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ORIGINAL ARTICLE

Categorization of apple cultivars based on seasonal powdery mildew disease progression in two disease management systems over 12 years

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Abstract

Key message **Five cultivar classification categories were determined from season-long powdery mildew disease progression in integrated and organic production systems. Parameters derived from the progress curve categories were suggested for disease warning improvements.**

Abstract The goal of this 12-year study was to evaluate the powdery mildew infection rates of nine resistant, nine commercial, and nine old apple cultivars in two production systems: integrated and organic. Cultivars were classified into five categories, from low to high, based on their shoot and fruit disease progress curves assessed during the season with the disease progress analysed separately in all five classification categories. Powdery mildew incidence at harvest had increased considerably more for both fruit and shoots in the organic than in the integrated plots, except for the shoots of cultivars 'Reglindis', 'Reka', 'Rewena', 'Parker Pepin', and 'Kings of the Pippin'. Control efficacy was acceptable for all resistant and most old cultivars in both production systems (final disease incidence was below 7.5%), but the level of powdery mildew incidence at harvest was middle-to-high or high for cultivars 'Idared', 'Jonagold', 'Jonathan', 'Jonica' and 'Royal Gala' from the commercial cultivar group in both production systems. Cultivar categorization for powdery mildew showed that season-long disease progress was low for the old; low-to-middle for the resistant; and middle-to-high for the commercial cultivars. A three-parameter logistic function was fitted to the temporal progress data of each classification category. Then the upper asymptote (Y_f), rate parameter (β), and inflection point (M) were estimated from the fitted function and the standardized area under the disease progress curves ($AUDPC_S$) were also calculated. Results demonstrated that $AUDPC_S$ and partially Y_f were able to differentiate the five mildew classification categories for both shoot and fruit in both production systems. Therefore, $AUDPC_S$ and Y_f were suggested as input parameters in disease warning systems for measuring host resistance. Yields in the integrated plots were higher compared with those in the organic ones. Powdery mildew classification categories, together with yield, can contribute to a more appropriate cultivar selection for establishing orchards managed by environmentally friendly approaches.

Keywords Apple powdery mildew · *Podosphaera leucotricha* · *Malus* × *domestica* Bork. · Apple cultivars · Classification category · Epidemiology

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Introduction

Apple powdery mildew, caused by the ascomycete fungus *Podosphaera leucotricha* (Ellis & Everh.) E. S. Salmon, is a devastating disease in cultivated apple throughout the world (Marine et al. 2010; Hickey and Yoder 2014). It can cause reduced growth of terminal shoots with defoliation, aborted blossoms and fruit russet with reduced yield, and can result in vitality and vigour losses of the tree due to a reduction in carbohydrate assimilation (Ellis et al. 1998;

Yoder 2000; Hickey and Yoder 2014). Powdery mildew epidemics are often severe under Central European conditions causing economic losses up to 50% (Blazek 2004; Holb and Kunz 2016). Apple powdery mildew management may require 5–10 fungicide sprays from the appearance of first green tissue until extensive shoot growth depending on weather conditions, presence of inoculum sources and cultivar susceptibility (Butt 1972; Berrie 1997; Xu 1999; Yoder 2000; Holb and Kunz 2016). The use of non-chemical management options is increasing because of fungicide resistance issues and high fungicide registration costs (Holb 2009). The use of mildew-free or less susceptible cultivars is the most favourable non-chemical management option as other non-chemical disease management practices may only have low-to-moderate effectiveness against powdery mildew (Korban and Dayton 1983; Gallott et al. 1985; Caffier and Laurens 2005; Holb 2009; Holb and Kunz 2016). Therefore, cultivar susceptibility as a management option becomes a key component in environmentally friendly disease management. Powdery mildew susceptibility of apple cultivars has been demonstrated in many previous field studies (Aldwinckle 1974; Norton 1981; Pedersen et al. 1994; Washington et al. 1998; Afzal et al. 2002; Biggs et al. 2009; Bálint et al. 2013; Blazek and Krenilova 2013; Paz-Cuadra et al. 2014), but the response of apple cultivars to *P. leucotricha* infection has not been incorporated into disease management practices in integrated or organic fruit production (Reganold et al. 2001; Holb 2009). In integrated production systems disease management is more effective compared with the organic ones because of the generally higher mildew-inoculum pressure and lower effectiveness of approved fungicides in the latter system (Ellis et al. 1998; Holb et al. 2005; Holb 2009; Parisi et al. 2013; Holb and Kunz 2016). Accordingly, different disease warning systems were designed for the two management systems for diseases, such as apple scab and brown rot (Holb et al. 2005, 2011). The same applies to existing apple powdery mildew warning systems (Xu and Butt 1996; Xu 1999; Berrie and Xu 2003), which also require detailed information on the degree of host (cultivar) susceptibility. Therefore, categorising apple cultivar reactions to apple powdery mildew in the different disease management systems will be a crucial step for improving powdery mildew warning systems.

Powdery mildew incidence (ranging from 0 to 100%) and/or a disease index for powdery mildew (ranging from 0 to 4 or 5) have been used in disease assessments to assign cultivars to susceptibility classes (Aldwinckle 1974; Norton 1981; Pedersen et al. 1994; Washington et al. 1998; Afzal et al. 2002; Biggs et al. 2009; Kellerhals et al. 2012; Bálint et al. 2013; Paz-Cuadra et al. 2014). Another study based its classification of partial resistance of apple cultivars on disease incidence (Jeger et al. 1986); however, this study did not assess disease development throughout the whole season, nor for different disease management systems. For some other plant species, cultivar classification involved season-long data collection based on 4–8 regular disease ratings (Thompson and Rees 1979; Pataky et al. 1988; Lebeda and Jendrulek 1988; Holb 2007). These studies proposed that curve parameters, such as disease growth rates and upper asymptote, or area under the disease progress curve (AUDPC) could be used for analysing cultivar classification categories. Such classification procedures are likely to be a useful option for classifying apple cultivars for powdery mildew susceptibility and for improving powdery mildew forecasting.

