Developing a management strategy based on the relationships between brown rot and codling moth in two apple production systems

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Abstract

Brown rot (BR) in relation to codling moth damage (CMD) is a key issue in apple production but the impact of these pests has not been assessed jointly. In addition, categorising cultivar reaction to these two pests for sustainable production systems could be essential for improving pest management. Therefore, in a 12-year study, 27 apple cultivars (9 scab-resistant, 9 commercial, and 9 old) were assessed for their reactions to BR in relation to CMD in integrated and organic production systems, and classified into 3 categories ("low", "medium", and "high") based on their season-long BR and CMD incidences. Then the 12-year temporal BR and CMD progresses in each category were analysed by fitting three-parameter logistic functions to process data and then by deriving 5 model variables for BR and CMD incidences. Here, we showed BR-CMD relationships in both production systems, which indicated that final BR and CMD incidences were significantly higher in organic systems. Our results show that season-long BR and CMD incidences were "low" for most resistant cultivars, and "medium" or "high" for most commercial and old ones. The area under the disease and pest progress curves indicated consistent differences among all categories in both production systems; and they were used to differentiate cultivar reactions to BR and CMD. Based on these categories and BR-CMD relationships, here we developed a new brown rot and codling moth forecasting and management strategy (BRCM-FMS). BRCM-FMS and general pest management programme (GPMP) were then compared in an additional 4-year study. This was the first study to show that the BRCM-FMS reduced annual spray applications by 21.4–41.7% in integrated and 12.5–31.3% in organic production system compared to GPMP. Disease incidences in the two programmes were similar in all years, production systems and classification categories. Less sprays and similar disease incidences provide economic and environmental benefits for growers.

Keywords *Monilinia fructigena* · *Cydia pomonella* · *Malus* x *domestica* · Integrated farming · Organic farming

1 Introduction

Monilinia fructigena (Aderh. & Ruhl.) Honey is a fungal pathogen that causes brown rot (BR) and considerable pre- and postharvest fruit loss in pome fruit orchards (Byrde and

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Willetts 1977; Xu and Robinson 2000; Zhu et al. 2016). BR causes a major fruit rot of apple in Central Europe (Holb et al. 2011; Holb 2019). In integrated apple orchards, yield losses due to BR are usually low and below 10% (Xu and Robinson 2000). However, preharvest yield losses up to 46% have been reported in organic apple orchards in Hungary (Holb and Scherm 2008; Holb et al. 2011). In integrated production system (IPS), synthetic plant protection products are restricted but they are banned in organic production system (OPS; Anon. 2000); therefore, the used plant production products are less effective in OPS than in IPS with the consequences that disease and pest damages are likely to be more serious in OPS, which results in a considerable yield reduction (e.g. Rader et al. 1985; Holb et al. 2012).

Preharvest fruit damage caused by *M. fructigena* occurs mainly a few weeks before harvest and at harvest (Xu and Robinson 2000; Holb and Scherm 2008). *M. fructigena* can

infect fruit via fresh or partially healed wounds, whereas infection of ripe apples via lenticels or fruit-to-fruit contact occurs only at low frequency (Byrde and Willetts 1977; Xu and Robinson 2000; Vasić et al. 2018). Wounds on fruit can be caused by various abiotic or biotic factors, such as insects, birds, growth cracks, and mechanical injury due to wind storms or hail, with insect injury having the highest incidence (Xu and Robinson 2000; Holb and Scherm 2008). Holb and Scherm (2008) indicated that insect injury accounted for 79.4% of the total injury in OPS and 36.6% in IPS by harvest time, which was mainly caused by codling moth (CM, *Cydia pomonella* L.). Codling moth is a serious pest of apple worldwide and accounts for large amount of the insecticides used in apple orchards (Witzgall et al. 2008; Walker et al. 2017; Kadoić Balaško et al. 2020). Severe codling moth damage (CMD) usually occurs in back gardens, abandoned orchards as well as on wild apple, pear, and sorbus trees (Kadoić Balaško et al. 2020). CMD causes the market damage of 10–30% of the apple fruits especially in OPS (Holb and Scherm 2008). CM management may require 8–15 insecticide treatments including a large amount of pesticide use per season (Kadoić Balaško et al. 2020). Therefore, classification of cultivar reaction to BR could only be measured reliably in relation to CMD.

Few studies have assessed apple cultivar reactions or susceptibility to *M. fructigena* (Byrde and Willetts 1977; Sharma and Kaul 1988). Some earlier studies assessed apple cultivar reaction to CM attack (e.g. Hogmire and Miller 2005; Holb et al. 2012; Danelski et al. 2017), while recently cultivar reaction or susceptibility was based on CM oviposition and not on direct larval damage (e.g. Davis et al. 2013; Joshi et al. 2015; Danelski et al. 2017). However, no information is available on the reaction of apple cultivars to BR in relation to CMD under regularly sprayed orchard conditions. This knowledge would be important especially in the two prominent components of sustainable apple production: in IPS and OPS (Alaphilippe et al. 2013; Kadoić Balaško et al. 2020). Efficacy of BR and CM control is significantly greater in IPS compared to OPS, which results in different disease inoculum pressure and CM gradation from year to year in these orchards (Judd and Gardiner 2005; Holb and Scherm 2008; Holb et al. 2011).

Most disease warning and pest forecasting systems in fruit production require information on host susceptibility (e.g. Berrie and Xu 2003; Chappell et al. 2015). A BR warning system was suggested for OPS (Holb et al. 2011) based on disease progress curve variables, seasonal spore dispersal, and weather parameters. However, cultivar classification (CC) and BR-CMD relationship have not been considered in the submodels of this warning system; though both factors could be essential in IPS and OPS.

In previous research, BR susceptibility of apple cultivars was rated based on % of BR incidence at the end of the season, and then cultivars were sorted into classes (Byrde and Willetts 1977; Sharma and Kaul 1988; Zhu et al. 2016). Similarly, CM susceptibility classification was based mainly on CMD incidence (0–100%; e.g. Hogmire and Miller 2005; Holb et al. 2012; Danelski et al. 2017) or on susceptibility index (0–1; Joshi et al. 2015). Thus, CCs for both pests have been based only on one assessment date so far; and therefore, these classifications do not represent the seasonal progress of pest damage, based on repeated assessments under various pesticide treatments. Other studies, investigating different plant diseases, classified cultivars into categories using season-long disease progress data based on 4–8 disease assessments (Thompson and Rees 1979; Holb 2017). These studies suggested that the area under the disease progress curve (*AUDPC*), the upper asymptote or the disease growth rate derived from the disease progress curves could be appropriate for analysing temporal disease progress of each classification category. Such a procedure could be of use for classifying apple cultivars for BR and CMD, and maybe be incorporated successfully into a newly developed pest management strategy for IPS and OPS, which may also result in a reduction of the pesticide use in apple production.

This 12-year study (2000–2011) with an original data set was aimed at (i) evaluating the reaction of 27 apple cultivars to BR and CMD under IPS and OPS, (ii) classifying cultivar reactions into categories based on their BR and CMD incidences assessed during the whole season, (iii) analysing the temporal BR and CMD progress in each classification category, (iv) determining any relationships between BR and CMD incidence for each classification category, and (v) developing a new pest management strategy based on the classification categories and the BR-CMD relationships. In an additional 4-year study (2016–2019), the efficacy of the new pest management programme was evaluated for the two production systems in comparison with general pest management programmes.

2 Materials and methods

2.1 Experimental area and environmental monitoring

A 12-year study (from 2000 to 2011) was performed in the apple orchard of the University of Debrecen, which consisted of a mixed stand of cultivars and was located in Debrecen-Pallag (47° 31′ 60″ N, 21° 37′ 60″ E), eastern Hungary (Fig. 1a). The orchard was established in 1996 and trees were grafted on M.26 rootstock. Trees were arranged in a 4 m between-row and a 1.5-m within-row distances using a 3.2-m-wide bare soil strip between rows (maintained mechanically with a disc-tiller) and 0.8 m straw mulch strip along the rows. Trees were annually pruned to a spindle shape and were about 1.8–2.5 m tall during the evaluation period. Integrated and organic

