

**Guidelines for Spinach Downy Mildew: *Peronospora farinosa* f. sp. *spinaciae* (Pfs)**

Jim Correll, Lindsey du Toit, Steven Koike, and Kees van Ettehoven

(Last updated November 2017)

**Host: *Spinacia oleracea* L.**

**Pathogen: *Peronospora farinosa* f. sp. *spinaciae* (= *P. effusa*)**

**Background:** In recent years spinach growers in the European Union (EU) and the USA have been confronted with outbreaks of downy mildew on spinach cultivars that, in the past, were resistant to this disease. Investigations showed that the cultivars grown had not changed, so it was concluded that the pathogen had overcome resistance in these cultivars through the emergence of new isolates or races. Until relatively recently, four races of spinach downy mildew were known to exist in the USA and EU. The name 'race 5' was introduced for the new strains that overcame resistance of cultivars formerly considered resistant to the disease. In time, a second new race was identified and called 'race 6'. However, comparison between strains of the races in the USA and EU showed that US races 5 and 6 were not identical to EU races 5 and 6, resulting in a confusing situation. Confusion and uncertainty developed among growers and seed companies.

Seed companies from the Netherlands set up a cooperative effort with Naktuinbouw (General Netherlands Inspection Service for Horticulture) and researchers from the University of Arkansas (Jim Correll) and the University of California (Steven Koike) to address this problem. Based on the current system for downy mildew race classification using genetic information provided by spinach breeders, a differential set of spinach lines, cultivars and F1 hybrids was developed for identifying races of the spinach downy mildew pathogen. Using this set, new downy mildew isolates from all over the world were tested at Naktuinbouw.

Extensive tests showed that 3 new isolates of Pfs had developed in different parts of the world. To avoid further confusion, an agreement was reached to identify known races 1, 2, 3 and 4 as Pf1, Pf2, Pf3 and Pf4 using the internationally accepted notation Pfs for *Peronospora farinosa* f. sp. *spinaciae*. The relatively new race, Pfs5, found in the USA and the EU was formerly called race 5 in the US and race 6 in Europe. Pfs6, found in the USA, was formerly US race 6. Pf7, found in the EU, had formerly been named race 5 in the EU. The cooperators established that some F1 spinach hybrids were resistant to one or more of the identified races, allowing growers to choose (in cooperation with seed companies), resistant cultivars for their growing areas.

The International Working Group on *Peronospora farinosa* (IWGP) cooperates on the naming of spinach downy mildew races and monitors outbreaks of downy mildew and development of new strains. If appropriate, new race names are approved in a systematic manner to avoid confusion with naming new races. Cultures of new races will be made available via Naktuinbouw in the Netherlands for seed companies willing to test their breeding material against the new races. Researchers from all over the world are invited to join this initiative and use the differential host set to identify new isolates in their regions. For more information, contact Diederik Smilde ([d.smilde@naktuinbouw.nl](mailto:d.smilde@naktuinbouw.nl)), Jim Correll ([jcorrell@uark.edu](mailto:jcorrell@uark.edu)), Steve Koike ([stkoike@ucdavis.edu](mailto:stkoike@ucdavis.edu)) or the chairman of the International Working Group on *Peronospora* (IWGP) Jan deVisser ([JandeVisser@popvriendseeds.nl](mailto:JandeVisser@popvriendseeds.nl)).

By 2017, 16 races of Pfs had been described, with races 4 through 16 identified since 1990 (Irish et al., 2008; Feng et al, 2014; Correll et al, unpublished). Although major (qualitative) and minor

(quantitative) gene resistance to the various races had been identified in spinach, major gene resistance was most widely used. More recent identification of races 12, 13, 14, 15 and 16 of Pfs led to releases of spinach cultivars with resistance to these races. However, soon thereafter, several of these cultivars were observed to be severely affected by downy mildew in both the USA and the EU. Efforts by Irish et al. (2007) and Feng et al (2014) were undertaken to identify and characterize the new virulence phenotypes. Characterization of Pfs races was based on qualitative disease reactions of isolates on a set of host differentials. The current set of spinach differentials (see Table 1) includes new and old commercial hybrids as well as open-pollinated cultivars and breeding lines. However, the nature of some of the differential hosts has been problematic as seeds of hybrids are produced using proprietary inbred lines, which may become unavailable when companies stop producing particular hybrids. As a result, a project has been initiated at the University of Arkansas to develop open-pollinated, near-isogenic lines (NILs) with single resistance loci in a common susceptible genetic background for race identification of Pfs (Irish et al., 2008). These NILs also could be used to elucidate the genetic basis of resistance and develop molecular markers linked to resistance loci.

