Registration of 'Summit,' a High-Yielding Soybean with Race-Specific Resistance to *Phytophthora sojae*

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ABSTRACT

Phytophthora sojae Kauffmann and Gerdemann, the causal agent of Phytophthora root and stem rot, may result in severe losses in soybean fields planted with susceptible cultivars. However, the disease can be successfully managed through the use of cultivars with genetic resistance. 'Summit' soybean [*Glycine max* (L.) Merr.] (Reg. No. CV-508, PI 665057) was developed by the Ohio Agricultural Research and Development Center of Ohio State University and was released in 2010. The cultivar was bred with the objective to develop a high-yielding maturity group (MG) II cultivar with resistance to *P. sojae*. Summit was developed through early-generation testing with yield-based selections of F_2–derived heterogenous lines and F_4 lines and originates from a single F_4 plant selection of a cross between 'IA3023' and breeding line HS99-4045. Summit was evaluated in 30 environments from 2006 to 2011. In the Ohio Preliminary and Advanced Line Tests, Summit had a significantly higher yield than check cultivars, with seed yield 106% of 'Wyandot' and 110% of 'OHS 202'. In the Northern Region Preliminary Test, Summit had a similar yield as the MG III check cultivar 'IA3024' and a significantly higher yield than the MG II check cultivar 'IA2068' (109%). Summit possesses *Rps1k* and *Rps3a* alleles for race-specific resistance to *P. sojae*. As a high-yielding, conventional, mid-MG II cultivar with resistance to *P. sojae*, Summit is a good choice for producers of non–genetically modified soybeans in Ohio and other regions with disease pressure from *P. sojae*..

Phytophthora sojae Kauffmann and Gerdemann, the causal agent of Phytophthora root and stem rot, has the potential to result in complete loss in soybean fields when highly susceptible cultivars are planted (Schmitthenner, 1985). The disease can be successfully managed through resistance conferred by race-specific resistance genes (*Rps*). However, pathogen populations have been shown to adapt following the deployment of the *Rps* genes, making these genes ineffective in many environments (Schmitthenner et al., 1994; Dorrance et al., 2003). More than 200 pathotypes of *P. sojae* have been identified in Ohio soils (Dorrance et al., 2003). The diversity and adaptation of this pathogen necessitates that *Rps* genes be deployed in combinations for race-specific resistance to be effective across multiple environments.

'Summit' soybean [*Glycine max* (L.) Merr.] (Reg. No. CV-508, PI 665057) was developed by the Ohio Agricultural Research and Development Center (OARDC) of Ohio State University (OSU) and was released by OSU-OARDC in 2010 as a high-yielding, maturity-group (MG) II (relative maturity 2.6), conventional (non–genetically modified) cultivar with race-specific resistance to *P. sojae*. Summit possesses both the *Rps1k* and *Rps3a* alleles conferring resistance to *P. sojae*. The cultivar, previously designated either HS5-3417 or OHS 204, was selected by early-generation testing with yield-based selections in both F_2–derived heterogenous lines and F_4 lines. Summit originates from a single F_4 plant selection from a cross between 'IA3023' (Iowa State Univ., Ames) and the OARDC breeding line HS99-4045. Summit was evaluated in 30 environments from 2006 to 2011. In the Ohio Preliminary and Advanced Line Tests, Summit had a significantly greater yield than the check cultivars, with a seed yield 106% of 'Wyandot' (OSU-OARDC) and 110% of 'OHS 202' (OSU-OARDC). In the Northern Region Preliminary Test, Summit had a similar or higher yield

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Abbreviations: MG, maturity group; OARDC, Ohio Agricultural Research and Development Center; OSU, Ohio State University; RCBD, randomized complete block design.

Published in the Journal of Plant Registrations.
doi: 10.3198/jpr2012.01.0012crc
Received 6 Jan. 2012. Registration by CSSA.

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than the check cultivars, with a seed yield similar (101%) to the MG III check cultivar 'IA3024' (Iowa State Univ., Ames) and 109% of the MG II check cultivar 'IA2068' (Iowa State Univ., Ames; Abney and Crochet, 2007). In the Ohio Soybean Performance Trials, Summit had the highest average seed yield of cultivars grown in each of the six environments (Kroon van Diest et al., 2011).