Fig. 1 Experimental field of apple cultivars collection in integrated and organic orchards (Debrecen-Pallag, Hungary). (**a**) experimental orchard, (**b**) Metos® agrometeorological station used in the orchard, (**c**) brown rot symptoms, and (**d**) codling moth damage in apple fruit.
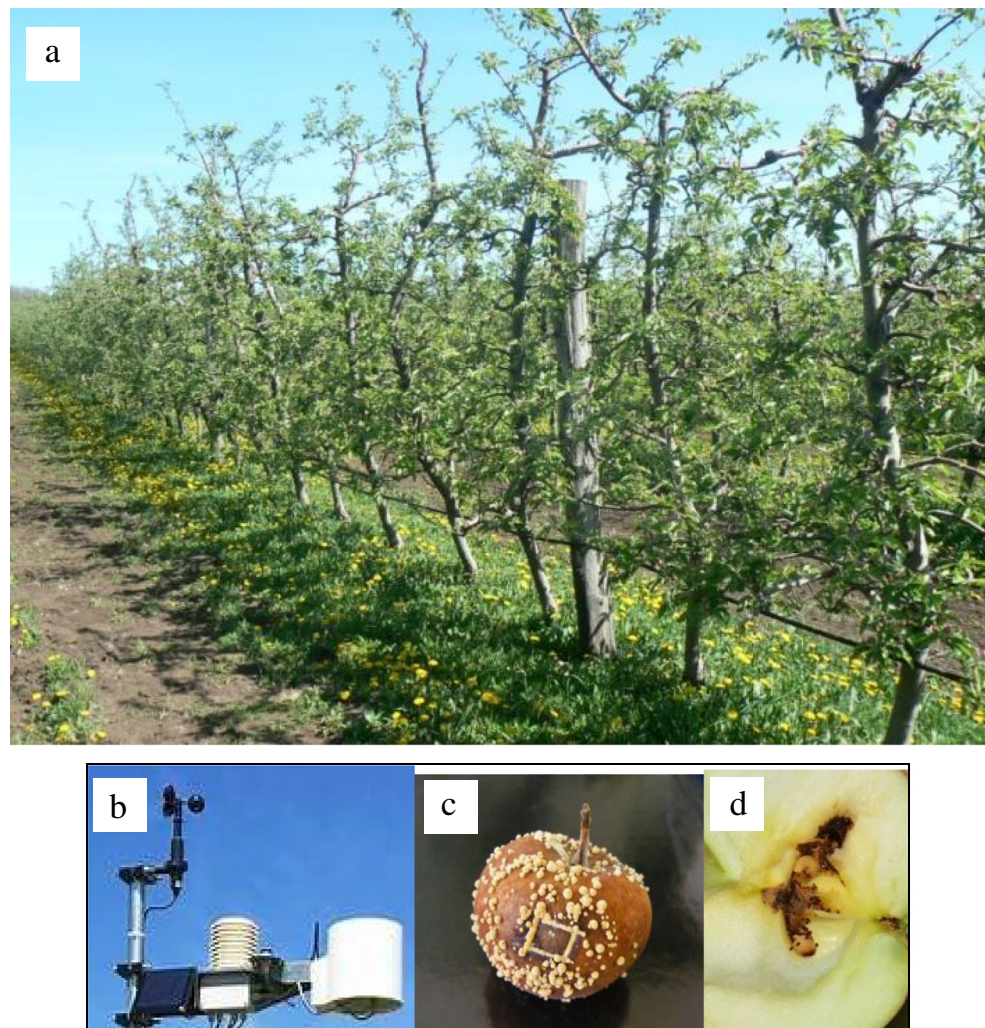
production blocks were setup within the orchard and replicated three times. Each block had nine rows that included the same 27 cultivars planted in a completely randomised design, using three replicate plots per cultivar with seven trees in each replicate. Windbreaks of Italian alder (*Alnus cordata)* and a 4-m-wide road were used for separating each block. The pedigree and origin of the planted cultivars are reported in the study of Holb (2017). Three subgroups of cultivars were planted: (i) the widely grown commercial cultivars, (ii) the scab-resistant cultivars bred in Dresden-Pillnitz (Fischer and Fischer 1999) (brown rot-resistant apple cultivars are not available), and (iii) those old cultivars which were the most known in the past in the apple growing regions of Central Europe.

The integrated system followed a pest management program according the European Integrated Fruit Production (IFP) guidelines (Cross and Dickler 1994). Pest management in the organic plots was performed according to the International Federation of Organic Agriculture Movements (IFOAM) organic production guidelines (Anon. 2000). These guidelines

had been applied since the setup of the orchard in 1996. The first flight of codling moth was checked by codling moth pheromone traps and it was always detected at the fruit set in all years. All key pests (codling moth, leaf rollers and aphids) and diseases (apple scab—*Venturia inaequalis* and powdery mildew—*Podosphaera leucotricha*) were managed according to the roles of IFP and IFOAM in integrated and organic orchard parts, respectively. Details on the orchard management in terms of the used pesticide products, pesticide applications, fertilisation, irrigation, pruning, and mechanical fruit thinning operations for the two production systems are included in the studies of Holb et al. (2012) and Holb (2017). All cultivars received the same orchard management practices.

Rainfall (mm day^{-1}) and mean daily temperature (°C day^{-1}) were recorded using a METOS agrometeorological station (Pessl Instrument GmbH, Weiz, Austria, Fig. 1b) from 1 April until 10 October in each consecutive year from 2000 until 2011. The agrometeorological station was placed in the centre of the orchard and recording sensors were established at a 1.5 m height from the ground.

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2.2 Assessments on brown rot, codling moth damage and yield

Brown rot and codling moth damage incidences were observed on the mid five trees of each cultivar within each replicate plot of integrated and organic systems at 15-day intervals from 15 May to 30 September (ten times per year) during all years of the study (from 2000 to 2011). On each tree, 30 fruits were chosen typical for the given phenological stage and assessed on each date. Fruits were considered to be infected by *M. fructigena* or damaged by codling moth larvae if there was at least one visible brown rot lesion (Fig. 1c) or fruit damage symptoms associated with activities of codling moth larvae (Fig. 1d), respectively. Brown rot and codling moth damage incidences were then expressed as percentage of diseased and damaged fruits.

Yield was determined each year in each replicate plot of integrated and organic systems. The weight of all fruits was measured on the mid five trees of each cultivar at harvest. Timing of fruit harvest was determined by using the starch-iodine index chart for apples.

2.3 Practical evaluations of the newly developed brown rot and codling moth forecasting and management strategy

A new brown rot and codling moth forecasting and management strategy (BRCM-FMS) was developed based on cultivar classification categories, progress curve variables, and the relationships of brown rot and codling moth damage incidences. The newly developed BRCM-FMS was tested and compared to general spray programmes in commercial apple orchards at Eperjeske (eastern Hungary, 48° 21′ 30″ N, 22° 13′ 10″ E) on cv. 'Idared', with a planting distance of 4 × 1 m, grafted on rootstocks M26. A 4-year (2016–2019) spray programme was established in the blocks of integrated and organic systems, containing three equally sized treatment blocks (replicated four times with a minimum of 50 trees block^{-1} cultivar^{-1}). Block 1: the brown rot and codling moth management strategy was applied based on the new developed BRCM-FMS in both systems; block 2: a general brown rot and codling moth management strategy (GBRCM-MS) was applied according to IFP and IFOAM standards, in the blocks of integrated and organic systems, respectively; and block 3: no brown rot and insect managements were applied in neither systems (control). All blocks were set up in 2016 and were re-randomised in every year until 2019. Treatment blocks were prepared at mid-February in every year. In organic blocks 1 and 2, copper and sulphur compounds were used against brown rot and *C. pomonella* granulosis virus combined with mating disruption with pheromones were used against codling moth. In each year and location, brown rot and codling moth damage

incidences were assessed in 50 fruit per cultivar at harvest according to Holb and Scherm (2008).

2.4 Data analyses

2.4.1 ANOVA for incidence and yield values

The first analysis was done to see the effect of year, production system and cultivar on brown rot and codling moth damage incidences as well as on yield. Statistical Analysis System v. 8.1 (SAS Institute Inc., Cary, NC) was the statistical package used for this analysis. All data recorded from the three replicates for brown rot and codling moth damage incidences and yield were averaged to a single value for each assessment date, cultivar, and production system. Then, final brown rot and codling moth damage incidences as well as yield data were subjected to a split-split-plot analysis of variance, where the 12 years were used as blocks, the two production systems as main plots, and the 27 cultivars as sub-plots. Brown rot and codling moth damage incidences data were arcsine-square root transformed prior to the analyses to normalise data distribution.

2.4.2 Bayesian least significant difference test and nonlinear mixed-effect model for cultivar categorisation

For cultivar classification, mean data of brown rot and codling moth damage incidences for each assessment date and for each system were analysed by the Waller-Duncan Bayesian least significant difference (BLSD) test (Holb 2017) using BLSD values with $k = 100$ to compare cultivars. Cultivars were then classified into "low", "medium", or "high" level of brown rot or codling moth damage incidence for the two systems according to the categorisation procedure used by Holb (2017) for classifying apple cultivar reactions to apple scab. The categorisation procedure for the cultivars was performed for each assessment date and each year and then cultivars were assigned to the 12-year period. Mean disease and pest progresses for each classification category were then plotted against time between the first and final assessment dates.