**Table 1. Disease reactions of spinach differentials for determining the race identification of isolates of the spinach downy mildew pathogen, *Peronospora farinosa* f. sp. *spinaciae*.**

Differential cultivar	Race of <i>Peronospora farinosa</i> f. sp. <i>spinaciae</i> *															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Viroflay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Resistoflay	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Califlay	-	+	-	+	-	+	+	-	-	+	-	-	+	-	+	-
Clermont	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	+
Campania	-	-	-	-	-	+	-	+	+	+	-	+	+/-	+	-	-
Boeing <sup>#</sup>	-	-	-	-	-	-	-	+	-	+	-	+	-	+	-	+
Lion	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
Lazio	-	-	-	-	-	-	-	-	-	-	+	+	+	+	-	+
Whale	-	-	-	(-)	-	(-)	(-)	-	-	+	-	+	+	-	+	-
Pigeon	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	+
Caladonia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
Meerkat	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+

\* Races of the downy mildew pathogen as of November 2017.

# Differential response of Boeing to these known races of Pfs is the same as that of Avenger.

+ = Susceptible reaction = sporulation observed on cotyledons in the differential seedling test.

- = Resistant reaction = no sporulation observed on cotyledons in the differential seedling test.

(-)= Reduced level of infection, often referred to as field resistance = sparse sporulation on the tips of cotyledons in the differential seedling test.

+/- = Variability in the number of resistant and susceptible plants observed.

nt = Not (yet) tested.

**Guidelines on differentiating races of Pfs using the spinach differential lines listed in Table 1, and screening for resistance of spinach lines to races of Pfs (updated March 2015 J. C. Correll):**

The following is a summary protocol for screening disease resistance to the downy mildew pathogen. More detailed accounts of the protocol have been published (see references below). Others have effectively used a similar protocol with minor differences in temperature, number of days for incubation, plant age, etc.

Spinach is typically planted in a commercial potting mix in 100 cm x 50 cm flats. Ten differentials (see Table 1 for the spinach differentials currently used, and reactions of these differentials to the known races of Pfs) are grown per tray with approximately 15 plants of a given differential per row. Plants are fertilized once a week after seedling emergence with Peter's commercial fertilizer (13-13-13). Seedlings are inoculated with a sporangial suspension ( $1.0$  to  $2.5 \times 10^5$  sporangia/ml) of the appropriate isolate of the pathogen at the first true-leaf stage, when the true leaves are approximately 2 cm long (**Figure 1**). Inoculum is applied using an air-brush paint sprayer with compressed air (**Figure 2**). Between 20 and 40 ml of inoculum is used to inoculate approximately 150 seedlings per flat.



**Figure 1.** Seedlings of spinach differential cultivars ready for inoculation with an isolate of the downy mildew pathogen, *Peronospora farinosa* f. sp. *spinaciae*.



**Figure 2.** Inoculating seedlings of spinach differential cultivars with *Peronospora farinosa* f. sp. *spinaciae* using an air-brush paint sprayer with compressed air.

The inoculated plants are placed in a dew chamber maintained at 18-20°C with 100% relative humidity for a 24 h period. The plants are then moved to a growth chamber maintained at 18-20°C with a 12 h photoperiod for 6 days. After the 6 days, the plants are returned to the dew chamber for 24 h at 18-20°C to induce sporulation of Pfs, and the seedlings are scored for



reaction to the inoculated isolate. Typically, both the cotyledons and the first set of true leaves are scored for disease.

