rot of sunflower in Nebraska. NebGuide (revised) G1677, University of Nebraska Cooperative Extension. <http://extensionpublications.unl.edu/assets/pdf/g1677.pdf>
- Harveson, R. M. 2016a. Rhizopus head rot. Pages 49-51 in: Compendium of Sunflower Diseases and Pests. R. M. Harveson, S. G. Markell, C. C. Block, and T. J. Gulya, eds. American Phytopathological Society, St. Paul, MN.
- Harveson, R. M., Al Rwahnih, M., Tian, T., Karasev, A. V., and Gulya, T. 2017. A new virus disease of sunflower in Nebraska. *Phytopathology* 107:S5.101-102.
- Harveson, R. M., Giesler, L. J., Jackson, T. A., Liu, B., Wegulo, S. N., and Korus, K. A. 2012b. Sunflower Disease Profiles I. Foliar Diseases. EC 1900, University of Nebraska, Cooperative Extension. <http://digitalcommons.unl.edu/plantpathpapers/544/>
- Harveson, R. M., Giesler, L. J., Jackson, T. A., Liu, B., Wegulo, S. N., and Korus, K. A. 2012c. Sunflower Disease Profiles II. Head and Stalk Rots and Wilts. EC 1902, University of Nebraska, Cooperative Extension. <http://digitalcommons.unl.edu/plantpathpapers/543/>
- Harveson, R. M., Markell, S. M., Block, C. C., and Gulya, T. J. 2016b. Compendium of Sunflower Diseases and Insects. APS Press, St. Paul, MN.
- Harveson, R. M., Mathew, F. M., Gulya, T. J., Markell, S. G., Block, C. C., and Thompson, S. 2018a. Sunflower stalk diseases initiated through leaf infections. *Plant Health Prog.* 19:82-91.
- Harveson, R. M., Nelson, A., Mathew, F. M., and Seiler, G. J. 2015. First report of *Orobanche ludoviciana* parasitizing sunflowers. *Plant Health Prog.* 16: 216-217.
- Harveson, R. M., Nielsen, P. T., Carlson, C., Mathew, F. M., Braun, N., Kontz, B., Markell, S., Gilley, M., Halvorson, J., and Berghuis, B. 2018b. Quantification of yield loss from Rhizopus head rot in sunflower. Proc. of the 40th Annual Sunflower Res. Forum, Fargo, ND. January 10-11, 2018. Natl. Sunflower Assoc., Mandan, ND.
- Heiser, C. 1951. The sunflower among the North American Indians. *Proc. Am. Philos. Soc.* 95:432-448.
- Hoes, J. A., and Huang, H. C. 1976. Importance of disease to sunflower in Manitoba in 1975. *Can. Plant Dis. Surv.* 56:75-76.
- Hoes, J. A., and Putt, E. D. 1963. Sunflower diseases in Manitoba in 1963. *Can. Plant Dis. Surv.* 43:210-211.
- Humann, R., Crane, E., Friskop, A., Jordahl, J., Markell, S., Meyer, S., Gulya, T., Johnson, K., and Wunsch, M. 2016a. The development and future of Oxathiapiprolin – A novel fungicide seed treatment to manage downy mildew. Proc. of the 38th Annual Sunflower Res. Forum, Fargo, ND. January 12-13, 2016. Natl. Sunflower Assoc., Mandan, ND.
- Humann, R., Gulya, T., Acevedo, M., Marek, L., Jordahl, J., Meyer, S., and Markell, S. 2016b. Identification of *Helianthus* accessions resistant to *Plasmopara halstedii* (downy mildew) and *Puccinia helianthi* (rust). Proc. of the American Phytopathological Society. Tampa, FL. July 29-August 4, 2016.
- Humann, R. M., Gulya, T. J., and Markell, S. G. 2016c. Downy mildew. Pages 18-20 in: Compendium of Sunflower Diseases and Insects. R. M. Harveson, S. M. Markell, C. C. Block, and T. J. Gulya, eds. APS Press, St. Paul, MN.
- Lamey, H. A., McBride, D. K., Zollinger, R. K., Luecke, J. L., McMullen, M. P., and Berglund, D. R. 1992. 1990 Sunflower grower survey of pest problems and pesticide use in North Dakota. Rpt. No. 9. North Dakota Coop. Ext. Service, Fargo, ND.
- Lamey, H. A., McMullen, M. P., Luecke, J. L., Zollinger, R. K., Glogoza, P. K., and Berglund, D. R. 1999. 1997 Sunflower grower survey of pest problems and pesticide use in Kansas, Minnesota, North Dakota and South Dakota. Rpt. No. 46. North Dakota Coop. Ext. Service, Fargo, ND.

