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Research Papers

Control strategies for grapevine phytoplasma diseases: factors influencing the profitability of replacing symptomatic plants

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Summary. The course of 'flavescence dorée' (FD) and 'bois noir' (BN) diseases can result in either recovery or death of affected grapevines. When farmers observe symptomatic grapevines, they must choose whether to replace or maintain the plants. To establish whether there is an advantage in replacing symptomatic grapevines, data were collected on the costs of replacing them (removing the diseased plants and planting new grapevines, with resultant yield loss during the rearing period) and growing them on (yield losses in symptomatic grapevines over the following years). To calculate the cost of maintaining FD-infected plants, the possibility was also considered that symptomatic grapevines may be sources of phytoplasmas for the vector *Scaphoideus titanus* Ball. The symptomatic course of BN was observed in 'Chardonnay', and of FD in 'Chardonnay', 'Merlot' and 'Perera' grape cultivars. The costs of replacement decreased with the increase in the productive lifetime of the vineyards. The cost of maintenance was greatly influenced by the course of the diseases, and in the case of FD, also by the risk of new infections due to the fact that *S. titanus* acquires phytoplasmas from infected grapevines. The replacement of plants affected by BN is not profitable when recovery is the most frequent course of the disease, particularly when it is considered that replantings can, in turn, become infected. The replacement of plants affected by FD is not profitable for cultivars with a recovery near to 100% ('Merlot'), whereas it is necessary for cultivars where the course of the disease is frequently lethal ('Perera'). For cultivars with intermediate sensitivity, the decision varies in relation to agronomic/economic factors and to the risk of new infections ('Chardonnay'). For FD, both replacement and maintenance strategies need to be associated with *S. titanus* control inside and outside the vineyards. In the case of maintenance the infected plants can be sources of phytoplasmas, and in the case of replacement, the vector can also inoculate the new grapevines.

Key words: 'flavescence dorée', 'bois noir', susceptibility, sensitivity, recovery, *Scaphoideus titanus*.

Introduction

'Flavescence dorée' (FD) and 'bois noir' (BN) are two phytoplasma diseases associated with severe yield losses in European vineyards (Schvester *et al.*, 1969; Credi, 1989; Caudwell, 1990; Posenato *et al.*, 1996; Pavan *et al.*, 1997; Mutton *et al.*, 2002; Bellomo *et al.*, 2007; Morone *et al.*, 2007). FD phytoplasma is transmitted from grapevine to grapevine by *Scaphoideus titanus* Ball (Homoptera, Cicadellidae) (Schvester *et al.*, 1963; Carraro *et al.*, 1994; Bianco *et al.*, 2001; Mori *et al.*, 2002), while *Hyalesthes obsoletus* Signoret (Homoptera, Cixiidae) transmits BN phytoplasma from herbaceous plants to grapevines (Maixner, 1994; Sforza *et al.*, 1998; Alma *et al.*, 2002; Bressan *et al.*, 2007; Maixner, 2010).

Control strategies against phytoplasma diseases in the field have been based mostly on vector control and roguing of infected plants, both cultivated and spontaneous, that are sources of the phytoplasmas (Weintraub and Beanland, 2006; Weintraub and Wilson, 2010). Both of these strategies are used for FD (Caudwell, 1981; Planas, 1987; Barba, 2005). Insecticide treatments are the most important tool for

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S. titanus control and the efficacy of chemical control to reduce the disease is known (Carle and Schvester, 1964; Posenato *et al.*, 1996; Girolami *et al.*, 2002; Pavan *et al.*, 2005; Bressan *et al.*, 2006; Morone *et al.*, 2007). Roguing of symptomatic grapevines is a practice recommended for FD control, because *S. titanus* acquires the phytoplasmas from diseased grapevines. In contrast to FD, neither insecticide treatments in vineyards nor symptomatic grapevine roguing are effective for BN control (Pavan, 1989; Pavan *et al*., 1989; Sforza and Boudon-Padieu, 1998; Maixner, 2007; Mori *et al*., 2008). This is because infected vectors often move into vineyards from outside, and there is no evidence that *H. obsoletus* can acquire BN phytoplasmas from infected grapevines (Maixner, 2010).