Methods

Parental Selection and Pedigree

Summit was developed from a cross between IA3023 and the OSU-OARDC experimental line designated HS99-4045. IA3023 (previously designated A99-315026) is a high-yielding, general-use soybean with good emergence and excellent lodging resistance (Crochet, 2003). HS99-4045 was selected as a parent due to its high level of resistance to multiple races of *P. sojae*. HS99-4045 is an F_4–derived selection from a backcross with 'General' (St. Martin et al., 1997) as the recurrent parent and the experimental line HS93-135 as the donor for resistance to *P. sojae*. HS93-135 is derived from a cross between the experimental line HS88-6786 ['Conrad' × (Conrad × PI 360844)] (Fehr et al., 1989; USDA-ARS NGRP, 2012b) and the experimental line HS88-4988. HS88-4988 is an ancestor of 'Kottman' (St. Martin et al., 2001).

Breeding Line Development

The IA3023 × HS99-4045 cross was made in 2001 in Columbus, OH, and subsequent line development was by early-generation testing (Weiss et al., 1947). In 2002, F_2 individuals derived from this cross were grown in a single-row plot. Thirty individuals were selected on the basis of maturity date (MG II to III) and single-plant threshed. Single-row plots of F_2 families were grown and harvested in 2003. $F_{2:4}$ and $F_{2:5}$ heterogenous lines derived from this cross were evaluated in early-generation yield tests in Ohio during 2004 and 2005. Concurrent to the early-generation test in 2004, $F_{2:4}$ heterogenous lines were grown in single-row plots from which F_4 plants were harvested. Single F_4 plants were selected for threshing from $F_{2:4}$ heterogenous lines on the basis of the corresponding seed yield of the 2004 early-generation yield tests. In 2005, concurrent to the second year of the early-generation tests, $F_{4:5}$ families were grown in single rows. $F_{4:5}$ families were selected on the basis of the 2-yr average yield of the F_2–derived heterogenous line from which they were selected. F_4 lines derived from the highest yielding F_2–derived heterogenous lines were selected on the basis of preliminary yield data from the $F_{4:5}$ lines grown in single rows in 2005. In 2006, 17 $F_{4:6}$ lines were grown in the Ohio Preliminary Tests by the OSU-OARDC soybean breeding program. These 17 lines were also evaluated for resistance to *P. sojae*. Selections among these lines were made on the basis of yield as well as the presence of the *Rps3a* and *Rps1k* alleles for resistance to *P. sojae*.

Evaluation of Agronomic Performance

The field plots for the early-generation testing and the Ohio Preliminary Tests were rated for seed yield, maturity date, and lodging. Field plots for the Ohio Advanced Line Tests and the Northern Region Preliminary Tests of the Soybean Uniform Test were rated for seed yield, maturity date, plant height, lodging, seed protein and oil content, and 100-seed weight. For the Ohio Advanced Line Tests, data on 100-seed weight, protein content, and oil content were collected from a single replicate and single location each year. Protein and oil content were analyzed using near-infrared spectroscopy (Infratec 1255, Foss North America) performed at the National Center for Agricultural Utilization Research, USDA-ARS, Peoria, IL.

In 2006 Summit was evaluated in the Ohio Preliminary Test A in two replications at 3 locations (Hoytville, South Charleston, and Wooster) in Ohio and was evaluated in the Ohio Advanced Line Tests in 12 Ohio environments (South Charleston, Plain City, Hoytville, Wooster and Lakeview) from 2007 to 2009. In addition, Summit was evaluated in 11 locations (Ames and Rippey, IA; Urbana, IL; Lafayette, IN; Ingham County, MI; Beermer, Cotesfield, and Mead, NE; Hoytville, OH; Aurora, SD; and Harrow, Ontario) in the 2007 Northern Regional Soybean Preliminary Test IIB (Abney and Crochet, 2007) and in 6 locations (Henry, Erie, Mercer, Delaware, Preble, and Fayette counties in Ohio) in the 2011 Ohio Soybean Performance Trials (Kroon van Diest et al., 2011).