The goals of this research were: (1) to investigate the reactions of 27 apple cultivars to *P. leucotricha* infections in two production systems managed by integrated or organic growing practices; (2) to separate cultivars into powdery mildew classification categories for shoot and fruit based on season-long disease assessments; and (3) to analyse the powdery mildew progress in all classification categories for both production systems. Yield was also determined to estimate possible cultivar effects in the two disease management systems.

Materials and methods

Experimental orchard

The experimental apple orchard was planted in 1996 in Debrecen-Pallag (47°31′60″N, 21°37′60″E) and the trials were performed from 2000 to 2011. The orchard contained integrated and organic production blocks, which were separated by alder windbreaks and a 4 m-wide road. Blocks were replicated three times and consisted of the same 27 cultivars planted in seven tree plots on M.26 rootstock in a completely randomized design. The study was performed on nine resistant cultivars bred by Fischer and Fisher (1996, 1999), nine commercially grown cultivars, and nine old cultivars that originated from Central Europe (Table 1). Tree density was 1667 trees ha^{-1} with a 4 m between-row and a 1.5 m within-row distances with the trees pruned to a spindle shape. A straw mulch cover was applied in the rows and a bare soil strip was maintained in the space between rows where a disc-tiller was used for weed management.

Since orchard establishment, the integrated plots had been managed according to the European integrated fruit production (IFP) guidelines (Cross and Dickler 1994), while the organic ones were maintained according to the global growing standards for organic production (Anonymous 2000). The plant protection products are given in

Table 1 Pedigree, country of origin and literature citation on powdery mildew susceptibility for the 25 cultivars in the apple orchard at Debrecen-Pallag, Hungary

Cultivar	Pedigree	Country of origin	Harvest time in Hungary
Disease resistant			
'Reanda'[a]	'Clivia' × *Malus floribunda*	Germany	End September
'Reglindis'	'James Grieve' × 'Antonovka'	Germany	End August
'Reka'[a]	'Apollo' × *Malus pumila*	Germany	Mid September
'Releika'	'Clivia' × *M. floribunda*	Germany	Early September
'Renora'	'Clivia' × *M. floribunda*	Germany	Mid October
'Remo'[a]	'James Grieve' × *M. floribunda*	Germany	Early September
'Resi'[a]	'Clivia' × *M. floribunda*	Germany	Mid September
'Retina'	'Apollo' × *M. floribunda*	Germany	End August
'Rewena'	('Cox Orange' × 'Oldenburg') × *M. floribunda*	Germany	Early October
Commercial			
'Elstar'	'Golden Delicious' × 'Ingrid Marie'	The Netherlands	Early September
'Granny Smith'	bred from 'French Crab'	Australia	Early November
'Idared'	'Jonathan' × 'Wagener'	USA	Early October
'Jonagold'	'Golden Delicious' × 'Jonathan'	USA	End September
'Jonathan'	bred from 'Esopus Spizenberg'	USA	End September
'Jonica'	Mutant of 'Jonagold'	USA	End September
'Mutsu'	'Golden Delicious' × 'Indo'	Japan	Early October
'Red Elstar'	Mutant of 'Elstar'	The Netherlands	Early September
'Royal Gala'	'Kidd's Orange Red' × 'Golden Delicious'	New Zealand	End August
Old			
'Batul'	Unknown	Romania	End September
'Darusóvári'	Unknown	Hungary	Mid September
'Gravenstein'	Unknown	Italy	End August
'Húsvéti rozmaring'	Unknown	Hungary	Mid October
'King of the Pippins'	Unknown	England	Mid September
'London Pippin'	Unknown	England	End October
'Nyári fontos'	Unknown	Hungary	Mid August
'Orleans Reinette'	Unknown	France	Mid October
'Parker Pippin'	Unknown	England	Mid September

The disease resistant, commercial and old cultivars are described by Fischer and Fischer (1996, 1999), Khanizadeh and Cousineau (1998) and Nagy-Tóth (1998), respectively

[a] Bred for both scab and powdery mildew resistance according to Fischer and Fischer (1996, 1999)

Table 2 and their application schedules were according to the studies of Holb et al. (2005, 2007, 2012). N–P–K synthetic fertilizers (10:15:15 N–P–K ratio) was applied annually in the integrated plots at a dosage of 100 kg ha^{-1} active ingredient, while cattle manure was applied at a dosage of 30 t ha^{-1} every other year in the organic plots. The orchard was irrigated between 2000 and 2003 in July and August using a drip irrigation system. Irrigation was not needed in the years between 2004 and 2011. Winter pruning was performed annually in late winter and two summer prunings were carried out each year at the beginning of June and August. In both production systems, hand fruit thinning was performed annually in early June for all cultivars.

Environmental monitoring and assessments of disease and yield

Rainfall and mean daily temperature were measured with an agrometeorological station (METOS, Pessl Instrument GmbH, Weiz, Austria) from 1 April until 10 October in each year from 2000 until 2011. The weather station was placed at the centre of the experimental orchard and sensors were placed at a 1.5 m height from the ground.

Powdery mildew was assessed on the middle five trees of all cultivars within each replicate plot of both production systems. Both shoot and fruit were assessed on each of these five trees. The annual assessment period during the 12 years started from 15 April and ended on 30 August

Table 2 Fungicide, insecticide, and herbicide active ingredients used in the apple orchard at Debrecen-Pallag, Hungary, 2000–2011

Integrated	Organic
Fungicides	
Captan, 50%	Calcium polysulfides, 29%
Copper hydroxide, 77%	Copper hydroxide, 77%
Copper sulphate, 350 g l^{-1}	Copper sulphate, 350 g l^{-1}
Difenoconazole, 250 g l^{-1}	Elemental sulphur, 80%
Dithianon, 70%	Elemental sulfur, 900 g l^{-1}
Dodine, 500 g l^{-1}	
Kresoxim-methyl, 50%	
Pyrimethanil, 300 g l^{-1}	
Trifloxystrobin, 50%	
Insecticides	
Acetamipirid, 20%	*Bacillus thuringiensis*, 3.2%
Fenoxicarb, 25%	Mineral oil, 90%
Flufenzin, 200 g l^{-1}	Plant oil extract, 50%
Hexytiazox, 10%	
Lufenuron, 50 g l^{-1}	
Mineral oil, 90%	
Teflubenzuron, 150 g l^{-1}	
Thiacloprid, 480 g l^{-1}	
Triflumuron, 25%	
Herbicides	
Glyphosinate-ammonium, 360 g l^{-1}	

using a 15-day interval within this period, which resulted in ten assessments each year. Disease presence/absence was assessed on 30 growing shoots and 30 fruit. Both plant parts were selected randomly on each tree at each assessment date. Disease incidence for shoot and fruit was calculated as the percentage of diseased shoots and fruits, respectively.