Plants are scored as resistant or susceptible based on symptoms of chlorosis (**Figure 3**) and sporulation of the downy mildew pathogen on the cotyledons (**Figure 4**) and true leaves (**Figure 5**). Plants exhibiting any evidence of chlorosis and sporulation are considered susceptible. In a reliable test, a resistant line will have >95% of the plants resistant to the isolate, and the susceptible differential (Viroflay) will have >95% susceptible plants in the test.



**Figure 3.** Chlorosis on a cotyledon of a spinach seedling inoculated with an isolate of *Peronospora farinosa* f. sp. *spinaciae*.



**Figure 4.** Sporulation of *Peronospora farinosa* f. sp. *spinaciae* on a cotyledon of an inoculated spinach seedling, representing a susceptible reaction to that race of the pathogen.



**Figure 5.** Sporulation of *Peronospora farinosa* f. sp. *spinaciae* on a true leaf of an inoculated spinach seedling, representing a susceptible reaction to that race of the pathogen.

#### Pitfalls and trouble-shooting

1. When examining field isolates of Pfs, samples should be kept cool (<20°C) in containers or in bags with high humidity but no free moisture. The spores should be washed off the plants

into cold water and the water kept cold until the spore suspension is sprayed onto spinach plants.

2. When inoculating an isolate of Pfs, the inoculum should be sprayed onto the surface of one or two water agar plates. The lids should be replaced and the plates incubated in the dew chamber along with the inoculated plants. Spore germination should be checked using a microscope after 24 h (**Figure 6**). If the Pfs isolate is viable, 10 to 50% of the spores should have germinated within 24 h.



**Figure 6.** Germinating sporangia of *Peronospora farinosa* f. sp. *spinaciae* on a plate of water agar 24 hours after spraying a sporangial suspension onto the agar, as a test of viability of the pathogen isolate.

3. Extreme care and very good sterile technique should be used to avoid cross-contamination when working with multiple strains of Pfs. Each strain should be handled separately, at a different time, and seedlings inoculated with different strains should be kept in different growth chambers or incubators in different rooms.
4. Intermediate levels of infection (>5% but <95%) suggests the isolate being examined may be a mixture of more than one race, or the material being examined may be segregating for resistance.

The UPOV (Union for the Protection of Varieties) in the EU has similar guidelines for characterizing races of Pfs and verifying resistance claims of specific spinach cultivars. For details on the UPOV guidelines, contact Kees van Ettehoven or Diederik Smilde at Naktuinbouw in the Netherlands (see their contact information below).

**Ordering seeds of spinach differential lines:**

Seeds of each of the nine spinach differentials listed in Table 1 can be ordered from the USDA GRIN (Germplasm Resources Information Network) website of the USDA National Plant Germplasm System (NPGS) at:

<http://www.ars-grin.gov/cgi-bin/npgs/html/close.pl?279001+ISF3>

**NOTE 1:** Click 'Request these accessions' at the bottom of the list to add them all to an order. Click 'Complete the germplasm request and order the material' to provide requestor contact information.

**NOTE 2:** A limited supply of 100 seeds per differential can be ordered at no charge, as long as there is adequate seed in supply. The NPGS may not always have adequate seed of all the differentials listed above to provide a full set of differentials.

**Note 3:** Seeds of differential hosts, including some of the new NILs can be also ordered from Dr Diederik Smilde via CPPSI (<http://www.cppsi.org>).

**Ordering strains of contemporary US races of *Peronospora farinosa* f. sp. *spinaciae*:**

Reference strains of contemporary races of *Peronospora farinosa* f. sp. *spinaciae* known to occur in the US can be ordered from either Dr. Smilde at Naktuinbouw or Dr. Jim Correll via CPPSI (<http://www.cppsi.org>).

**NOTE 1:** Please contact Dr. Correll ([jcorrell@uark.edu](mailto:jcorrell@uark.edu) or tel: 479-575-2710) to determine availability of particular races of interest, and for details on paying for the order. The estimated cost for ordering strains of specific races of *P. farinosa* f. sp. *spinaciae* is \$400 to \$500/strain, depending on the prevalence of the races requested and/or the difficulty of increasing inoculum of the particular strain(s)/race(s) requested.

**NOTE 2:** People ordering strains of various races must provide proof of appropriate USDA APHIS permit for those races. Dr. Correll may not be able to provide cultures of all known races. Dr. Smilde may be able to provide cultures of the more recently reported races.