Plot Technique

Early-generation tests and Ohio Preliminary Test plots grown in South Charleston were planted in a lattice design with two replicates and consisted of three rows 4 m long planted at a row spacing of 38 cm. Approximately 300 seeds were planted in each plot. The three rows were harvested with a Massey Ferguson 8 plot combine (AGCO Corp.). Early-generation tests and Ohio Preliminary Test plots grown in Hoytville and Wooster were planted in a randomized complete block design (RCBD) with two replicates and consisted of two rows 4.9 m long planted at a row spacing of 61 cm. Approximately 260 seeds were planted in each plot. Both rows were harvested with a Wintersteiger Classic plot combine (Wintersteiger Inc.).

Ohio Advanced Line Test plots grown in South Charleston, Plain City, and Lakeview were planted in a lattice design with three replicates and consisted of six rows 4 m long planted at a row spacing of 38 cm. Approximately 500 seeds were planted in each plot. The inner four rows were harvested with a Massey Ferguson 8 plot combine. Ohio Advanced Line Test plots grown in Hoytville and Wooster were planted in a RCBD with three replicates and consisted of eight rows 4.9 m long planted at a row spacing of 19 cm. Approximately 600 seeds were planted in each plot. The inner six rows were harvested with a Wintersteiger Classic plot combine.

For the Northern Region Soybean Preliminary Tests, plot technique varied due to the capabilities and equipment of each collaborator. In general, plots had two replications and were multiple-rows of 4.6 to 6 m with the central 3.7 to 4.9 m harvested (Abney and Crochet, 2007). For the Ohio Soybean Performance Trials, plots were grown in a RCBD with four replicates and consisted of four rows 12.2 m long at a row spacing of 38 cm (Kroon van Diest et al., 2011).

In 2003 and 2004, F_2–derived heterogenous lines were evaluated for yield in the early-generation tests. In 2006, F_4 lines were evaluated for yield in the Ohio Preliminary Test as well as for the presence of *Rps1k* and *Rps3a* by hypocotyl inoculation with *P. sojae*. F_4 lines were evaluated for yield in the Ohio Advanced Line Tests (2007 to 2009) as well as the Northern Regional Preliminary Test (2007). Evaluations in the 2011 Ohio Soybean Performance Trial were conducted after the release of Summit as a cultivar.

Evaluation of Resistance to *Phytophthora sojae*

Resistance or susceptibility to *P. sojae* was determined by screening seedlings with differential races of *P. sojae* in a greenhouse using the hypocotyl assay procedure described by Schmitthenner and Bhat (1994) and recently updated by Dorrance et al. (2008). Briefly, 15 to 20 seeds of each soybean genotype were placed on a germination paper (Anchor Paper), wetted, and rolled up. After 7 d, the germination paper was unrolled, malformed seedlings were removed, and seedlings were wounded with the needle from a syringe. The seedlings were inoculated by covering the wound with a mycelium slurry from a 7-d-old culture of *P. sojae* grown on lima bean agar (20 g lima beans, 15 g of water agar). The germination paper was wetted and rerolled for an additional 5 to 7 d. Seedlings were rated for the presence or absence of a lesion at the inoculation site. Where few seedlings were inoculated, the assay was repeated. The differential checks used to verify the pathotype of each isolate were 'Williams' (*rps*/*rps*) (Bernard and Lindahl, 1972); 'Harlon' (*Rps1a*/*Rps1a*) (Buzzell et al., 1976); Harosoy 13XX (*Rps1b*/*Rps1b*) (Buzzell et al., 1987); 'Williams 79' (*Rps1c*/*Rps1c*) (Bernard and Cremeens, 1988a); PI 103091 (*Rps1d*/*Rps1d*) (USDA-ARS NGRP, 2012a); 'Williams 82' (*Rps1k*/*Rps1k*) (Bernard and Cremeens, 1988b); L76-1988 (*Rps2*/*Rps2*) (Bernard et al., 1991); L83-570 (*Rps3a*/*Rps3a*) (Bernard et al., 1991); PRX 146-36 (*Rps3b*/*Rps3b*) (Dorrance et al., 2003); PRX 145-48 (*Rps3c*/*Rps3c*) (Dorrance et al., 2003); L85-2352 (*Rps4*/*Rps4*) (Bernard et al., 1991); L85-3059 (*Rps5*/*Rps5*) (Bernard et al., 1991); Harosoy 62XX (*Rps6*/*Rps6*) (Buzzell et al., 1987); 'Harosoy' (*Rps7*/*Rps7*) (Weiss and Stevenson, 1955); and PI 399073 (*Rps8*/*Rps8*) (USDA-ARS NGRP, 2012c) (Dorrance et al., 2004).