Yield at harvest was determined each year by measuring fruit weight per tree from the middle five trees for each cultivar in both the integrated and organic plots. The starch–iodine index chart for apples was used to determine timing of fruit harvest (Blanpied and Silsby 1992) for each year, cultivar, and management system. Organic/integrated yield ratio was also calculated for each cultivar as organic yield was divided by integrated yield and multiplied with 100.

Data analyses

The 12-year data set of powdery mildew incidences was averaged to obtain a single value for each assessment date, cultivar, plant part and production system. Then, split–split-plot analysis of variance was used to analyse the data of final powdery mildew incidence (Statistical Analysis System v. 8.1; SAS Institute Inc., Cary, NC, USA), where years were assigned as blocks, production systems as main plots, apple cultivars as sub-plots and plant parts as sub–sub-plots. Before the analyses, powdery mildew incidence data were arcsine-square root transformed for data normality.

Powdery mildew incidence was analysed (separately for fruit and shoot) using Waller–Duncan Bayesian least significant difference (BLSD) test according to the classification procedure in the study by Holb (2007). The procedure was applied to each year and each disease assessment date, after which the cultivars were assigned to the classification category in which they were most frequently classified by the BLSD classification procedure. Five cultivar classification categories were obtained for the two plant parts and for the two productions systems: (1) low, (2) low-to-middle, (3) middle, (4) middle-to-high, and (5) high level of powdery mildew.

Mean powdery mildew incidences were calculated for each BLSD classification category separated by plant part, production system and assessment date. Then incidence data of each classification category was plotted against time from 15 April in each year. Non-linear growth functions were fitted to these disease incidence data and disease parameters upper asymptote Y_f (maximum percentage of disease incidence), relative rate parameter β (percent incidence day^{-1}), and inflection point M (days) were estimated from the best fitted three-parameter logistic function according to Holb (2007). In addition, the area under the disease progress curve (AUDPC) was calculated for powdery mildew progress of each classification category according to Madden et al. (2007). Then standardized AUDPC ($AUDPC_S$) was calculated as the AUDPC values were divided by the duration of the epidemic in days from 15 April to 30 August. Y_f, β, M, and $AUDPC_S$ values were compared using LSD tests ($\alpha = 0.05$) for the five classification categories.

Results

Weather conditions

Rainfall was 221.3, 300.4, 295.3, 244.1, 388.3, 391.5, 366.8, 359.8, 355.1, 353.2, 577.5, and 365.7 mm during the period of 1 April–10 October in 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, and 2011, respectively. Mean daily temperature was 16.9, 16.2, 15.9, 16.4, 15.3, 14.7, 15.5, 15.8, 15.3, 14.8, 13.5, and 15.9 °C during the period of 1 April–10 October from 2000 until 2011. The driest years with the most suitable weather periods for powdery mildew epidemics were 2001, 2002, 2003, and 2004. In these years, the seasonal dry periods, longer than 2 weeks, occurred in April, June, July, and

August. Weather conditions for powdery mildew epidemics were moderately to highly suitable during the assessed periods from 2000 until 2011.

Final powdery mildew incidence

ANOVA indicated significant ($P < 0.05$) differences among production systems, cultivars, and plant parts for final powdery mildew incidence (Table 3). In addition, interactions among treatment factors were non-significant. With the effect for years being non-significant, the mean of the 12-year data set were presented (Table 4).

The 12-year pooled data of final powdery mildew incidence on shoots and fruit ranged from 0.0 to 7.4 for the resistant, from 1.3 to 34.9 for commercial, and 0.0–1.8 for the old cultivars (Table 4). Final mildew incidences of the cultivars were generally lower in the integrated than in the organic production system, except for shoots of cvs 'Reglindis', 'Reka', 'Rewena', 'Parker Pepin', and 'Kings of the Pippin', which had very light infection, but showed the opposite case. Final powdery mildew incidences for fruit were lower for the cultivars compared with final shoot incidences in both production systems with the exception of cv 'Rewena', which showed a higher fruit than shoot incidence. Mildew infection at harvest was moderate or high for cultivars 'Idared', 'Jonagold', 'Jonathan', 'Jonica' and 'Royal Gala' from the commercial cultivar group in both production systems. However, both shoots and fruit of all resistant and old cultivars remained free from *P. leucotricha* infections to an acceptable level in both production systems (final incidence was below 7.5%). Two resistant and five old cultivars ('Reglindis', 'Reka', 'Orleans Reinette', 'Gravenstein', 'Húsvéti rozmaring', 'Nyári fontos' and 'Parker Pippin') showed no symptoms on fruit in either production system.

Cultivar classification and powdery mildew progress in cultivar classification categories

Disease resistant cultivars received a low, a low-to-middle, or a middle classification category for the season-long powdery mildew assessments (Table 4). In contrast, the most frequent classification categories were middle, middle-to-high or high for the commercial cultivars, while the old cultivars were consistently assigned to the low classification category for powdery mildew development. The classification categories of most cultivars were slightly or not different between shoot and fruit powdery mildew, nor between integrated and organic production systems (Tables 4, 5). Least frequent differences (0 and 1 case, respectively) were obtained among the resistant cultivars between shoot and fruit, and most frequent (4 and 5 cases, respectively) among the resistant cultivars between integrated and organic production system (Table 5).