Tom Gulya

Bob Harveson

Febina Mathew

Charlie Block

Sue Thompson

Hans Kandel

Duane Berglund

John Sandbakken

Larry Kleingartner

Sam Markell

Dr. Tom Gulya (retired) was a research plant pathologist with the USDA-ARS Sunflower Research Unit (Fargo, ND) for 35 years, as well as an adjunct professor of plant pathology at North Dakota State University. His research covered all diseases of sunflower, but concentrated mostly on downy mildew, rust, *Phomopsis* stem canker, and *Sclerotinia* wilt and head rot. He worked closely with the unit's other scientists to find disease resistance in wild and domesticated sunflower and incorporate it into USDA germplasm releases. His accomplishments and international collaborations earned him the "Pustovoit Award" from the International Sunflower Association. He has been involved with the annual NSA Sunflower Survey from its inception in 2001, serving in 2017 as the coordinator. He currently resides in Santa Rosa, CA, and continues to collaborate with U.S. and international sunflower pathologists.

Dr. Harveson is a professor and extension plant pathology specialist with the University of Nebraska and is stationed at the Panhandle Research and Extension Center in Scottsbluff, NE. He received an M.S. degree in 1989 from Texas A&M University and his Ph.D. from the University of Florida in 1999, both in plant pathology. He began his current appointment as assistant professor in that same year and rose through the ranks, becoming a full professor in 2009. He has a joint appointment (50% research and 50% extension) with programming responsibility for specialty crop diseases emphasizing sugar beet root rots, bacterial diseases of dry-edible beans, and diseases of sunflowers and pulse crops. His research program focuses on the etiology and applied management of these crops utilizing the integration of biological, cultural, chemical, and predictive measures.

Febina Mathew received a B.S. in biotechnology and biochemical engineering from the Indian Institute of Technology (Kharagpur, India), and an M.S. and Ph.D. in plant pathology at North Dakota State University (Fargo, ND). In 2014, Febina joined the faculty at South Dakota State University as a research plant pathologist with responsibilities for field crops, including sunflower. Febina has focused her research program on diversity and management of pathogens causing disease of field crops in South Dakota, which includes *Phomopsis* stem canker of soybean and sunflower, root rot of soybean and corn, and bacterial diseases of pulse crops. Febina teaches an undergraduate/graduate course on field crop diseases and management at South Dakota State University. Other professional interests include the development of national/international partnerships

with stakeholders, private industry, and researchers, and mentoring undergraduate/graduate student researchers.

Dr. Charles Block currently serves as the seed health testing coordinator at the ISU Seed Science Center, the largest public seed health testing laboratory in the U.S. Charles joined the Seed Science Center in July 2016, where he also serves as co-administrator of the U.S. National Seed Health System. He previously served for 37 years as a plant pathologist at the North Central Regional Plant Introduction Station (NCRPIS) in Ames, IA, a USDA germplasm resources station. At NCRPIS, he gained extensive experience in seed health testing, knowledge of seed-borne diseases, emerging disease topics, international phytosanitary regulations and quarantine issues, and conducted research studies with more than 20 host-pathogen combinations in corn, sunflower, tomato, amaranth, cucurbits, and alfalfa. In sunflower, he conducted disease resistance evaluations of the USDA collection for both *Alternaria* and *Septoria* leaf blights as well as extensive greenhouse and field evaluations for *Sclerotinia* wilt resistance in wild annual and perennial species.