Statistical Analysis

Data from the Ohio Preliminary and Advanced Lines Tests were analyzed by SAS software (SAS Institute) using general linear model analysis. Within any individual year and location, replications were considered random effects and genotypes fixed effects. Because most breeding lines were not included in multiple years of testing, assessment of Summit across years was by comparison to check cultivars and promising breeding lines only. Thus, multiyear analysis was performed on a subset of the original data. Multiyear analysis was conducted using the genotypic least squares means for each individual environment (location-year); environments were considered random. Fisher's protected LSD was employed for comparisons over environments when the genotypic effect was significant (F-test; $p \leq 0.05$). Data from the 2007 Northern Regional Preliminary Test IIB and the 2011 Ohio Soybean Performance Trials were analyzed similarly. Because raw data were not available, genotypic means from each location were used for comparison across locations. Locations with a coefficient of variance greater than 15% were excluded from the overall yield means (Abney and Crochet, 2007). Because entries varied across locations in the 2011 Ohio Soybean Performance Trials, only a subset of lines which were included in all locations was incorporated in the analysis.

Seed Purification and Increase

Seed purification and increase began in 2006 with the selection of 30 single F_6 plants. In 2007, the 30 $F_{6:7}$ lines were grown for purification and seed increase. The line increases were rogued of any flower color, pubescence, or pod color off-types. Each $F_{6:7}$ line was tested for resistance to *P. sojae* as described above. Six of the lines were segregating for *Rps* genes and as such were excluded. The remaining 24 lines were grown as large increases in 2008 and rogued of any botanical off-types as above. Seed from large increases were bulked as breeder seed and used as seed for field trials and disease assays occurring after 2008. Seed was provided to Ohio Foundation Seed, Inc. for the production of foundation seed in 2009.

Characteristics

Agronomic and Botanical Description

Summit matures (relative maturity, 2.6) approximately 1 d later than the branded release OHS 202 (relative maturity, 2.5; Table 1) and between the check cultivars MG II (IA2068) and MG III (IA3024, relative maturity 3.0; Table 2). It has an indeterminate growth habit, purple flowers, light tawny pubescence, tan pods, and seeds with a dull yellow seed coat and black hila. The average height was 71 cm, similar to Wyandot (Table 1). Summit has a mean lodging score of 1.5 (Table 1).

Seed Characteristics

Summit had an average 100-seed weight of 15.5 g (Table 1). Seed protein (396–400 g kg^{-1}) and oil (203–210 g kg^{-1}) contents of Summit were similar to or within the range of the check cultivars (Tables 1 and 2).

Yield Performance

Summit was evaluated for yield in a total of 15 environments from 2006 to 2009 by the OSU-OARDC soybean breeding program in the Ohio Preliminary Tests A (2006) and the Ohio Advanced Line Tests A (2007 to 2009), yielding an average of 3998 kg ha^{-1} (Table 1). With seed yields 110% of OHS 202 and 106% of Wyandot, Summit had a significantly higher yield than those check cultivars and a similar yield as HS0-3243 (Table 1). Wyandot and OHS 202 are high-yielding conventional cultivars released in 2006 and 2007; OHS 202 is especially high-yielding for its early maturity (relative maturity, 2.5). The yield of Summit was greater than the average yield for check cultivars in 13 out of 15 environments.

Table 1. Means of agronomic traits of Summit and check cultivars in the Ohio Preliminary Tests A (2006) and the Ohio Advanced Line Tests A (2007 to 2009).