In the integrated production system, no shoot or fruit powdery mildew was observed on the cultivars in the low classification (Fig. 1). Shoot powdery mildew progress commenced at mid-April (on day 0) on cultivars in the low-to-middle and middle classification category, while disease symptoms appeared 2 weeks before the first assessment date (early April) for the two highest classification categories (middle-to-high and high). Shoot powdery mildew incidence increased quickly up to day 30 (mid-May) for the low-to-middle and middle categories, and up to day 60 (mid-July) for the two highest categories (middle-to-high and high). Fruit powdery mildew in the integrated plots commenced in mid-April (day 0) for the high classification category and in mid-May (day 30) for the classification categories of low-to-middle, middle, and middle-to-high. The disease levelled off by mid-July (day 60) for the low-

Table 3 Analysis of variance for the effects of year (2000–2011), production system (organic versus integrated), cultivar (27 apple cultivars), and plant part (shoot versus fruit) on final powdery mildew incidence (%) and yield (kg tree^{-1}) in the apple orchard at Debrecen-Pallag, Hungary

Source of variation	*df*	Final powdery mildew incidence[a]			Yield		
		MS	*F*	*P*	MS	*F*	*P*
Year (Y)	11	241.2	3.1	0.0522	424.9	17.9	<0.0001
Production system (PS)	1	765.4	9.2	0.0115	1170.7	49.3	0.0001
Main plot error	11	83.4			20.6		
Cultivar (C)	26	937.9	41.9	0.0001	38.3	56.4	<0.0001
MS × C	26	708.3	27.2	0.2133	33.2	1.4	0.0920
Sub-plot error	572	22.4			23.7		
Plant part (PP)	1	177.8	7.9	0.0051			
MS × PP	1	27.2	1.2	0.2165			
C × PP	26	18.9	0.8	0.6904			
MS × C × PP	26	22.4	1.0	0.5150			
Sub–sub-plot error	594	22.5					

df degree of freedom, *MS* mean square, *F F* test, *P* probability values from analyses of variance

[a] Based on arcsine-square root transformed disease incidence data

Table 4 Mean powdery mildew incidences for shoot and fruit, and cultivar classification categories of 27 apple cultivars based on their season-long powdery mildew development on shoot and fruit in integrated and organic production systems (Debrecen-Pallag, Hungary, 2000–2011)

Cultivar	Integrated				Organic			
	Shoot powdery mildew		Fruit powdery mildew		Shoot powdery mildew		Fruit powdery mildew	
	Incidence[a]	Classification[b]	Incidence	Classification	Incidence	Classification	Incidence	Classification
Disease resistant								
'Reanda'	2.4	2	1.8	2	5.3	3	3.3	3
'Reglindis'	0.1	1	0.0	1	0.0	1	0.0	1
'Reka'	0.2	1	0.0	1	0.0	1	0.0	1
'Releika'	3.9	3	3.3	3	7.1	3	5.1	3
'Renora'	2.4	2	1.6	2	4.6	3	3.4	3
'Remo'	2.7	2	1.2	2	4.1	3	2.8	3
'Resi'	4.1	3	3.4	3	7.4	3	5.0	3
'Retina'	2.0	2	1.2	2	4.3	3	3.3	3
'Rewena'	0.3	1	0.0	1	0.1	1	1.1	2
Mean\sum[c]	2.0	17	1.8	17	3.7	21	2.6	22
Commercial								
'Elstar'	4.5	3	3.6	3	10.3	4	4.3	3
'Granny Smith'	8.1	4	3.8	3	10.3	4	5.0	3
'Idared'	9.8	4	6.0	4	16.3	4	8.4	4
'Jonagold'	11.5	5	7.4	5	17.0	4	12.8	4
'Jonathan'	15.5	5	10.8	5	34.9	5	23.4	5
'Jonica'	9.7	4	5.8	4	19.5	4	17.5	5
'Mutsu'	2.5	2	1.3	2	4.0	3	3.4	3
'Red Elstar'	6.7	4	4.3	4	9.8	4	4.4	3
'Royal Gala'	7.5	4	5.5	4	12.1	4	7.5	4
Mean\sum	8.4	35	5.4	34	14.9	36	9.6	34
Old								
'Batul'	0.8	1	0.0	1	1.8	2	1.3	2
'Darusóvári'	0.5	1	0.0	1	1.1	2	0.8	2
'Gravenstein'	0.0	1	0.0	1	0.6	1	0.0	1
'Húsvéti rozmaring'	0.1	1	0.0	1	0.5	1	0.0	1
'King of the Pippins'	1.5	2	0.0	1	0.8	2	0.4	1
'London Pippin'	0.4	1	0.0	1	1.0	2	0.8	2
'Nyári fontos'	0.1	1	0.0	1	0.1	1	0.0	1
'Orleans Reinette'	0.4	1	0.0	1	0.8	2	0.0	1
'Parker Pippin'	1.4	2	0.0	1	0.7	2	0.0	1
Mean\sum	0.6	11	0.0	9	0.8	15	0.4	12

[a] Incidence = final disease incidence (%). Data are means of 12-year observations from 2000 to 2011 where 5 tree-replicates were used in each year ($n = 60$)

[b] Classification = cultivar classification categories. Waller–Duncan Bayesian least significant difference (BLSD) values with $k = 100$ were used to compare cultivars. Then, means were classified as low (1), low-to-moderate (2), moderate (3), moderate-to-high (4), or high (5) level of powdery mildew to shoot or fruit separately for integrated and organic production systems following the categorization procedures described by Holb (2007)

[c] Mean\sum = Mean final disease incidences of each cultivar subgroup (resistant, commercial, and old)/sum of each cultivar classification group for each cultivar subgroup (resistant, commercial, and old)

to-middle and by late August (between days 100 and 110) for middle, middle-to-high and high categories.