In order to quantify disease and pest progress curves for each classification category, nonlinear growth functions were fitted within years to the temporal brown rot and codling moth damage progress data by a nonlinear mixed-effect model using the 'nlme' statistical package of the statistical software R version 2.0.0 (Pinheiro et al. 2004). Model selection criteria were applied to find the best fitted model to the observed data set and the parameters derived from the best model were used in the cultivar submodels. Three criteria (i) overall goodness-of-fit, (ii) the visual examination of standardised residuals versus predicted values, and (iii) the AIC (Akaike's information criterion) were used for model selection and the following three-parameter logistic function was considered as

most suitable for describing the brown rot and codling moth damage progress data for the two systems:

$$y = \frac{y_f}{1 + e^{-\beta(t-M)}} \tag{1}$$

where y is the brown rot or codling moth damage incidence (%) at time t (days after 15 May); Y_f, the estimated final brown rot or codling moth damage incidence or upper asymptote; β, the estimated relative rate parameter of brown rot or codling moth damage progress (days^{-1}); and M, the inflection point (the time when the absolute rate dy/dt is at a maximum). Moreover, in each classification category, $AUDPC$ and the area under the pest progress curve ($AUPPC$) were determined for mean brown rot and codling moth damage progresses, respectively, for both systems. Y_f, β, M, $AUDPC$, and $AUPPC$ values for each classification category were then compared using the least significance difference (LSD) t-test ($\alpha = 0.05$).

2.4.3 Contributions of codling moth damage to brown rot incidence

Contributions of codling moth damage to brown rot incidence were also calculated for all cultivar classification categories in both systems. Total brown rot incidence for each classification category and production system was considered as 100% and codling moth damage contribution (%) was calculated accordingly. Percentages were determined for combining the 12-year data set and the overall 27 cultivars.

2.4.4 Pearson correlation analyses

In order to identify the relationship between brown rot and codling moth damage incidences and between weather parameters (precipitation and mean temperature) and brown rot, Pearson correlation coefficient (r) was calculated to identify the two relationships (BR vs CMD; weather parameters vs BR) using data from all assessment dates of each year. This analysis was done separately for each production system and for each classification category using Genstat 5 Release 4.1 (Lawes Agricultural Trust, IACR, Rothamsted, UK).

2.4.5 ANOVA for spray treatments

Finally, ANOVA was performed for determining the effect of spray treatment (BRCD-FMS, GBRCD-MS and control), production system (integrated vs organic), cultivar classification category ("low", "medium", and "high") and year (2016, 2017, 2018, and 2019) on the number of sprays as well as brown rot and codling moth damage incidences. Both brown rot and codling moth damage incidences were transformed to angular (Y=arcsine $[\%]^{1/2}$) before the analysis. For all the three

measures, F-tests ($P< 0.05$) were followed by an LSD t-test for comparison of the means of the spray treatments' data using LSD$_{0.05}$ values.

3 Results and discussion

### 3.1 Weather conditions and final incidences of brown rot and codling moth damage

Climatic conditions for the development of brown rot epidemics and codling moth gradations were moderately to highly suitable during the assessed period from 2000 to 2011. Total rainfall recorded from 1 April to 10 October each year, respectively, 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. Mean daily temperature recorded from 1 April to 10 October each year, respectively, 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.

ANOVA for final brown rot and codling moth damage incidences as well as for yield indicated significant ($P < 0.05$) differences between years ($df = 11$, 11, and 11, $MS = 250.3$, 196.8, and 356.7, $F = 8.1$, 3.1, and 4.4, and $P = 0.0008$, 0.0387, and 0.0422, respectively), production systems ($df = 1$, 1, and 1, $MS = 24976.1$, 20796.7, and 33457.3, $F = 811.7$, 322.3, and 411.2, and $P < 0.0001$, < 0.0001, and < 0.0001, respectively), and cultivars ($df = 26$, 26, and 26, $MS = 79.6$, 45.1, and 97.4, $F = 91.5$, 85.6, and 101.3, and $P < 0.0001 < 0.0001$, and < 0.0001, respectively). There were no significant interactions between treatment factors, i.e. production systems × cultivars ($df = 26$, 26, and 26, $MS = 13.8$, 5.1, and 15,2, $F = 1.4$, 1.5, and 1.9, and $P = 0.1153$, 0.0762, and 0.0582, respectively).

Overall, the 12-year means of final brown rot incidence across production systems ranged from 3.3 to 18.7% for the scab-resistant, from 3.0 to 22.5% for the commercial, and 2.8 to 20.0% for the old cultivars (Fig. 2 and 3). Mean final brown rot incidence was significantly higher ($P < 0.001$) in organic compared to integrated system (ranging from 12.3 to 22.3% and from 2.8 to 5.6%, respectively). Cultivar 'Gravensteiner' from the old cultivar subgroup showed the lowest mean final brown rot incidence (2.8%) in integrated while the highest mean incidence (22.5%) was determined on cultivar 'Mutsu' from the commercial cultivar subgroup in organic system.

In terms of final codling moth damage incidence, the 12-year means ranged from 1.3 to 15.3% for the scab-resistant, 1.3 to 18.6% for the commercial, and 1.3 to 17.0% for the old cultivars (Fig. 2 and 3). Mean final codling moth damage was also significantly higher ($P < 0.001$) in organic than in integrated system (ranging from 8.4 to 18.6% and from 1.3 to 2.6%, respectively). Cultivars 'Releika', 'Remo', 'Resi', 'Red Elstar', 'Gravensteiner', and 'King of the Pippins'

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Fig. 2 Incidences of brown rot (BR), codling moth damage (CMD) and their classification categories as well as yield (kg tree^{-1}) for 27 apple cultivars (**A** resistant, **B** commercial, and **C** old) in the integrated production system (Debrecen-Pallag, Hungary, 2000–2011). Brown, red, and green horizontal lines within the columns are the mean of 2000–2011 for BR, CMD, and yield, respectively. Columns represent the 12-year range of the data set and bars represent the standard error values.
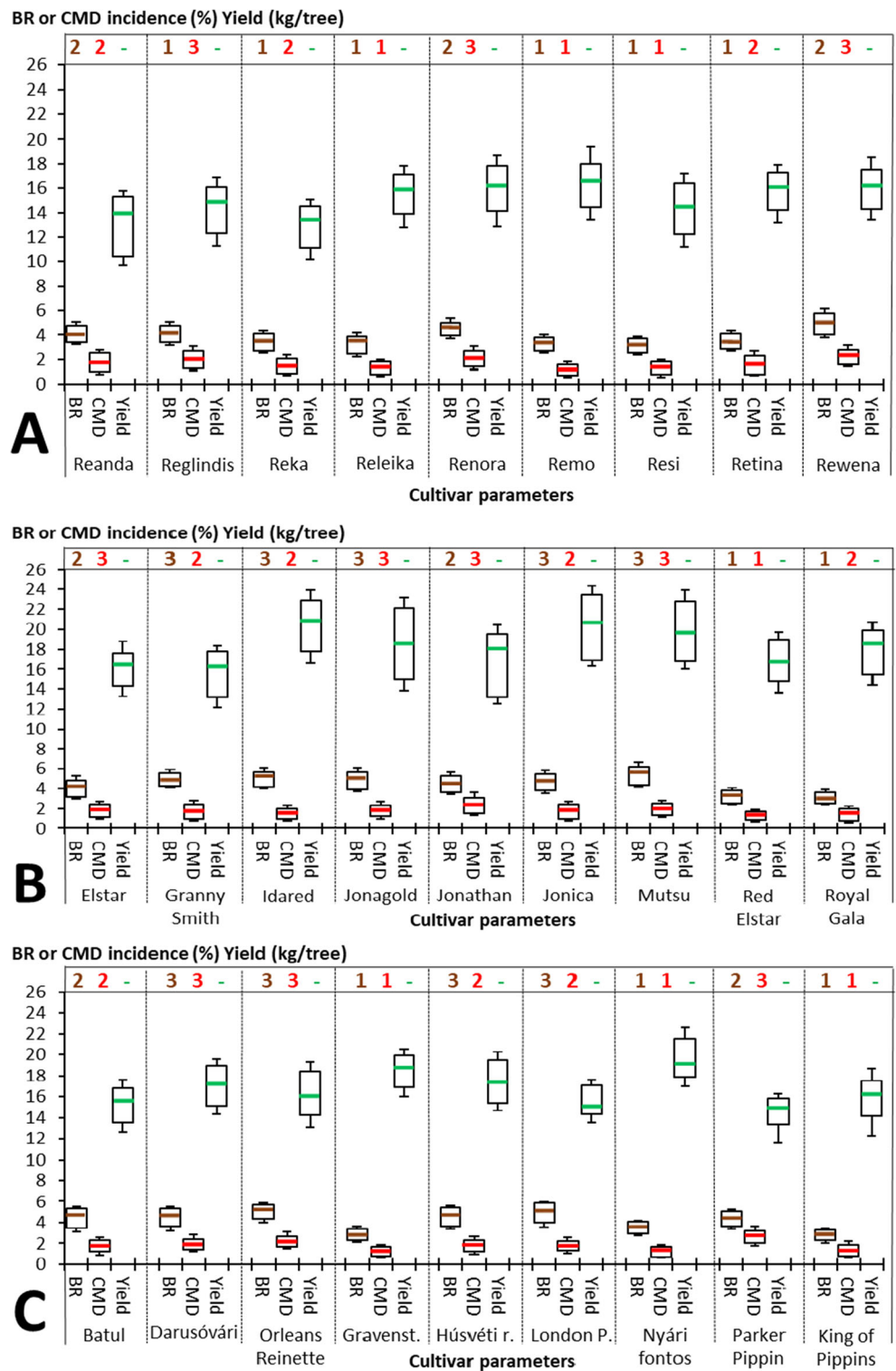

showed the lowest mean final codling moth damage incidence (1.3%) in integrated while the highest mean incidence (18.6%) was assessed again on cultivar 'Mutsu' from the commercial cultivar subgroup in integrated system.