Sue Thompson graduated from the University of Queensland (Gatton) in 1978 and has more than 35 years' experience in research, extension, and diagnostics across broadacre summer crops in Australia, including 25 years in sunflower. She is primarily a specialist sunflower pathologist and most recently was based in Toowoomba with the Queensland Department of Agriculture, and then at the University of Southern Queensland prior to retirement in 2017. Internationally recognized for her work on *Diaporthe* species, Sue led the investigation into Australia's first *Phomopsis* stem canker outbreak in sunflower, revealing three new *Diaporthe* species including the highly damaging *D. gulyae*. Sue's University of Queensland Ph.D. dissertation of the *Diaporthe* species on green and brown summer crop and weed bridges, including descriptions of 11 new *Diaporthe* species and a further 20 novel species, is currently nearing submission. Australian industry recognition includes an ASG Award for Contributions to the Australian Sunflower Industry in 2014 and the APPS Lester Burgess Award for Diagnostics in 2017. Continuing her passionate association with sunflower, Sue is a long-term committee member of the Australian Sunflower Association and also an active member of the U.S. Sunflower Pathology Group.

Dr. Hans Kandel is a professor and extension agronomist based on the North Dakota State University (NDSU) main campus in Fargo, ND. He received his M.Sc. from the University of

Reading in England and his Ph.D. from NDSU. Kandel has developed innovative extension programs for producers in north-west Minnesota and North Dakota that blend agronomy, sustainability, soil science, and economics. Kandel's extension programs address the needs of traditional crops including sunflower, soybeans, dry bean canola, and dry pea; water management; and alternative cropping systems such as cover crops. He also conducts applied research with various broadleaf crops. Kandel has been involved with and coordinated the National Sunflower Survey since 2007, written two chapters in the book, *Compendium of Sunflower Diseases and Pests*, and annually compiles sunflower hybrid testing data for North Dakota and South Dakota. He also serves on the sunflower research committee advising the National Sunflower Association on research projects. Kandel brings extensive international experience to his position from his work with farmers, farming communities, and extension work in many developing countries including Zambia, Indonesia, Kenya, and Uganda.

Dr. Duane Berglund received his Ph.D. in agronomy at North Dakota State University in 1971. Dr. Berglund began his career at the University of Minnesota-Waseca before joining the faculty at NDSU as an extension agronomist, where he had responsibilities for broadleaf crops. Throughout his career, Dr. Berglund also served as assistant director of agriculture and natural resources, community resource development, and the pesticide programs coordinator at NDSU. In addition to many other contributions Dr. Berglund has made to North Dakota agriculture, he helped develop, expand, and coordinate the sunflower survey until his retirement in 2006. Currently, Dr. Berglund is a professor emeritus at NDSU.

John Sandbakken became executive director of the National Sunflower Association located in Mandan, ND, in January 2012. Prior to this, he was the international marketing director for 16 years. The National Sunflower Association is a combination of United States sunflower growers and industry members. NSA

is a non-profit agricultural organization working in the areas of market development, education, production, and utilization research. Before working at NSA, Mr. Sandbakken worked for the North Dakota Department of Agriculture's marketing division for 11 years, heading the division for the last 7 years. In that position, he assisted various commodity groups and private companies in their international marketing programs.