**Feedback:** Please contact Phyllis Himmel ([pthimmel@ucdavis.edu](mailto:pthimmel@ucdavis.edu)) for inquiries on how to participate and support CPPSI, provide feedback on new strains identified and views on the inoculation protocols, differential hosts, or any related matter is welcomed.

**Liability waiver:** The CPPSI Collaboration for Plant Pathogen Strain Identification, USDA NPGS/GRIN, APS, ASTA, and all other associated members and participating organizations or companies have done their best to provide information that is up-to-date and published in refereed journals and, therefore, no liability for the use of this information is accepted. The inoculation protocol described in this document has been demonstrated to be effective at identifying races of the spinach downy mildew and resistance traits of spinach cultivars.

**People/programs with expertise on spinach downy mildew races and host differentials:**

Diederik Smilde  
Naktuinbouw  
P.O. Box 40  
NL-2370 AA Roelofarendsveen

Netherlands

[www.naktuinbouw.com](http://www.naktuinbouw.com)

Email: [d.smilde@naktuinbouw.nl](mailto:d.smilde@naktuinbouw.nl)

Tel (from the USA): (011) 31 (0)71 332 62 13

Fax (from the USA): (011) 31 (0)71 332 63 63

Jim C. Correll

Department of Plant Pathology

University of Arkansas

316 Plant Science Building

Fayetteville, AR 72701

USA

Email: [jcorrell@uark.edu](mailto:jcorrell@uark.edu)

Tel: (479) 575-2710

Fax: (479) 575-8619

#### **Selected literature:**

1. Bentley, T. C. 2006. Development of a near-isogenic line, scar marker evaluation, and storage procedure assessment for downy mildew of spinach. M.S. thesis, University of Arkansas, Fayetteville, AR.
2. Brandenberger, L. P., Correll, J. C., and Morelock, T. E. 1991. Nomenclature of the downy mildew fungus on spinach. *Mycotaxon* 41:157-160.
3. Brandenberger, L. P., Correll, J. C., Morelock, T. E., and McNew, R. W. 1991. Identification and cultivar reactions to a new race (race 4) of *Peronospora farinosa* f. sp. *spinaciae* on spinach in the United States. *Plant Dis.* 75:630-634.
4. Brandenberger, L. P., Correll, J. C., Morelock, T. E., and McNew, R. W. 1994. Characterization of resistance of spinach to white rust (*Albugo occidentalis*) and downy mildew (*Peronospora farinosa* f. sp. *spinaciae*). *Phytopathology* 84:431-437.
5. Brandenberger, L. P., Morelock, T. E., and Correll, J. C. 1992. Evaluation of spinach germplasm for resistance to a new race (race 4) of *Peronospora farinosa* f. sp. *spinaciae*. *HortSci.* 27:1118-1119.
6. Choi, Y. J., Hong, S. B., and Shin, H. D. 2007. Re-consideration of *Peronospora farinosa* infecting *Spinacia oleracea* as a distinct species, *Peronospora effusa*. *Mycol. Res.* 111:381-391
7. Correll, J. C., Bluhm, B. H., Feng, C., Lamour, K., du Toit, L. J., and Koike, S.T. 2011. Spinach: Better management of downy mildew and white rust through genomics. *Europ. J. Plant Pathol.* 129:193-205.
8. Correll, J. C., Koike, S. T., Brandenberger, L. P., Black, M. C., and Morelock, T. E. 1990. A new race of downy mildew threatens spinach. *Calif. Agric.* 44:14-15.
9. Correll, J. C., Morelock, T. E., Black, M. C., Koike, S. T., Brandenberger, L. P., and Dainello, F. J. 1994. Economically important diseases of spinach. *Plant Dis.* 78:653-660.
10. Eenink, A. H. 1974. Linkage in *Spinacia oleracea* L. between the locus for resistance to *Peronospora spinaciae* Laub. and the locus for tolerance for cucumber virus 1. *Euphytica* 23:485-487.
11. Eenink, A. H., 1976. Linkage in *Spinacia oleracea* L. of two race-specific genes for resistance to downy mildew *Peronospora farinosa* f. sp. *spinaciae* Byford. *Euphytica* 25:713-715.