Mean yield for the 12-year period ranged from 13.7 to 20.9 kg tree^{-1} for integrated and 10.1 to 14.8 kg tree^{-1} for organic system, and from 11.8 to 16.5 kg tree^{-1} for the scab-resistant, 11.1 to 20.9 kg tree^{-1} for the commercial and 10.1 to 19.0 kg tree^{-1} for the old cultivars (Fig. 2 and 3). Overall, yield in all years was significantly lower ($P < 0.05$) in organic compared to integrated system. In the overall 12-year period, 20.9 kg tree^{-1} fruit was the highest yield at harvest on the

Fig. 3 Incidences of brown rot (BR), codling moth damage (CMD) and their classification categories as well as yield (kg tree^{-1}) for 27 apple cultivars (**A** resistant, **B** commercial, and **C** old) in the organic production systems (Debrecen-Pallag, Hungary, 2000−2011). Brown, red, and green horizontal lines within the columns are the mean of 2000–2011 for BR, CMD, and yield, respectively. Columns represent the 12-year range of the data set and bars represent the standard error values.
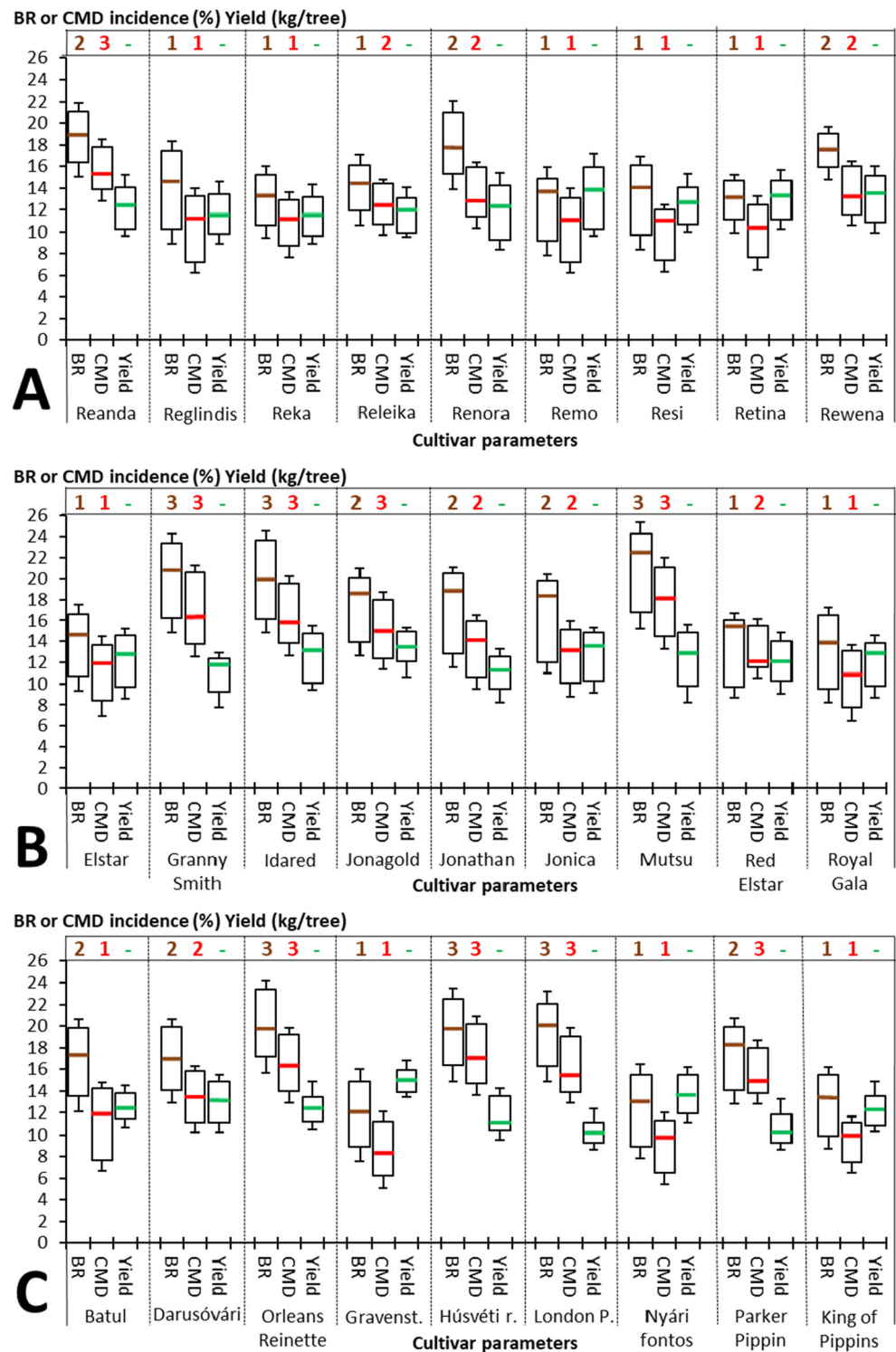
commercial cultivar 'Jonica' in integrated, while 10.1 kg tree^{-1} of fruit was the lowest on the old cultivar 'Parker Pippin' in organic system. Yields of most cultivars significantly differed from each other depending on years and production systems.

Our results clearly demonstrated that brown rot incidence largely varied among cultivars in both production systems. So far, only few studies assessed the reaction of apple cultivars to *M. fructigena* infection (Byrde and Willetts 1977; Sharma and Kaul 1988) as this pathogen is causing low yield loss in well

managed apple orchards (e.g. Xu and Robinson 2000; Holb and Scherm 2008). Under laboratory conditions, brown rot incidence of various cultivars was positively correlated with pH and negatively to fruit acidity and firmness (Sharma and Kaul 1988). This means that when a fruit starts to mature, acid content decreases while sugar content increases resulting in higher pH. At the same time, pectin and cellulose will decrease due to increased activity of cell wall degrading enzymes, which results in lower fruit firmness of a mature fruit compared to unripe fruit. Indeed brown rot incidence in this study was also higher at harvest compared to previous fruit phenological stages of all cultivars and in all brown rot classification categories. In recent field studies, Holb and Scherm (2008) indicated that final brown rot incidence was generally higher in the order of early, mid, and late harvesting cultivars in both integrated and organic apple orchards. In agreement with this study, final brown rot incidence and classification categories also showed that most cultivars with early maturity dates received a "low" classification, while cultivars with late maturity dates received a "high" classification category. This is possibly because late maturity/late harvest cultivars had a longer exposition time for brown rot infection compared to earlier ripening/harvested ones (Fig. 2 and 3).

3.2 Cultivar classification for brown rot and codling moth damage

The level of brown rot incidence was the lowest for the scab-resistant cultivar subgroup (Fig. 2 and 3) as most scab-resistant cultivars received a "low" (1) classification category score in both production systems. In contrast, most commercial and old cultivars were classified as having "medium" (2) or "high" (3) level of brown rot, whereas, overall, most cultivars with early, mid, and late maturity dates received "low", "medium", and "high" classification for brown rot incidence, respectively.

The season-long classification for codling moth damage was the lowest for scab-resistant cultivar subgroup in organic system (Fig. 2 and 3). Most commercial cultivars received a "medium" or "high" classification score for the season-long CMD incidence in both production systems. Again, early maturity cultivars received a "low", while the late ones a "high" CMD classification score.

The cultivar classification category scores determined for each cultivar were not so different between brown rot and codling moth damage, as well as between integrated and organic systems (Fig. 2 and 3). Differences were least frequent among the old cultivars for brown rot between integrated and organic and most frequent among the scab-resistant cultivars for codling moth damage between integrated and organic. The scab-resistant cultivar 'Reglindis' showed lower codling moth damage incidences in integrated than in organic system but the cultivar received classification category "high" for integrated and "low" for organic; because the maximum values of CMD incidence was generally low in integrated and high in organic for the classification category "high".

In a field study, Holb and Scherm (2008) indicated that final brown rot incidence was generally higher in the order of early, mid, and late harvesting cultivars. Cultivar susceptibility to *M. fructigena* strongly depended on the wound causing agents of codling moth as previously indicated by Xu and Robinson (2000) and Holb and Scherm (2008), but this study was the first to demonstrate cultivar classification categories for brown rot in relation to codling moth damage. In agreement with previous studies, both brown rot and codling moth damage incidences and related classification categories increased in the order of early, mid, and late maturity date of cultivars, especially in organic system. This is possibly because late maturity/late harvest cultivars had a longer exposition time for brown rot infection and for codling moth damage on late than on early maturity cultivars (Fig. 4).