Larry Kleingartner was raised on a North Dakota family farm. He is a graduate of Jamestown College and the University of Hawaii. He was a Peace Corps volunteer in India where he provided assistance to farmers in the production of small grains and vegetables. He was the executive director of the (USA) National Sunflower Association from 1980 to 2011. In that capacity he supervised market development activities domestically and overseas, including the introduction of NuSun mid-oleic sunflower. He worked closely with the research community and played a key role in the creation of the Sclerotinia Initiative, a source of federal funding for Sclerotinia research. Larry was the editor of *The Sunflower* magazine, which is published six times a year. He was inducted into the ND Agriculture Hall of Fame in 2008. Larry and his wife Nancy have three daughters and three granddaughters.

Sam Markell is a professor and extension specialist at North Dakota State University. Sam received a B.S. in biology and an M.S. in plant pathology at North Dakota State University, and a Ph.D. in plant pathology at the University of Arkansas. In 2007, Sam joined the faculty at North Dakota State University as an extension/research plant pathologist with responsibilities for broadleaf crops, including sunflower. Sam has focused his program on developing tools and strategies to manage economically important diseases of broadleaf crops in the state, including downy mildew, rust, and *Phomopsis* stem canker of sunflower. Other professional interests include the development of public-private partnerships, international relationships, and providing the best possible education for graduate students.