Like in the integrated plots, no shoot or fruit powdery mildew was observed for the low classification category in the organic plots (Fig. 1). Shoot powdery mildew progress started in early April (before the first assessment date) for the two highest categories (middle-to-high and high) (Fig. 1). Shoot powdery mildew incidence progressed from

Table 5 Differences of cultivar classification category between powdery mildew progress on shoot and fruit separately for integrated and organic production systems, and between integrated and organic production systems separately for powdery mildew progress on shoot and fruit (Debrecen-Pallag, Hungary, 2000–2011)

Differences of classification category[a]	Between S & F		Between I & O		Differences of classification category	Between S & F		Between I & O		Differences of classification category	Between S & F		Between I & O	
	Int	Org	S	F		Int	Org	S	F		Int	Org	S	F
Disease resistant					Commercial					Old				
'Reanda'	0	0	1	1	'Elstar'	0	1	1	0	'Batul'	0	0	1	1
'Reglindis'	0	0	0	0	'Granny Smith'	1	1	0	0	'Darusóvári'	0	0	1	1
'Reka'	0	0	0	0	'Idared'	0	0	0	0	'Gravenstein'	0	0	0	0
'Releika'	0	0	0	0	'Jonagold'	0	0	1	1	'Húsvéti rozmaring'	0	0	0	0
'Renora'	0	0	1	1	'Jonathan'	0	0	0	0	'King of the Pippins'	1	1	0	0
'Remo'	0	0	1	1	'Jonica'	0	1	0	1	'London Pippin'	0	0	1	1
'Resi'	0	0	0	0	'Mutsu'	0	0	1	1	'Nyári fontos'	0	0	0	0
'Retina'	0	0	1	1	'Red Elstar'	0	1	0	1	'Orleans Reinette'	0	1	1	0
'Rewena'	0	1	0	1	'Royal Gala'	0	0	0	0	'Parker Pippin'	1	1	0	0
Sum of cultivar subgroup	0	1	4	5	Sum of cultivar subgroup	1	4	3	4	Sum of cultivar subgroup	2	3	4	3

Between S & F between shoot and fruit, *Int* integrated, *Org* organic, *Between I & O* between integrated and organic, *S* shoot, *F* fruit

[a] Differences of classification categories were calculated from Table 4, e.g. cultivar 'Reanda' (differences between shoot and fruit, integrated) is 0 = 2 (shoot classification category) − 2 (fruit classification category)

mid-April for the other two categories (low-to-middle and middle), and then levelled off at asymptotic levels between days 20 and 45 for all categories. Fruit powdery mildew in the organic plots started in mid-April (day 0) for the high and middle-to-high, in early May (day 15) for the middle, and in mid-May (day 30) for the low-to-middle classification categories. Y_f (upper asymptote) for fruit incidence was reached on days 55–65 for the low-to-middle, on days 85–95 for the middle and middle-to-high, and on days 100–110 for the high classification categories.

Disease progress parameters in cultivar classification categories

$AUDPC_S$ and Y_f values of the cultivar classification categories were generally lower in the integrated plots compared with those in the organic ones (Table 6). Values of both parameters were significantly different ($P < 0.05$) among the classification categories in both production systems, and for both plant parts except for one case in the organic plots for fruit Y_f.

Relative rate parameter (β) values decreased with classification categories in the integrated plots but no decrease or increase of β values with cultivar classification categories could be observed for the organic plots (Table 6). Values of the inflection point (M) consistently decreased for fruit in the organic production system, but no consistent decrease or increase of M values with cultivar classification categories could be observed for other cases of plant part versus production system (Table 6). Disease parameters of β or M values did not show consistent differences ($P < 0.05$) among the cultivar classification categories.

Yield

ANOVA for yield data showed significant ($P < 0.05$) differences among years, production systems, and cultivars (Table 3). Due to the large size of the yield data set, only the overall mean yield for the 12-year period was presented (Table 7).

Mean yield ranged from 13.7 to 20.9 kg tree^{-1} for the integrated and 10.1–14.8 kg tree^{-1} for the organic production system, and from 11.8 to 16.5 kg tree^{-1} for the resistant, 11.1–20.9 kg tree^{-1} for the commercial and 10.1–19.0 kg tree^{-1} for the old cultivars for the 12-year period (Table 7). Over the overall 12-year period, 20.9 kg tree^{-1} was the highest yield at harvest on the commercial cultivar 'Jonica' in the integrated production systems, while 10.1 kg tree^{-1} fruit was the lowest on the old cultivar 'Parker Pippin' in the organic production system.

Yield for the 12-year period was significantly lower ($P < 0.05$) in the organic plots than in the integrated ones (Table 7). Commercial cultivars had significantly higher yields than the resistant ones, whereas yields of old cultivars did not differ from the other cultivar subgroups in integrated plots. Cultivars did not differ in yields under organic production systems in the 12-year data set. Comparisons at cultivar group level showed that the commercial and old cultivar groups indicated significantly higher yield in the integrated orchard compared with organic one, while