12. Feng, C., Correll, J.C., Kammeijer, K.E., and Koike, S.T. 2011. Characterization of new races (races 11 and 12) and several novel strains of the spinach downy mildew pathogen *Peronospora farinosa* f. sp. *spinaciae*. *Phytopathology* 101:S52 (Abstract).
13. Feng, C., Correll, J. C., Kammeijer, K. E., and Koike, S. T. 2014. Identification of new races and deviating
14. strains of the spinach downy mildew pathogen *Peronospora farinosa* f. sp. *spinaciae*. *Plant Disease* 98:145-152.
15. Holton, M. 1991. Inheritance of resistance to downy mildew (*Peronospora farinosa* f. sp. *spinaciae*) in spinach (*Spinacia oleracea* L.). Ph.D. dissertation, University of California, Davis, CA.
16. Irish, B. 2004. New races of the downy mildew pathogen of spinach, identification of molecular markers for disease resistance, and molecular characterization of diversity in spinach germplasm. Ph.D. dissertation, University of Arkansas, Fayetteville, AR.
17. Irish, B. M., Correll, J. C., Feng, C., Bentley, T., and de los Reyes, B. G. 2008. Characterization of a resistance locus (*Pfs-1*) to the spinach downy mildew pathogen (*Peronospora farinosa* f. sp. *spinaciae*) and the development of a molecular marker linked to *Pfs-1*. *Phytopathology* 98:894-900.
18. Irish, B. M., Correll, J. C., Koike, S. T., and Morelock, T. E. 2007. Three new races of the spinach downy mildew pathogen identified by a modified set of spinach differentials. *Plant Dis.* 91:1392-1396.
19. Irish, B. M., Correll, J. C., Koike, S. T., Schafer, J., and Morelock, T. E. 2003. Identification and cultivar reaction to three new races of the spinach downy mildew pathogen (*Peronospora farinosa* f. sp. *spinaciae*), from the United States and Europe. *Plant Dis.* 87:567-572.
20. Irish, B. M., Correll, J. C., Raid, R. N., and Morelock, T. E. 2004. First report of *Peronospora farinosa* f. sp. *spinaciae* (race 5) of spinach in Florida. *Plant Dis.* 88:84.
21. Jones, R. K., and Dainello, F. J. 1982. Occurrence of race 3 of *Peronospora effusa* on spinach in Texas and identification of sources of resistance. *Plant Dis.* 66:1078-1079.
22. Lorenzini, G., and Nali, C. 1994. A new race (race 4) of spinach downy mildew in Italy. *Plant Dis.* 78:208.
23. Nali, C. 1998. A novel threat for spinach in Italy: A new race of downy mildew. *Adv. Hortic. Sci.* 12:179-182.
24. Satou, M., Nishi, K, Kubota, M., Fukami, M., Tsuji, H., and Van Ettehoven, K. 2006. Appearance of race 5 of spinach downy mildew fungus, *Peronospora farinosa* f. sp. *spinaciae*, in Japan. *J. Gen. Plant Pathol.* 72:193-194.
25. Satou, M., Sugiura, T., Ohsaki, R., Honda, N., Horiuchi, S., and Yamauchi, N. 2002. A new race of spinach downy mildew in Japan. *J. Gen. Plant Pathol.* 68:49-51.
26. Shimazaki, Y. 1990. Appearance of a new race 4 of downy mildew on spinach. *Ann. Phytopathol. Soc. Jpn.* 56:95.
27. Smith, P. G. 1950. Downy mildew immunity in spinach. *Phytopathology* 40:65-68.
28. Smith, P. G., Webb, R. E., Millett, A. M., and Luhn, C. H. 1961. Downy mildew on spinach. *Calif. Agric.* 15:5.
29. Smith, P. G., Webb, R. E., and Luhn, C. H. 1962. Immunity to race 2 of spinach downy mildew. *Phytopathology* 52:597-599.
30. Zink, F. W., and Smith, P. G. 1958. A second physiologic race of spinach downy mildew. *Plant Dis. Rep.* 42:818.15.