- Markell, S., Gulya, T., McKay, K., Hutter, M., Hollingsworth, C., Ulstad, V., Kock, R., and Knudsvig, A. 2009. Widespread occurrence of the aelial stage of sunflower rust caused by *Puccinia helianthi* in North Dakota and Minnesota in 2008. *Plant Dis.* 93:668-669.
- Markell, S., Harveson, R., Block, C., and Gulya, T. 2014. Sunflower Disease Diagnostic Series. Publ. PP-1727. North Dakota State Coop. Ext. Serv, Fargo, ND. <https://www.ag.ndsu.edu/publications/crops/sunflower-disease-diagnostic-series/pp1727.pdf>
- Markell, S., Harveson, R., Block, C., Gulya, T., and Mathew, F. 2015b. The sunflower pathology working group. Proceedings of the 8th International Integrated Pest Management Symposium. Salt Lake City, UT. March 23-26, 2015.
- Markell, S. G., Harveson, R. M., Block, C. C., and Gulya, T. J. 2015a. Sunflower Diseases. Pages 93-128 in: *Sunflower: Chemistry, Production, Processing and Utilization*. E. E. Martínez-Force, N. T. Dunford, and J. J. Salas, eds. Amer. Oil Chem. Soc. Press, Urbana, IL.
- Markell, S. G., Harveson, R. M., Block, C. C., Gulya, T. J., Mathew, F. M. and Thompson, S. 2017. The sunflower pathology working group. *Phytopathology* 107:S5.106.
- Masirevic, S., and Gulya, T. J. 1992. *Sclerotinia* and *Phomopsis* – two devastating sunflower pathogens. *Field Crops Res.* 30:271-300.
- Mathew, F. M., Alananbeh, K. M., Jordahl, J. G., Meyer, S. M., Castlebury, L. A., Gulya, T. J., and Markell, S. G. 2015. *Phomopsis* stem canker: A re-emerging threat to sunflowers (*Helianthus annuus*) in the United States. *Phytopathology* 105:990-997.
- Mathew, F., Harveson, R., Gulya, T., Thompson, S., Block, C., and Markell, S. 2018a. *Phomopsis* Stem Canker of Sunflower. *Plant Health Instructor*. doi: 10.1094/PHI-I-2018-1103-01
- Mathew, F. M., Jordahl, J. G., Gulya, T. J., and Markell, S. G. 2018b. Comparison of greenhouse-based inoculation methods to study aggressiveness of *Diaporthe helianthi* isolates causing *Phomopsis* stem canker of sunflower (*Helianthus annuus*). *Plant Health Prog.* 19:92-96.
- Mathew, F. M., Olson, T. R., Marek, L. F., Gulya, T. J., and Markell, S. G. 2018c. Identification of sunflower (*Helianthus annuus*) accessions resistant to *Diaporthe helianthi* and *Diaporthe gulyae*. *Plant Health Prog.* 19:97-102.
- Mirza, M. S., and Beg, A. 1983. Diseases of sunflower in Pakistan. *Helia* 6:55-56.
- Olson, T., Kontz, B., Marek, L., and Mathew, F. 2016. A diagnostic assay to detect the *Phomopsis* stem canker pathogens. Proc. of the 38th Annual Sunflower Res. Forum. Fargo, ND. January 12-13, 2016. Natl. Sunflower Assoc., Mandan, ND.
- Putt, E. D. 1997. Early history of sunflower. Pages 1-19 in: *Sunflower Technology and Production*. Agronomy Monograph 35. A. A. Schneiter, ed. Agron. Soc. Amer. Madison, WI.
- Rashid, K. Y. 1989. Survey of flax and sunflower diseases in Manitoba in 1988. *Can. Plant Dis. Surv.* 69:64-65.
- Rashid, K. Y., Block, C. C., and Gulya, T. J. 2016. Sclerotinia head rot and midstalk rot. Pages 51-55 in: *Compendium of Sunflower Diseases and Insects*. R. M. Harveson, S. M. Markell, C. C. Block, and T. J. Gulya, eds. APS Press, St. Paul, MN.
- Rashid, K. Y., Turner, T., and Pradhan, M. 2017. Diseases of sunflower in Manitoba in 2016. *Can. Plant Dis. Surv.* 97:224.
- Sackston, W. E. 1949. Sunflower diseases in Manitoba in 1948. *Can. Plant Dis. Surv.* 28:31-33.
- Sackston, W. E. 1954. Sunflower diseases in Manitoba in 1953. *Can. Plant Dis. Surv.* 33:45-48.
- Sackston, W. E. 1957. Sunflower diseases in Manitoba. *Can. Plant Dis. Surv.* 37:43-44.
- Sackston, W. E. 1978. Sunflower disease mapping in Europe and adjacent Mediterranean countries. *Helia* 1:21-31.
- Sandbakken, J. 2017. 2017 Sunflower crop quality report. Nat. Sunflower Assoc., Mandan, ND.
- Smith, B. D. 2014. The domestication of *Helianthus annuus* L. (sunflower). *Veg. Hist. Archaeobot.* 23:57-74.
- Thompson, S. M., Tan, Y. P., Young, A. J., Neate, S. M., Aitken, E. A. B., and Shivas, R. G. 2011. Stem cankers on sunflower (*Helianthus annuus*) in Australia reveal a complex of pathogenic *Diaporthe* (*Phomopsis*) species. *Persoonia* 27:80-89.
- Vicente, P. M., and Zizzerini, A. 1997. Current status of sunflower diseases in Mozambique. *Helia* 20:31-38.
- Zizzerini, A. 1981. Sunflower diseases in Italy. *Helia* 3:45-46.
- Zizzerini, A., Monotti, M., and Tosi, L. 1987. Results of a two-year investigation on the most important pathogens in Italy. *Helia* 10:47-51.
- Zollinger, R., Glogoza, P., McMullen, M., Bradley, C., Dexter, A., Knopf, D., Wilson, E., DeJong, T., and Meyer, W. 2006. Pesticide use and management practices in North Dakota 2004. Publ. W-1308. North Dakota Coop. Ext. Serv, Fargo, ND.
- Zollinger, R., Markell, S., Knodel, J., Gray, J., Jantzi, D., Hagemeister, K., and Kilpatrick, P. 2014. Pesticide use and management practices in North Dakota 2012. Publ. W-1711. North Dakota State Coop. Ext. Serv, Fargo, ND.
- Zollinger, R., McMullen, M., Knodel, J., Gray, J., Jantzi, D., Kimmet, G., Hagemeister, K., and Schmitt, C. 2009. Pesticide use and management practices in North Dakota 2008. W-1446. North Dakota State Coop. Ext. Serv, Fargo, ND.