When farmers observe grapevines with phytoplasma symptoms, they may choose between replacing or maintaining the plants (Girolami, 2000; Osler *et al*., 2002). The choice should be guided by economic criteria. Two factors associated with the grapevines are involved in such decisions: (i) the course of the disease in the plants and (ii), only for FD, the risk of new infections due to the fact that *S. titanus* acquires phytoplasmas from infected grapevines. The course of both FD and BN can result in the recovery or death of the infected grapevines (Caudwell, 1990; Osler *et al.*, 1993; Mutton *et al*., 2002; Bellomo *et al*., 2007). Recently, it was suggested that the mechanisms of recovery involve systemic acquired resistance and the presence of fungal endophytes (Musetti *et al*., 2007; Martini *et al.*, 2009). For FD in grape-growing areas of North Italy the "recovery course" was observed in 'Prosecco' and 'Merlot' cultivars, whereas the "death course" was observed in 'Garganega' and 'Perera' cultivars (Posenato and Girolami, 1994; Posenato *et al.*, 1996; Pavan *et al.*, 1997; Bellomo *et al.*, 2007). The disease in other cultivars (e.g. 'Chardonnay' and 'Verdiso') has an intermediate course. For BN in northern Italy, recovery is the predominant outcome, but an important percentage of grapevines can also die (Credi, 1989; Mutton *et al*., 2002). As is generally the case with epidemic plant diseases (Purcell, 1985), the spread of FD is highly conditioned by the amount of infected grapevines in the affected area, although it also strongly depends on the density of vector populations and on the grapevine cultivar involved (Bressan *et al.*, 2005, 2006). Less susceptible cultivars not only have lower liability to disease, but they are also poorer sources of FD phytoplasmas (Bressan *et al*., 2005).

The aim of the present study was to establish when it is profitable to replace grapevines affected by FD and BN. For FD, cultivars with different courses of the disease were also considered.

Materials and methods

To establish the advantage of replacing symptomatic grapevines, the cost of grapevine replacement was compared with that of maintenance. The comparison was carried out on three cultivars ('Chardonnay', 'Merlot' and 'Perera') for FD and on 'Chardonnay' for BN. Data were collected in 19 vineyards (Sylvoz grapevine training systems) located in north-eastern Italy (Table 1). Chardonnay' and 'Merlot' vineyards affected by FD (four per cultivar) were placed two by two in the same farm where they were subjected to the same cultivation practices. For the ten vineyards of 'Chardonnay' infected by BN and for the vineyard of 'Perera' infected by FD the phytoplasma identification was based on literature (Carraro *et al*., 1994; Pavan *et al*., 1997; Refatti *et al*., 1998; Mutton *et al*., 2002). For 'Merlot' and 'Chardonnay' vineyards infected by FD the phytoplasma identification was based on specific nested-PCR analyses performed on six to 15 grapevines per vineyard (Firrao *et al*., 2000; Frausin *et al*., 2000; Bellomo, 2003). The vineyards of 'Chardonnay' and 'Merlot' affected by FD were treated with insecticide against *S. titanus*, whereas the vineyard of 'Perera' was untreated.

Because the annual average costs of replacement and maintenance vary with the productive lifetime of vineyards, the comparison between replacement and maintenance costs were considered in relation to 5, 10, 15, 20 and 25 years of remaining productivity.

Cost to replace symptomatic grapevines

The replacement of symptomatic grapevines involves both direct costs (removing grapevines and planting new grapevines) and indirect costs (yield loss during the grapevine rearing period) (equation 1).

Referring to conditions in north-eastern Italy for the year 2008, the values of direct costs (DC; equation 2) were: 2.00 €/plant for removing symptomatic grapevines (R) and 2.50 € for each new grapevine and it's planting (P). It was also considered that some new plants did not take root and were replanted a second time. In this study, on the basis of data referring to 405 new grapevines planted in seven

Table 1. Number of vineyards sampled for phytoplasma type and cultivar, their spatial localization and number of grapevines checked for symptom expression over the sampling years.