3.3 Temporal brown rot and codling moth damage incidences in the cultivar classification categories

The onset of both brown rot and codling moth damage incidences was in mid-June (i.e. day 29 after 15 May) and end-June (i.e. day 44) in integrated and organic systems, respectively and on cultivars classified with "low" susceptibility category (Fig. 4). Whereas on cultivars that received a "high" susceptibility category, the onset of both brown rot and codling moth damage was much later in mid-July (i.e. day 59) in organic and end-July (i.e. day 74) in integrated system (Fig. 4). Then, both brown rot and codling moth damage incidences continuously increased towards harvest date in both production systems, with a significant difference among classification categories in end-August (i.e. day 104) and onwards in all cases.

For both brown rot and codling moth damage incidences, ANOVA (with black horizontal rectangles in Fig. 4) showed significant differences among the cultivar classification categories after days 91 in organic and 106 in integrated, in the order of "low", "medium", and "high" categories. In the case of brown rot in integrated (Fig. 4a), an inverse category order ("high", "medium", and "low") was established between days 52 and 66. This phenomenon is linked to the earlier maturity of the cultivars in the "low" category. These cultivars are matured earlier resulting in earlier brown rot incidence in the earlier period of the season compared to either "medium" or "high" categories.

Final brown rot incidences were 4 to 7 times higher and final codling moth damage incidences 8 to 12 times higher in the organic than in integrated system (Fig. 2, 3, 4, and 5). This result is in agreement with previous studies where brown rot and codling moth damage incidences were also much higher in organic than integrated system (Holb and Scherm 2008; Wearing et al. 2012). The higher brown rot and codling

Fig. 4 Progress curves for the three cultivar classification categories (CCC, "low", "medium", and "high") for brown rot (BR) and codling moth damage (CMD) incidence on fruit (%) in integrated and organic apple production systems at Debrecen-Pallag, Hungary (2000 to 2011). (**A**) BR vs integrated; (**B**) BR vs organic; (**C**) CMD vs integrated; and (**D**) CMD vs organic. Each symbol represents the mean incidence value of a given assessment date over 12 years for CCC. Bars represent standard errors of means. Black horizontal rectangles represent significant periods ($P < 0.05$) among "low", "medium", and "high" CCC (black vertical lines represent separations between significant and non-significant periods). Dotted, oblique-striped, and vertical-striped rectangles represent E1/G1, E2/G2, and E3/G3 epidemic/gradation intensity levels (orange vertical lines represent separation of E1/G1, E2/G2, and E3/G3 intensity periods).
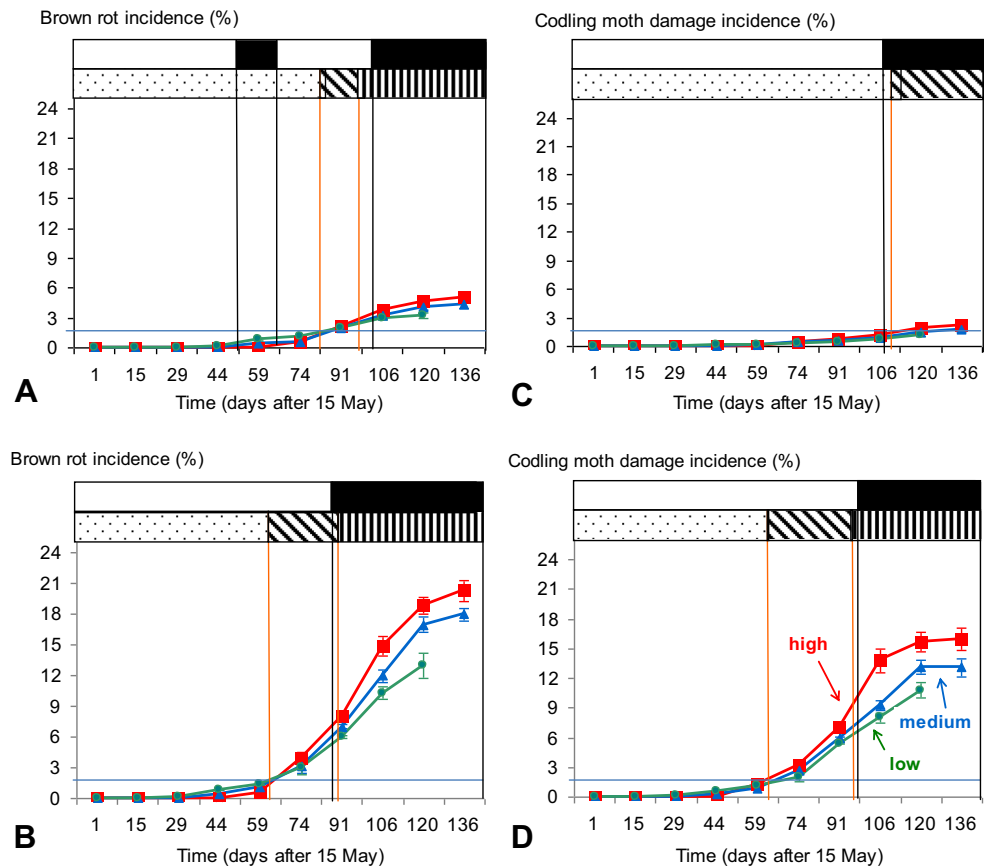

moth damage incidences in organic system were likely due to the less effective fungicides and insecticides available (Holb 2009, 2019) and the larger diversity of invertebrate populations, including codling moth (Witzgall et al. 2008; Kadoić Balaško et al. 2020).

3.4 Disease and pest parameters in each cultivar classification category

AUDPC and *AUPPC* values for brown rot and codling moth damage, respectively, were overall lower in integrated than in organic system in all cultivar classification categories (Fig. 5). For both parameters (*AUDPC* and *AUPPC*), significant differences ($P < 0.05$) were determined between each classification category in the two production systems. Values of upper asymptote (Y_f) were also lower in integrated system, whereas no significant differences were determined between each of the classification categories for brown rot or codling moth damage (Fig. 5). Overall, no consistent increase or decrease was observed with classification categories or for production systems for the relative rate parameter of disease increase (β) and the estimates of the inflection point (M) for both brown rot and codling moth damage (Fig. 5).

These results suggest that *AUDPC* and *AUPPC* could differentiate brown rot and codling moth damage classification categories in both production systems. Therefore, *AUDPC* and *AUPPC* can be suitable for evaluation of cultivar susceptibility to brown rot in relation to codling moth damage, as they were previously reported for some arable and fruit crops (e.g. Thompson and Rees 1979; Holb 2017). Nevertheless, the rate parameter (β) was found to be less sensitive compared to *AUDPC* in the brown rot or *AUPPC* in the codling moth damage classification categories in the two production systems as was also previously reported that logistic rate parameter had low effect on treatments such as disease management, cultural practices, or host genotype (Thompson and Rees 1979; Holb 2017). Similar difficulties were reported for the inflection point (M) of the progress curves. Therefore, in accordance with previous research (e.g. Thompson and Rees 1979; Holb 2017), results here indicated that neither relative rate (β) nor the inflection point (M) can be advisable in separating brown rot classification categories of apple cultivars in relation to codling moth damage. Overall, results obtained here showed that *AUDPC* and *AUPPC* on host susceptibility to brown rot in relation to codling moth damage can be used successfully as input for forecasting systems.