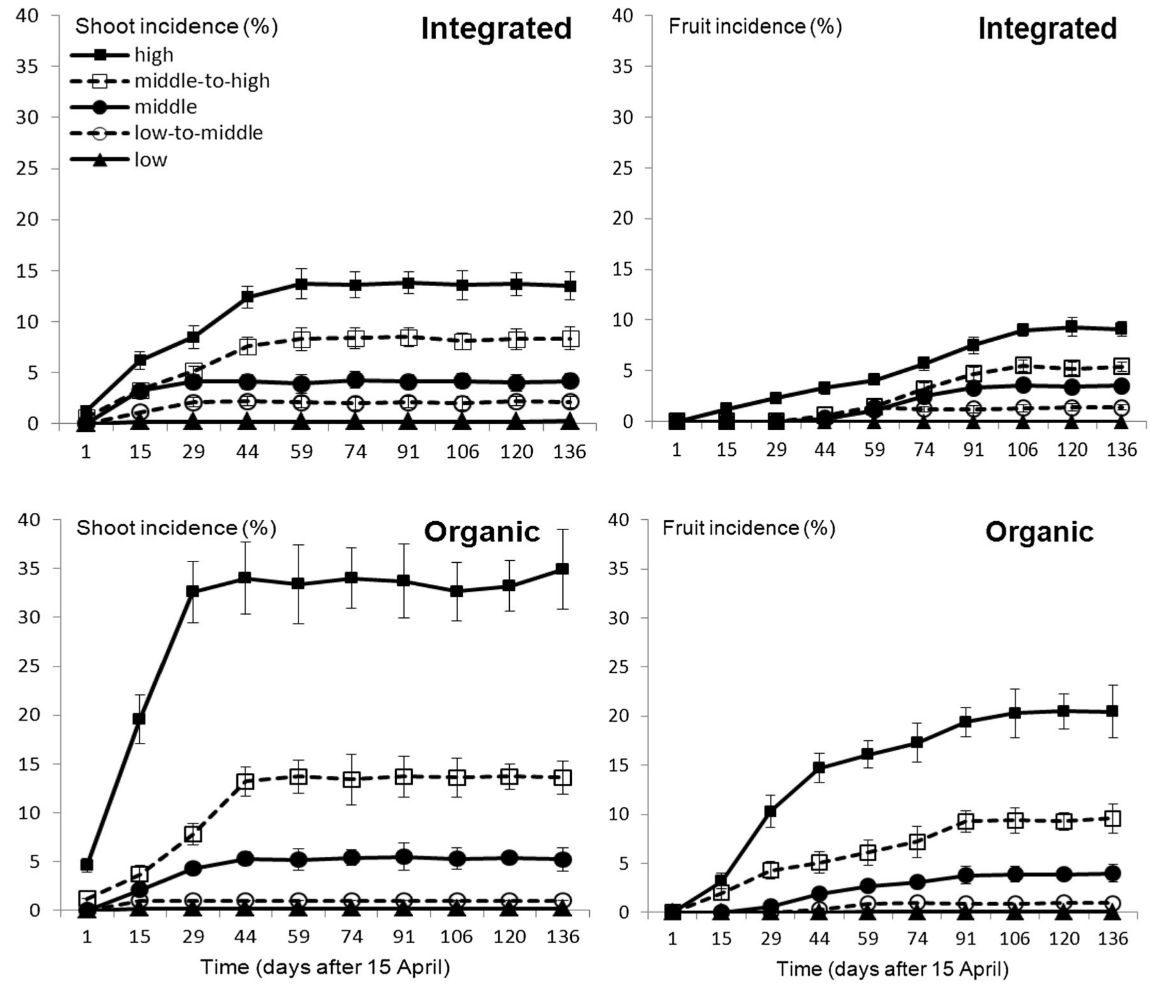

Fig. 1 Mean disease progress curves for each cultivar classification category for shoot and fruit powdery development in integrated and organic production systems (Debrecen-Pallag, Hungary, 2000–2011). Each *symbol* represents mean incidence values of a given assessment date over 12 years for each cultivar classification category. *Bars* represent standard error of mean values. In the assessed years, tight cluster or blooming phenological stages occurred at the day of 15 April

yield in the resistant cultivar group was not so much dependent on the disease management system.

Yield reduction of the cultivars ranged from 11.0 to 37.4% in the organic plots over the 12-year period compared with the integrated ones (Table 7). Mean yield reduction was the highest for the commercial cultivars (32.0%) while the lowest was for the resistant ones (17.2%). Overall, yield reduction was 25.7% for the organic plots compared with the integrated ones.

Discussion

In this study, season-long shoot and fruit powdery mildew progressions were evaluated on 27 apple cultivars to classify cultivars into five categories for integrated and organic apple orchards. Disease progress parameters for each classification category were also analysed and their possible significance was estimated for integrated and organic disease management. In addition, yield indicated differences in adaptability of the cultivars to the two production systems.

Categorising host resistance of apple cultivars to key fungal diseases, including powdery mildew, has been done for instance for supporting cultivar selection for growers and breeders (Aldwinckle 1974; Norton 1981; Pedersen et al. 1994; Washington et al. 1998; Afzal et al. 2002; Biggs et al. 2009; Bálint et al. 2013; Kellerhals et al. 2012; Blazek and Krenilova 2013; Paz-Cuadra et al. 2014). However, our study was the first where the cultivar categorisation was based on long-term, season-long disease progression for powdery mildew; and in addition, the categorisation was separated for the two prominent production systems: organic and integrated. Cultivar classification categories for powdery mildew showed that some cultivars (e.g. 'Jonathan', 'Jonagold', 'Jonica', 'Idared', 'Royal

Table 6 Disease parameters in the five cultivar classification categories for powdery mildew progress on shoot and fruit in integrated and organic production systems (Debrecen-Pallag, Hungary, 2000–2011).[a]

Cultivar classification category	$AUDPC_S$	Y_f	β	*M*
Integrated shoot				
Low (1)	0.10[b] a[c]	–[d]	–	–
Low-to-middle (2)	0.94 b	1.3 a	0.437 b	14.8 b
Middle (3)	1.89 c	4.2 b	0.341 b	11.2 a
Middle-to-high (4)	3.47 d	9.7 c	0.081 a	17.8 c
High (5)	5.74 e	17.9 d	0.069 a	12.6 ab
F test (*P* value)[e]	**	***	**	*
Integrated fruit				
Low (1)	0.00 a	–	–	–
Low-to-middle (2)	0.40 b	1.3 a	0.453 c	47.7 a
Middle (3)	0.91 c	3.5 b	0.112 b	65.8 b
Middle-to-high (4)	1.32 d	5.5 c	0.089 ab	69.5 b
High (5)	2.63 e	11.2 d	0.035 a	60.9 b
F test (*P* value)	*	***	**	*
Organic shoot				
Low (1)	0.09 a	–	–	–
Low-to-middle (2)	0.45 b	1.4 a	0.127 a	8.1 a
Middle (3)	2.29 c	6.2 b	0.124 a	15.9 b
Middle-to-high (4)	5.60 d	12.5 c	0.137 a	27.1 c
High (5)	15.18 e	30.5 d	0.226 b	14.2 b
F test (*P* value)	***	***	**	**
Organic fruit				
Low (1)	0.02 a	–	–	–
Low-to-middle (2)	0.31 b	0.9 a	0.244 a	47.2 a
Middle (3)	1.23 c	4.3 b	0.064 b	45.3 a
Middle-to-high (4)	3.21 d	30.1 c	0.021 b	27.4 c
High (5)	7.38 e	33.3 c	0.044 b	13.1 b
F test (*P* value)	***	**	**	**