Cultivar	Seed yield	Maturity	Height	Lodging†	Seed protein‡	Seed oil	Seed size
	kg ha^{-1}	1 Sept. = 1	cm	1–5	g kg^{-1}		g 100 seed^{-1}
HS0-3243§	4024	20.4	74	1.6	400	210	13.0
OHS 202	3639	15.5	66	1.5	392	225	12.9
Summit	3998	16.1	71	1.5	396	210	15.5
Wyandot	3774	19.0	71	1.4	405	212	16.4
$LSD_{0.05}$	200	1.5	3	Not estimable	8	6	0.8
Environments	15	15	13	13	4	4	4

†1 = erect plant; 5 = prostrate plant.

‡Expressed on a zero moisture basis.

§St. Martin et al., 2006.

Table 2. Means of agronomic traits of Summit and check cultivars in the 2007 Northern Regional Preliminary Test IIB.†

Cultivar	Seed yield	Maturity	Height	Lodging‡	Seed protein§	Seed oil	Seed size
	kg ha^{-1}	1 Sept. = 1	cm	1–5	g kg^{-1}		g 100 seed^{-1}
IA1021¶	3279	15.0	77	1.6	410	202	17.0
IA2068	3649	19.3	76	1.4	389	207	14.0
IA3024	3944	27.5	86	1.4	384	210	16.2
Summit	3969	24.8	83	1.4	400	203	16.2
$LSD_{0.05}$	276	1.8	5	0.3	8	6	1.9
Environments	9	8	9	10	7	7	11

†Abney and Crochet, 2007.

‡1 = erect plant; 5 = prostrate plant.

§Expressed on a zero moisture basis.

¶Iowa State University, Ames.

Summit was evaluated for yield in the 2007 Northern Region Preliminary MG II Test in nine environments (Table 2). Summit ranked first of 33 entries in its test and the yield of Summit was greater than the average yield for the check cultivars in seven out of nine locations (Abney and Crochet, 2007). Summit had a yield similar to that of the MG III check cultivar IA3024 and a significantly greater yield than the MG II check cultivar IA2068 (109%).

Summit was evaluated for yield in the 2011 Ohio Soybean Performance Trials in six locations and was ranked first for mean yield across all locations among the seven cultivars that were evaluated in all six locations (Table 3; Kroon van Diest et al., 2011). Summit had a significantly greater yield than three (IAR3001, Ohio FG1, and Wyandot) of the seven cultivars.

Resistance to *Phytophthora sojae*

Hypocotyl inoculation assays with *P. sojae* indicated that Summit carries both the *Rps1k* and *Rps3a* alleles for resistance to *P. sojae* (Table 4). Summit was resistant to *P. sojae* Races 1 (virulent on *Rps7*), 4 (virulent on *Rps1a*, *1c*, *7*), 7 (virulent on *Rps1a*, *2*, *3a*, *3c*, *4*, *5*, *6*, *7*), and 25 (virulent on *Rps1a*, *1b*, *1c*, *1k*, *7*). No dead seedlings were observed in the Summit hypocotyl assays conducted with Race 1. Of 20 seedlings, 1 dead (5%) was observed in assays conducted with Race 4. Of 19 seedlings, 1 dead (5%) was observed in assays conducted with Race 7. Of 32 seedlings, 3 dead (9%) were observed in assays conducted with Race 25. Both Races 1 and 4 are avirulent on soybean lines containing *Rps1k* and/or *Rps3a*. Race 7 is avirulent on lines containing *Rps1k*, but virulent on lines containing only *Rps3a*. Race 25 is avirulent on lines containing *Rps3a*, but virulent on lines on containing *Rps1k*. Summit was completely

Table 3. Yield means of Summit and cultivars in the 2011 Ohio Soybean Performance Trials.†

Cultivar	Relative maturity	Yield
		kg ha^{-1}
Dennison‡	3.6	3591
IAR3001§	3.1	3060
Ohio FG1¶	3.5	3203
Prohio#	4.3	3655
Streeter††	3.0	3714
Summit	2.6	3748
Wyandot	2.9	3147
$LSD_{0.05}$		323
Environments		6

†Kroon van Diest et al., 2011.

‡St. Martin et al., 2008.