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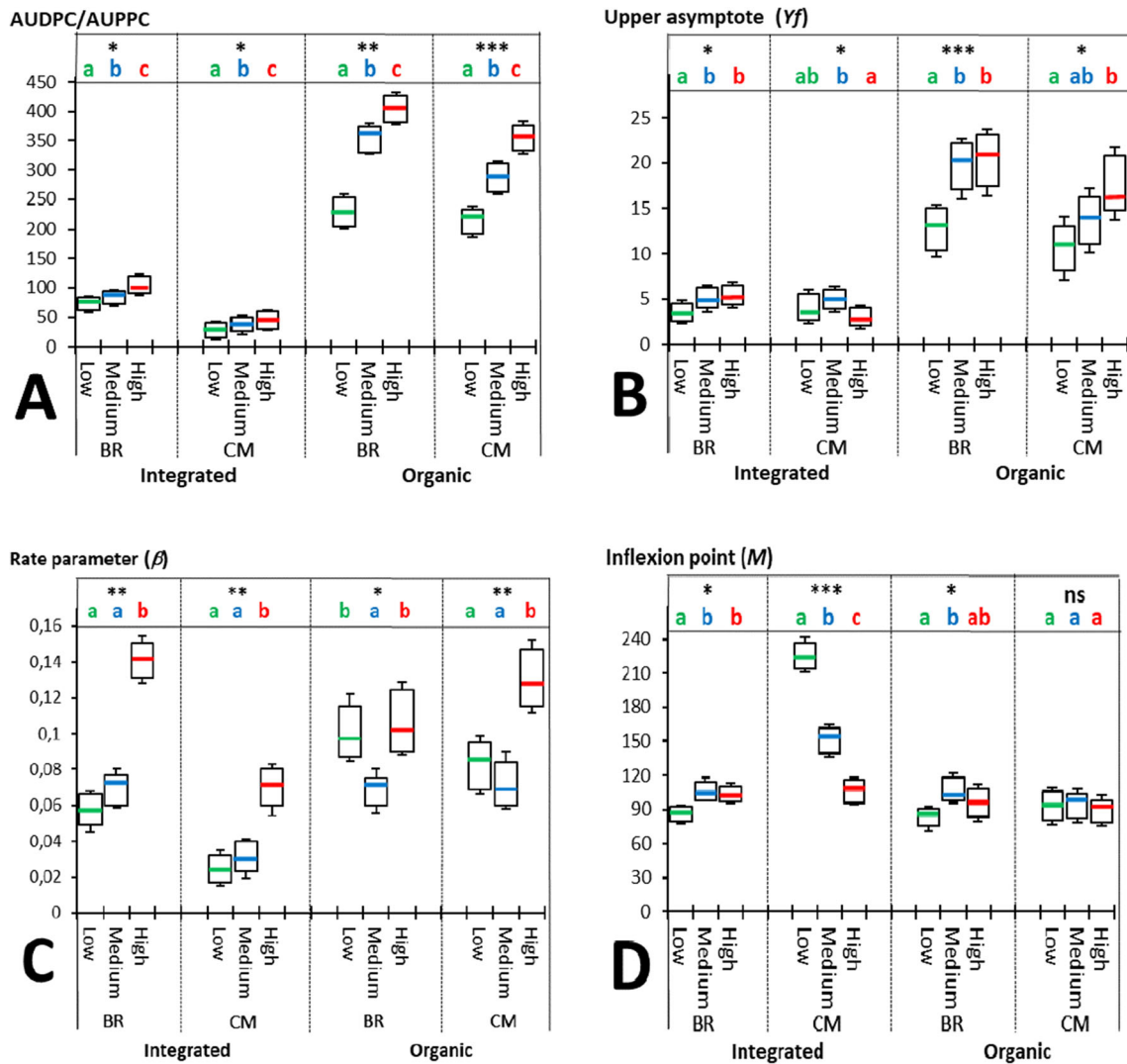
Fig. 5 Progress curve parameters in the three cultivar classification categories (CCC) for brown rot (BR) and codling moth damage (CMD) incidence in integrated and organic apple orchards at Debrecen-Pallag, Hungary (2000–2011). (**A**) Area under the disease and pest progress curves (*AUDPC*; *AUPPC*); (**B**) Y_f, upper asymptote for BR or CMD incidences (%); (**C**) β, relative rate parameter of BR and CMD progresses (day^{-1}); and (**D**) inflection point M. Data are means of 12 years (n = 12). Values within the CCC for BR and CMD followed by different letters are significantly different according to the LSD t-test. *, **, ***, and ns are significantly different at 0.05, 0.01, 0.001, and non-significant, respectively. Brown, red, and green horizontal lines within the columns are the mean of 2000–2011 for BR, CMD, and yield, respectively. Columns represent the 12-year range of the data set and bars represent the standard error values.

3.5 Relationships between brown rot and codling moth damage and between weather parameters and brown rot

Percent contributions of codling moth damage to total brown rot incidences were significantly higher ($P < 0.05$) in organic than in integrated systems (for "low", "medium", and "high" categories, values were 39.9, 39.1, and 43.2 % in organic and 81.8, 72.9, and 78.4 % in integrated) but "low", "medium", and "high" categories did not differ significantly from each other either in integrated or organic production system (Fig. 6A).

Pearson's correlation coefficient (r) showed that brown rot incidences correlated significantly ($P < 0.05$) with codling moth damage incidences in all cultivar classification

categories throughout the 12-year assessment period (Fig. 6B). The 12-year mean values of correlation coefficients were consistently larger in organic than in integrated system (values were r = 0.813, 0.835, and 0.871 with $P = 0.0115$, 0.0088, and 0.0047 for "low", "medium", and "high" categories, respectively, in the integrated and r = 0.902, 0.923, and 0.938 with $P = 0.0028$, 0.0013, and 0.0008 for "low", "medium", and "high" categories, respectively, in organic).

Pearson's correlation coefficient (r) showed that mean daily temperature correlated significantly ($P < 0.05$) with brown rot incidences in both production systems in all cultivar classification categories throughout the 12-year assessment period (Fig. 6C). The 12-year mean values of correlation coefficients were consistently larger in integrated than in organic system in
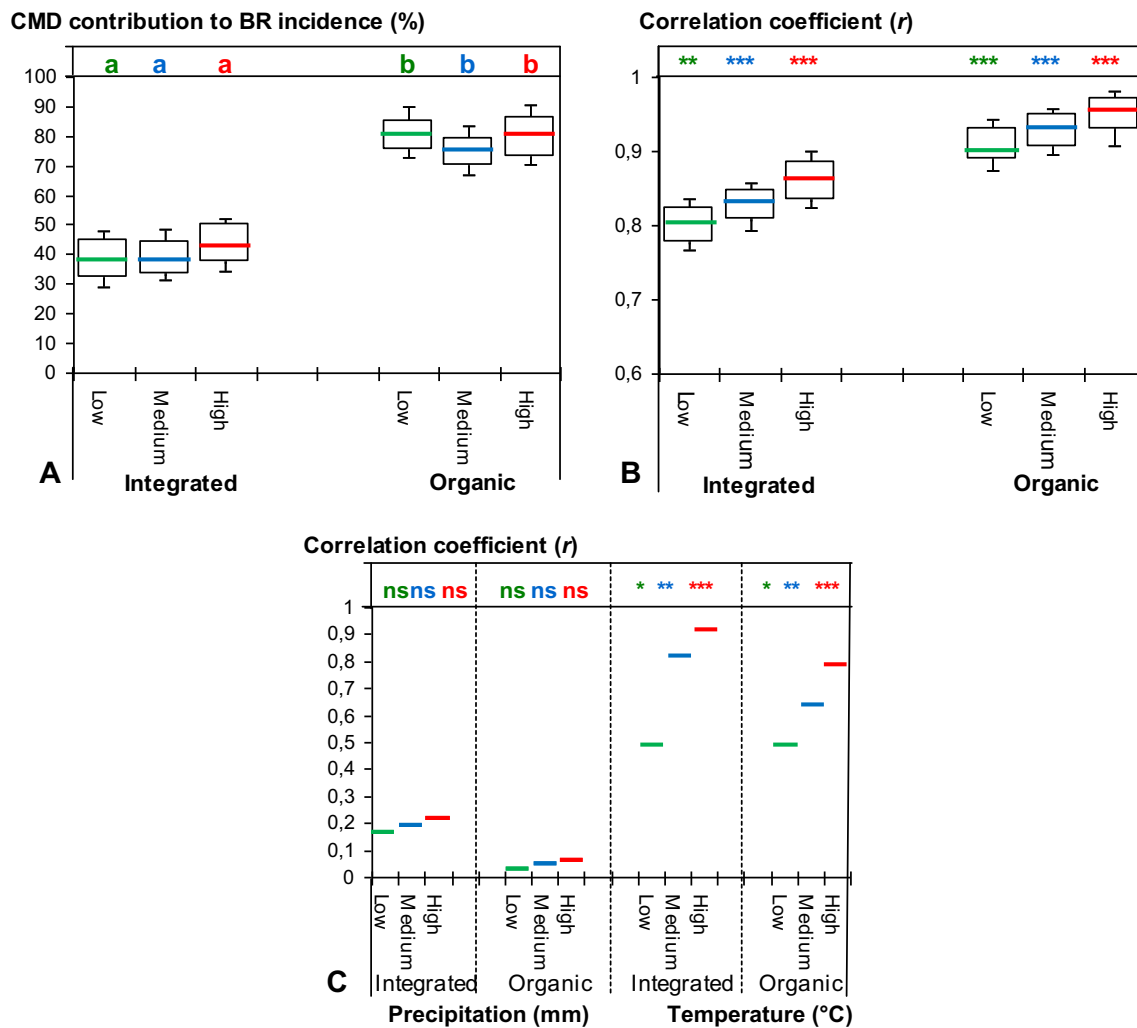
Fig. 6 Associations among codling moth damage (CMD), brown rot (BR) and weather parameters in the "low", "medium", and "high" cultivar classification categories (CCC) in integrated and organic apple production systems (Debrecen-Pallag, Hungary, 2000 to 2011). (**A**) Contribution of CMD to the total BR incidence on fruit. (**B**) Pearson's correlation coefficients (r) between BR and CMD incidences. $n = 120$ (12 years × 10 assessment dates) for CCC. (**C**) Pearson correlation coefficients (r) between weather parameters (precipitation and mean temperature) and BR incidence. Analyses were based on data from each year; $n = 12$ (12 years) for CCC. Brown, red, and green horizontal lines within the columns are the mean of 2000–2011 for BR, CMD, and yield, respectively. Columns represent the 12-year range of the data set and bars represent the standard error values. Values within the CCC for BR and CMD followed by different letters are significantly different according to the LSD t-test. *, **, ***, and ns are significantly different at 0.05, 0.01, 0.001, and non-significant, respectively.

the "medium" and "high" categories. However, low and non-significant correlation coefficients were obtained between precipitation and brown rot incidences in both the systems and cultivar classification categories (Fig. 6C). Correlation between damage/incidence data and weather parameters need to be further analyzed using empirical modelling/correlograms (Pierre et al. 2021).