[a] Disease parameters are: Y_f, upper asymptote; β relative rate parameter of disease progress (days^{-1}); and *M* the inflection point of disease progress; and standardized area under the disease progress curve ($AUDPC_S$) from the observed data set and divided by the duration of the epidemic in days from 15 April until 30 August (% days)

[b] Means of 12-year data ($n = 12$)

[c] Values within columns and within shoot or fruit followed by different letters are significantly different. LSD *t* test was used for comparing treatments

[d] Due to low incidence values, no Y_f, β, and *M* values were available from curve fitting

[e] *, **, and *** are significantly different at 0.05, 0.01, and 0.001, respectively

Gala') in the commercial cultivar group received high classification categories (middle-to-high or high) for both shoot and fruit in both production systems. Planting of these cultivars imposes a great risk of inadequate powdery mildew control in both production systems under Central European conditions.

Categorising host resistance of apple cultivars to powdery mildew has also been done for reducing fungicide use in apple orchards (Jeger and Butt 1986; Parisi et al. 2013; Didelot et al. 2016). If fungicide applications against powdery mildew are based on software prediction, a measure of host resistance is a crucial input into disease warning systems for reliable disease management (Lalancette and Hickey 1986; Xu and Butt 1996; Xu 1999; Berrie and Xu 2003). Our production system-related cultivar categorizations, based on season-long powdery mildew progression, add more accurate cultivar information for disease warning systems compared to previous studies in which categorisations were based on one assessment date. Previous studies were able to provide only a single susceptibility category for a cultivar (Aldwinckle 1974; Norton 1981; Pedersen et al. 1994; Washington et al. 1998; Afzal et al. 2002; Biggs et al. 2009; Kellerhals et al. 2012; Bálint et al. 2013; Blazek and Krenilova 2013; Paz-Cuadra

Table 7 Mean yield (kg tree^{-1}) and organic/integrated yield ratio (%) of 27 apple cultivars in the overall 2000–2011 period in integrated and organic production systems at Debrecen-Pallag, Hungary

Cultivar	Yield		Organic/integrated yield ratio
	Integrated	Organic	
Resistant			
'Reanda'	13.7 a[a]	12.3 efgh	89.8
'Reglindis'	14.7 ab	11.8 cde	80.3
'Reka'	13.6 a	12.1 cdefgh	89.0
'Releika'	15.7 abc	11.9 cdef	75.8
'Renora'	16.3 abcdef	12.4 efgh	76.1
'Remo'	16.5 abcdef	13.9 k	84.2
'Resi'	14.7 ab	12.6 efghi	85.7
'Retina'	16.1 abcde	13.1 hij	81.4
'Rewena'	16.2 abcde	13.7 jk	84.6
Commercial			
'Elstar'	16.3 abcdef	12.7 efghij	77.9
'Granny Smith'	16.1 abcde	11.1 abc	68.9
'Idared'	20.8 h	13.0 ghijk	62.6
'Jonagold'	19.2 fgh	13.5 ijk	70.3
'Jonathan'	18.1 cdefgh	11.2 bcd	61.9
'Jonica'	20.9 h	13.8 kl	66.0
'Mutsu'	19.5 gh	12.9 fghijk	66.2
'Red Elstar'	16.5 abcdef	12.0 cdefg	72.7
'Royal Gala'	18.9 efgh	12.9 fghijk	68.3
Old			
'Batul'	15.9 abcd	12.3 efgh	77.4
'Darusóvári'	17.1 bcdefg	12.9 fghijk	75.4
'Orleans Reinette'	16.3 abcdef	12.4 efgh	76.1
'Gravenstein'	18.7 defh	14.8 l	79.1
'Húsvéti rozmaring'	17.1 bcdefg	11.1 abc	64.9
'London Pippin'	15.0 ab	10.4 ab	69.3
'Nyári fontos'	19.0 efgh	13.7 jk	72.1
'Parker Pippin'	14.8 ab	10.1 a	68.2
'King of the Pippins'	16.1 abcde	12.2 defgh	75.8
$LSD^{b}_{0.05}$	2.9	1.0	–
Resistant[c]	15.3 aA[a]	12.6 aA	82.8
Commercial[c]	18.5 bA	12.6 aB	68.0
Old[c]	16.7 abA	12.2 aB	73.3
$LSD_{0.05}$	3.0	1.2	–
Overall (cultivar)	16.8 a	12.5 b	74.3
$LSD_{0.05}$	3.2		–

Data are means of 12-year observations from 2000 to 2011 where 5 tree-replicates were used in each year ($n = 60$). Organic/integrated yield ratio was calculated as organic yield was divided by integrated yield and multiplied with 100

[a] For columns, values followed by the same small letter are not significantly different according to LSD test ($P < 0.05$). For rows, values followed by the same capital letter are not significantly different according to LSD test ($P < 0.05$)

[b] $LSD_{0.05}$ = least significant differences at $P < 0.05$ level

[c] $LSD_{0.05}$ values are 2.7, 3.1, and 3.0 for resistant, commercial and old cultivar groups, respectively

et al. 2014), but our study provided disease parameters ($AUDPC_S$ and Y_f) for each cultivar classification category, which can be a useful input in powdery mildew warning systems. Both $AUDPC_S$ and Y_f could differentiate powdery mildew classification categories for the two plant parts in both production systems. These parameters may also be useful for field resistance studies of apple powdery mildew, as they were for other plant diseases, such as wheat stem rust, lettuce downy mildew and apple scab (Thompson and Rees 1979; Lebeda and Jendrulek 1988; Holb 2007). However, our study also revealed that the rate parameter (β) and the inflection point (M) of the disease progress curve may not be good choices for separating powdery mildew classification categories of apple cultivars and, as a consequence, for using as an input in disease warning systems. This is in agreement with previous studies of Gilligan (1990), Lebeda and Jendrulek (1988), Ngugi et al. (2000), Holb et al. (2005, 2011), and Holb (2007), who reported that rate parameters and/or inflection point were hardly affected by treatments, and therefore, did not seem to be proper parameters for cultivar differentiation.