§Iowa State University, Ames.

¶St. Martin et al., 1996.

#Mian et al., 2008.

††Ohio Agricultural Research and Development Center, Ohio State University.

Table 4. Reactions of Summit and differential check cultivars to hypocotyl inoculation assay with isolates of *Phytophthora sojae* from Ohio.

P. sojae race designation	R1	R4	R25	R7	1.S.11
Virulence pathotype†	7	1a, 1c, 7	1a, 1b, 1c, 1k, 7	1a, 2, 3a, 3c, 4, 5, 6, 7	1a-d, 1k, 2, 3a, 3c, 4, 5, 6, 7
Summit	0/11‡	1/20	3/32	1/19	12/12
Williams (*rps*/*rps*)§	9/13	14/22	21/21	12/12	5/9
Williams 82 (*Rps1k*/*Rps1k*)	0/11	0/24	21/23	2/18	11/17
L83-570 (*Rps3a*/*Rps3a*)	5/15	5/28	7/13	28/28	14/17

†The soybean differentials used to verify the pathotype of each isolate were Williams (*rps*/*rps*), Harlon (*Rps1a*/*Rps1a*), Harosoy 13XX (*Rps1b*/*Rps1b*), Williams 79 (*Rps*1c/*Rps1c*), PI 103091 (*Rps1d*/*Rps1d*), Williams 82 (*Rps1k*/*Rps1k*), L76-1988 (*Rps2*/*Rps2*), L83-570 (*Rps3a*/*Rps3a*), PRX 146-36 (*Rps3b*/*Rps3b*), PRX 145-48 (*Rps3c*/*Rps3c*), L85-2352 (*Rps4*/*Rps4*), L85-3059 (*Rps5*/*Rps5*), Harosoy 62XX (*Rps6*/*Rps6*), Harosoy (*Rps7*/*Rps7*), and PI 399073 (*Rps8*/*Rps8*).

‡Number of seedlings dead/number of seedlings inoculated.

§Williams, Williams 82, and L83-570 are soybean differentials for race-specific *P. sojae* interactions (Dorrance et al., 2004).

susceptible (12 dead out of 12 seedlings) to *P. sojae* isolate 1.S.11 (virulent on *Rps1a*, *1b*, *1c*, *1d*, *1k*, *2*, *3a*, *3c*, *4*, *5*, *6*, *7*), which is virulent on lines possessing *Rps1k* and/or *Rps3a*. It should be noted that a small fraction of dead plants are expected due to mechanical damage of the hypocotyls. Escapes may result from incomplete inoculation or loss of pathogen aggressiveness due to maintenance of the culture. This generally occurs in assays conducted on both the differential checks and experimental lines. Consistent with results from the hypocotyl assays conducted in this study, the hypocotyl assays performed in Lafayette, IN, for the Northern Regional Preliminary Test indicate Summit was resistant to race 4 (virulent on *Rps1a*, *1c*, *5*, and *7*) and race 7 (virulent on *Rps1a*, *2*, *3a*, *3c*, *4*, *5*, *6*, and *7*) of *P. sojae,* whereas IA3023 was susceptible to races 4 and 7 (Schmitthenner, 1985; Abney and Crochet, 2007). As IA3023 was susceptible to both races 4 and 7 of *P. sojae*, *Rps1k* and *Rps3a* were derived from the male parent of Summit, HS99-4045.

Availability

Breeder seed of Summit was distributed to Ohio Foundation Seeds, Inc. for production of foundation seed in 2010. Summit is available for research purposes and for use as parental stock in the development of new cultivars. Small amounts of seed of Summit are available from the corresponding author. Seed of Summit has been deposited in the National Plant Germplasm System, where it will be available upon publication.

Acknowledgments

We would like to thank Andrew Spring for his technical support. This research was supported in part by the Ohio soybean farmers and their checkoff and funds for germplasm development from the Ohio Biotechnology Innovation Center. We thank the National Center for Agricultural Utilization Research, USDA-ARS, Peoria, IL, for performing seed protein and oil analyses. Salaries and research support were provided by State and Federal Funds appropriated to the Ohio Agricultural Research and Development Center, Ohio State University.

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