The high brown rot and codling moth damage incidences in organic system means that any improvements in codling moth management have the potential to reduce injury associated brown rot in organic system. On the other hand, in integrated system, although the codling moth was a relevant contributor to brown rot infection, overall codling moth damage incidence was low, suggesting that intensifying codling moth control would not decrease considerably brown rot incidence as brown

rot incidence largely depends on wounds caused by codling moth. Therefore, since organically approved fungicides (such as sulphur and copper compounds) are less effective than systemic fungicides used in integrated (Holb and Scherm 2008; Holb 2019), a more effective codling moth control is essential in the brown rot management of organic system. A combined use of *Bacillus thuringiensis*, granulosis viruses, mating disruption, sterile insect technique, summer oils, postharvest fruit removal, tree banding, and netting are recommended against codling moth in organic system (e.g. Judd and Gardiner 2005; Wearing et al. 2012; Marliac et al. 2015; Walker et al. 2017; Kadoić Balaško et al. 2020). The cost of the use of a combined approach is considerably higher than the use of insecticide applications in integrated management (Wearing et al. 2012); however, the 'hidden costs' of the adverse effects of

insecticides used in integrated management should also be considered (Walker et al. 2017; Kadoić Balaško et al. 2020).

3.6 Development and practical evaluation of BRCM-FMS

Our overall results showed that brown rot is highly associated with codling moth damage in several aspects; hence, the two factors need to be treated together in a forecasting strategy for a reliable brown rot and codling moth damage management strategy. Based on this a new BRCM-FMS was developed for brown rot and codling moth damage management (Fig. 7).

The BRCM-FMS requires insertion of field data as weekly assessed fruit brown rot and codling moth damage incidences as well as the weather data set (Fig. 7a). Both brown rot and codling moth damage data sets go into cultivar classification panel where the cultivar sorted into "low", or "medium", or "high" category separately for brown rot and codling moth damage incidences according to Fig. 7b. Then, after the fourth assessment date, a three-parameter logistic function has to fit to brown rot and codling moth damage incidences by 'nlme' procedure based on $AUPPC$, $AUPPC$, Y_f, and β for the selected cultivar category (Fig 7c, details on fitting procedure are given in the study of Holb et al., 2011). After this, $AUDPC$ and $AUPPC$ of the selected cultivar category for brown rot and codling moth damage are calculated from the function. Then, these calculated values of $AUDPC$ and $AUPPC$ are compared with the given maximum values calculated from data of this 12-year study (Fig. 7d). If the calculated values reached the maximum values, then three types of yield loss threshold values for brown rot and codling moth damage development have to be calculated: (i) the action threshold, (ii) the warning threshold, and (iii) the damage threshold values according to Zadoks (1985) in order to make management decisions (Fig. 7e). For instance, if the grown cultivar is 'Idared', then the above calculations have to follow category of "high" for brown rot and "middle" for codling moth damage in integrated system according to the results of Figures 2 and 3. Three threshold values are determined according to epidemic/gradation intensity: (i) $T_{1.5}$, the time when brown rot or codling moth damage incidences reached 1.5%, (ii) M, the inflection point, and (iii) Y_f, final brown rot or codling moth damage incidences. Each threshold value represents a range for epidemic/gradation intensity level: (i) E1/G2, a range between Y_0 and $T_{1.5}$, (ii) E2/G2, a range between $T_{1.5}$ and M, and (iii) E3/G3, a range between M and Y_f (Fig. 7f and Fig. 4). Then, three decision levels are created based on the three epidemic/gradation intensity levels (Fig. 7g). Decision level 1 (D1) delays the occurrence of the first symptom/damage of brown rot and codling moth damage; decision level 2 (D2) delays the speed of epidemic/gradation of brown rot and codling moth damage, and decision level 3 (D3) reduces yield loss and incidences of brown rot and codling moth damage by suitable integrated or organic disease and pest management options.

ANOVA for the number of sprays as well as for final brown rot and codling moth damage incidences indicated significant differences (P values ranging from 0.011 to 0.047) between the two management systems, among the three cultivar classification categories and among the 4 years (*data not shown*). The number of sprays against brown rot and codling moth ranged from 10 to 19 in the general spray schedules (GBRCM-MS) while the number of sprays was significantly ($P < 0.05$) reduced to 6–15 in the new management strategy (BRCM-FMS) in both management systems, in the overall 4 years and in the three classification categories except for one case in organic system "high" categories (Table 1). The number of sprays against brown rot and codling moth was reduced with 21.4–41.7% for the integrated and 12.5–31.3% for organic system in the new management strategy (BRCM-FMS) compared to the general spray schedules (GBRCM-MS). Despite the reduction of spray number in the BRCM-FMS, both incidence types were not significantly different from each other in the four years, in the two management systems and in the three cultivar classification categories. Both brown rot and codling moth damage incidences were significantly ($P < 0.05$) lower in the BRCM-FMS and GBRCM-MS compared to untreated control plots in the 4 years, in the two management systems and in all cultivar classification categories (Table 1). Although economic measures were not the aims of this study, fewer numbers of annual sprays and similar incidences of the disease provide an economic and environmental benefit for growers as previous studies also aimed to develop disease warning and pest forecasting systems in fruit production (Berrie and Xu 2003; Holb et al. 2011; Chappell et al. 2015).

Previous studies emphasised that deep epidemiological and gradation knowledge is essential for developing an effective forecasting system (e.g. Zadoks, 1985; Walker et al., 2017). An effective forecasting system can ensure to develop such a pest management strategy which result in a successful annual spray reduction. These strategies were developed for a single pest and for conventional or integrated production systems based on 2 to 6 years evaluations (e.g. Berrie and Xu 2003; Holb et al., 2011, Joshi et al., 2015; Danelski et al., 2017, Kadoić Balaško et al., 2020). This study was the first to provide combined epidemiological, forecasting, and management approaches on two joint pests in long-term validation processes in order to reach a significant reduction in the number of sprays in environmentally friendly apple production systems. Although, this study focused on two specific plant pests, the provided approaches are likely to be an effective method for other plant pests, for other plant cultivars with different levels of pest susceptibility and for various production systems with different levels of plant protection intensity. As any new approach can be imperfect we have to note that in our approach, (i) the long-term collection of epidemiological data on large numbers of cultivars is time-consuming and costly which is likely to be able replacing with a more simple option and
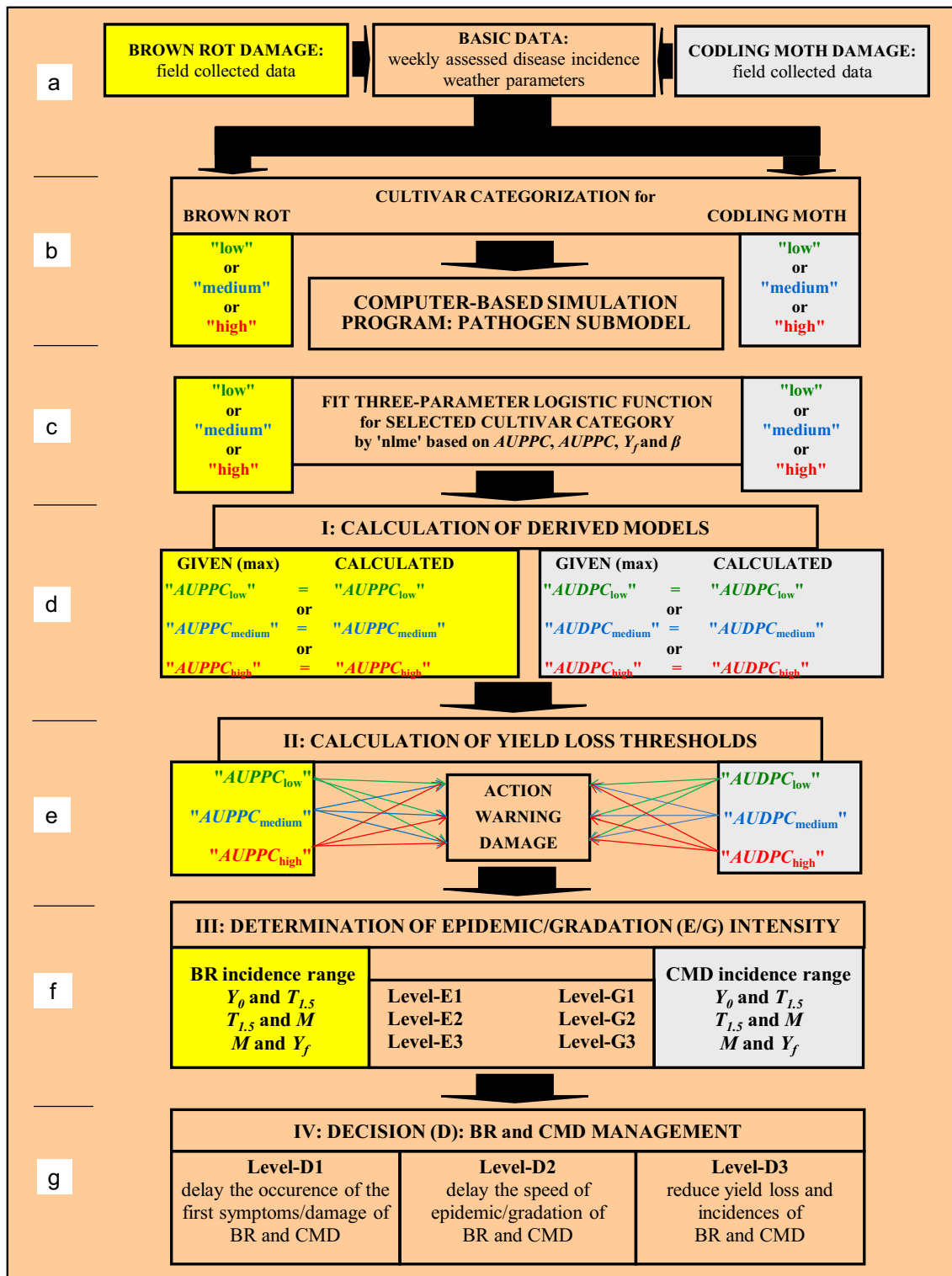
Fig. 7 Brown rot (BR) and codling moth damage (CMD) forecasting and management strategies (BRCM-FMS) for three cultivar classification categories ("low", "medium", and "high") separated for integrated and organic apple production systems. Data are means of 12 years ($n = 12$).