Previous studies demonstrated that powdery mildew development on shoots and fruit followed different epidemiological features; therefore, their disease incidence values can be different at various phenological stages (Jeger and Butt 1986; Jeger et al. 1986; Xu 1999). This study demonstrated that shoot incidence was consistently higher than fruit incidence on the cultivars that received classification categories from middle-to-high in both production systems. In addition, most shoot symptoms appeared early, while fruit symptoms only later in the season (Fig. 1). As the main inoculum sources of *P. leucotricha* originating from the overwintered mycelia inside or outside the bud (Jeger and Butt 1986; Jeger et al. 1986; Hickey and Yoder 2014; Xu 1999; Yoder 2000; Holb 2009; Marine et al. 2010), most infection occurs at green tip and early tight cluster stages, resulting in early leaf and shoot infections. For fruit, the most mildew-susceptible stages occur only later in the season from fruit set until 4- to 6-week old fruit (Holb 2009); therefore, first symptoms appear later in the spring. Moreover, shoot susceptibility decreases more slowly throughout the season than that for fruit, and therefore, the proportion of infected shoot increases more rapidly compared with infected fruit.

Temporal powdery mildew development was more rapid in the organic than in the integrated plots (Fig. 1) and the upper asymptote of powdery mildew progress curves was also higher in the organic than in the integrated plots (Table 4). This may be partially explained by the lower efficacy of fungicides in organic plots compared with integrated ones. However, relatively high mildew incidence of the commercial cultivars showed inadequate efficacy of applied fungicides such as ergosterol biosynthesis inhibitors in the integrated production systems, too (Holb 2009; Parisi et al. 2013). This suggests that an integration of management options is necessary for a more efficient powdery mildew control in both production systems. As mycelia of *P. leucotricha* mainly overwinter inside the buds, timing of the first sprays is a key issue for increasing efficacy of applied fungicides (Butt 1972; Jeger and Butt 1986; Holb 2009) not only for organic, but also for integrated orchards. Another option to increase spray efficacy against powdery mildew is the pruning of powdery mildew infected terminals during winter (Yoder and Hickey 1995; Holb 2009). This management option is also effective against overwintered conidia of *Venturia inaequalis* inside buds in organic apple orchards (Holb et al. 2004, 2005). Improved powdery mildew control was suggested by combining spray timing with winter pruning (Holb and Kunz 2016). The spray efficacy can be further increased if the orchard is established with a mixed cultivar-stand design using less mildew-susceptible cultivars in which cultivar selection can be based on the cultivar classification categories of this study.

This study demonstrated that powdery mildew control was unacceptable for most commercial cultivars in the organic plots, while it was sufficient for most old and all resistant cultivars (Table 4; Fig. 1). Although most old cultivars showed low powdery mildew incidence at harvest in the 12-year period, most of them had low yields (Tables 4, 5, 7). Kühn et al. (2003) and Holb et al. (2012) also noted that low susceptibility of old cultivars to diseases and/or pests is usually combined with inadequate yield, fruit size and fruit quality. Therefore, the old cultivars assessed in this study may only be suggested as parents for breeding purposes. Resistant cultivars may be viable options for organic production, as low disease incidence was coupled with acceptable yield for organic production (Holb 2007; Kellerhals et al. 2012; Holb et al. 2012) (Table 4). However, mildew resistant cultivars 'Reanda', 'Remo', 'Resi', and 'Rewena' showed both shoot and fruit powdery mildew symptoms, indicating a resistance breakdown of these cultivars and a possible pathogen adaptation. This phenomenon needs to be managed through, e.g. establishing mixed cultivar-stand and/or complementary application of highly effective fungicides, which is an issue in organic systems. Growers should be encouraged to establish a mixed cultivar-stand to reduce inoculum pressure of *P. leucotricha* to avoid adaptation of fungal pathogen populations to a cultivar planted in a large area. In addition, the practical use of new cultivars with durable resistance through gene pyramiding are also essential (Jeger and Butt 1986; MacHardy et al. 2001; Holb 2007; Dewdney et al. 2003; Parisi et al. 2013; Didelot et al. 2016; Passey et al. 2016).

In this study, a mean yield reduction of 25.7% was determined in the organic plots over the 12-year period compared with the integrated ones, confirming the findings of previous studies. Peck et al. (2006) reported a yield reduction of 50% for cv 'Galaxy Gala' in organic versus integrated treatments, whereas more recently Holb et al. (2012) reported an overall 27% yield reduction of 10 cultivars in an organic production system compared with an integrated one. Yield reduction in organic growing may relate to several factors, for instance: (1) low efficacy of approved plant protection products resulting in significant yield loss caused by diseases such as powdery mildew and pests (e.g. Holb et al. 2003; Holb 2007, 2009; Holb et al. 2012), (2) large amounts of applied sulphur compounds have a considerable fruit-thinning and a photosynthesis reduction effect in the organic orchards (e.g. Johnsson et al. 2010), and/or (3) unbalanced nutritional status of leaf and fruit tissues in the organic production system (e.g. Peck et al. 2006). This suggests that improvement in overall orchard management practices is essential for organic apple orchards to achieve more consistent and/or larger amounts of yields.

In summary, this study demonstrated a cultivar classification system that provides the disease progress parameters of $AUDPC_S$ and Y_f as useful inputs for software predicting powdery mildew infections related to host resistance. This classification system together with yield attributes can assist organic growers in choosing cultivars more suitable to regions with climate conditions similar to Central Europe if they also consider other agronomical features (e.g. fruit quality parameters and scab susceptibility) of the cultivars shown in the studies of Holb (2007) and Holb et al. (2012).

Author contribution statement IH performed the research, analyzed the data and wrote the manuscript. IH coordinated the research project.

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Compliance with ethical standards

Conflict of interest The author declares no conflict of interest.

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