Y_0 = starting point, Y_f = upper asymptote, β = relative rate parameter, $AUDPC$ and $AUPPC$ = area under the disease and pest progress curves, M = inflection point, $T_{1.5}$ = the time when incidences reached 1.5%.

Table 1 Number of sprays, final brown rot (BR) incidence, and final codling moth damage (CMD) incidence (%) in three cultivar classification categories ("low", "medium", and "high") under three management strategies in organic and integrated apple orchards (Eperjeske, Hungary, 2016–2019).

	Number of sprays against CM and BR						Final BR incidence						Final CMD incidence					
	2016	2017	2018	2019	Overall		2016	2017	2018	2019	Overall		2016	2017	2018	2019	Overall
Integrated																	
Low																	
BRCM-FMS	6 *	7	6	7	6.5	a	0a	1.1a	1.1a	0a	0.6	a	0a	2.2a	2.2a	1.8a	1.6a
GBRCM-MS	8	10	9	9	9	b	0a	1.4a	0a	1.2a	0.7	a	0a	1.4a	1.6a	2.1a	1.3a
Control	0	0	0	0	0		13.4b	16.7b	15.2b	15.4b	15.2	b	10.3b	12.4b	10.8b	13.2b	11.7b
LSD$_{0.05}$					2.1		1.8	2.8	1.9	1.6	2.0		1.1	2.1	1.7	1.3	1.5
Medium																	
BRCM-FMS	7	8	7	8	7.5	a	1.3a	2.1a	1.1a	0a	1.1	a	1.3a	2.2a	3.2a	2.4a	2.3a
GBRCM-MS	10	11	12	12	11.3	b	2.4a	2.9a	1.7a	2.1a	2.3	a	2.3a	1.7a	2.3a	1.8a	2a
Control	0	0	0	0	0		16.6b	17.2b	18.1b	18.4b	17.6	b	13.5b	12.4b	11.7b	14.1b	12.9b
LSD$_{0.05}$					2.4		3.6	3.9	2.9	3.1	3.3		3.2	3.1	2.6	2.9	2.9
High																	
BRCM-FMS	7	8	11	10	9	a	4.3a	6.1a	7.1a	5.2a	5.7	a	3.5a	4.3a	3.9a	5.1a	4.2a
GBRCM-MS	11	12	14	13	12.5	b	6.1a	4.8a	6.8a	5.8a	5.9	a	4.5a	3.7a	5.2a	2.9a	4.1a
Control	0	0	0	0	0		26.2b	28.3b	28.1b	25.8b	27.1	b	21.3b	20.8b	22.1b	18.9b	20.8b
LSD$_{0.05}$					2.6		4.1	4.1	4.2	3.6	4.0		3.1	3.4	3.5	3.9	3.4
Organic																	
Low																	
BRCM-FMS	12	12	11	12	11.8	a	12.2a	13.1a	12.1a	13.3a	12.7	a	8.3a	9.5a	9.3a	10.2a	9.3a
GBRCM-MS	14	15	16	14	14.8	b	12.9a	11.9a	10.7a	12.6a	12	a	9.1a	10.1a	8.6a	10.7a	9.6a
Control	0	0	0	0	0		25.4b	27.6b	27.1b	25.7b	26.5	b	21.4b	20.7b	22.2b	18.1b	20.6b
LSD$_{0.05}$					2.8		3.6	3.8	4.4	3.7	3.8		3.2	3.1	4.1	3.3	3.4
Medium																	
BRCM-FMS	12	12	13	12	12.3	a	15.8a	17.3a	16.2a	15.4a	16.2	a	11.2a	14.3a	13.2a	12.3a	12.8a
GBRCM-MS	15	15	16	14	15	b	16.2a	16.5a	15.3a	17.1a	16.3	a	14.6a	13.6a	12.3a	16.1a	14.2a
Control	0	0	0	0	0		35.8b	38.3b	37.8b	38.1b	37.5	b	28.3b	35.5b	34.7b	33.4b	33b
LSD$_{0.05}$					2.7		4.3	4.7	4.3	4.9	4.5		3.9	4.1	4.0	4.3	4.0
High																	
BRCM-FMS	14	14	15	15	14.5	a	20.9a	22.3a	21.2a	19.4a	21	a	15.1a	16.3a	19.1a	16.5a	16.8a
GBRCM-MS	16	17	19	18	17.5	a	21.5a	20.7a	19.8a	18.1a	20.1	a	17.3a	17.4a	18.4a	17.2a	17.6a
Control	0	0	0	0	0		52.8b	53.7b	56.1b	54.3b	54.2	b	48.5b	52.1b	55.3b	51.8b	51.9b
LSD$_{0.05}$					3.1		5.8	5.9	6.1	5.7	5.9		5.1	5.2	5.5	5.2	5.2

(ii) additional biological and environmental parameters may have to be added for the empirical modelling approach for further increase the efficacy of the management strategy. These points can be advised for a later research in order to improve the approaches provided in the this study.

4 Conclusions

To our knowledge, this is the first study to provide CC systems based on season-long BR and CMD incidences under long-term IPS and OPS. In addition, we demonstrated the relationships between BR and CMD incidences for these CC categories. In further results, we showed that the *AUDPC/AUPPC* of CC categories can be used successfully as input in BR and CM forecasting systems for measuring host susceptibility to BR in relation to CMD. The developed CC systems and yield attributes can also assist organic apple growers for choosing suitable cultivars in growing regions with similar climatic conditions to Central Europe, after considering other agronomical traits of the cultivars (e.g. fruit quality parameters and scab and powdery mildew susceptibility) which were previously investigated and reported by Holb (2017) and Holb et al. (2012). Here, we also show that the newly developed

BRCM-FMS is able to considerably reduce the annual spray applications in IPS and OPS compared to the commercial pest management programmes. In addition, this was the first to demonstrate that the newly developed BRCM-FMS reduced the number of sprays applied without increasing pest and disease incidence. Fewer sprays with similar incidences of the disease provide an economic and environmental benefit for growers.

Authors' contributions Conceptualization, I.J.H. and I.G.; methodology, I.J.H.; formal analysis, I.J.H and J.M.G.; investigation: I.J.H., P.D., F.A., I.B., P.L.; resources, I.J.H. and I.G.; writing—original draft, I.J.H. and V.P.V.; writing—review and editing, P.D., I.B., F.A., P.L., J.M.G. and I.G.; visualisation, supervision, and funding acquisition, I.J.H.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval   Not applicable

Consent to participate   Not applicable

Consent for publication   Not applicable

Conflict of interests   The authors declare no competing interests.

Disclaimer   Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the institutions the authors are affiliated to.

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