Cultivar	Number of vineyards sampled	Range of latitude N	Range of longitude E	First sampling year	Total number of symptomatic grapevines in the first sampling year
'BOIS NOIR'					
Chardonnay	10	45° 84′ – 46° 17′	12° 56′ – 12° 92′	1988	847
'FLAVESCENCE DORÉE'					
Chardonnay	4	45° 89′ – 45° 98′	12° 44′ – 12° 58′	2000	84
Merlot	4			2000	69
Perera	1	45° 78′	12° 04′	1989	74

different vineyards (average 9.9%, min 3.8%, max 18.4%), it was assumed that 10% of the new grapevines were replanted a second time. To establish the indirect costs (IC; equation 3) the following variables were considered: (i) proportion of missed yield in new grapevines during the rearing period calculated with respect to yield of grapevines in full production (first and second year = 1, third year = 0.8, fourth year = 0.2 and fifth year = 0) (unpublished data); (ii) the grape price based on the trade conditions of 2008 (250 € t^{-1} for 'Merlot', 400 € t^{-1} for 'Chardonnay', 1000 € t^{-1} for 'Perera'), (iii) a yield of 13 t ha^{-1} (yield normally obtained in the flatland vineyards of the grape-growing area considered) and (iv) a grapevine density of 3,000 grapevines ha^{-1} (density most frequently adopted in the considered grape-growing area). Also the effect on the replacement cost was considered, of reduced grapevine density (i.e. 1,500 plants ha^{-1}, which is the density adopted in the oldest vineyards) and yield per hectare (i.e. 8 t ha^{-1}, which is the yield normally obtained in the hilly vineyards). The cost of rearing new grapevines was not considered since this was assumed to be equal to that of managing the older grapevines. The 'do not take root' grapevines represent a complete yield loss for each year that the second replacement has been postponed from the first. In this study it was assumed that the second replacement occurs on average after 2 years.

$$RC_N = (DC + IC)/N \quad (1)$$

$$DC = R + P + (P \cdot NTR) \quad (2)$$

$$IC = \left[\left(\sum_{1}^{N} MY_N\right) + \left(MY_1 \cdot YS \cdot NTR\right)\right] \cdot YH \cdot GP / GD \quad (3)$$

RC_N = average annual cost of replanting for different productive lifetimes of vineyards
N = number of years (N=1 is the year after the first manifestation of symptoms corresponding to the year of the new grapevine planting)
R = removal cost
P = planting cost
MY = proportion of missed yield during the rearing period ($MY_1 = 1$; $MY_2 = 1$; $MY_3 = 0.8$; $MY_4 = 0.2$; MY_5 … $MY_N = 0$)
NTR = proportion of grapevines that do not take root
YS = average number of years from first planting to the replanting of grapevines that do not take root (e.g. YS = 2 the replacement occurs on average two years after the first planting)
YH = yield per hectare (t ha^{-1})
GP = grape price (€ t^{-1})
GD = grapevine density (number ha^{-1})

The possibility that vectors inoculate the new grapevines was also considered, because this increases the indirect costs, due to the necessity to replace these new grapevines. The incidence of disease in the new grapevines was recorded in infected vineyards by checking the new grapevines for at least 4 years.

Cost to maintain symptomatic grapevines

The cost of maintenance (MC_N) was calculated on the basis of the average from the sampled vineyards, because when growers are required to make a decision they cannot know the course of the disease in the grapevines in their vineyards. In any case, to verify *a posteriori* the value of the choice made, the profitability for each vineyard was also calculated.

The cost of maintenance (MC_N) is due to yield losses in symptomatic grapevines (YLSG) and, for FD, also in newly symptomatic grapevines (YLNSG) (equations 4, 5 and 6). In the following years the infected grapevines can induce yield losses if they continue to have symptoms (I) or die (II) (equation 7). In this second case, yield losses depend on how many years after the first manifestation of the disease the replacement of dead grapevines occurs, because new grapevines delay the attainment of full production. For FD, healthy grapevines can become infected and have yield losses (III) because *S. titanus* acquires phytoplasmas from symptomatic grapevines that are not rogued (equation 8 and 9).

Data to estimate yield losses in symptomatic grapevines were collected in the vineyards described in Table 1. For 'Chardonnay'/BN, part of the data was previously reported in Mutton *et al*. (2002) and for 'Perera', in Pavan *et al*. (1997). In particular, symptomatic grapevines were checked for 7 years from the first manifestation of symptoms in the case of FD, and for 10 years in the case of 'Chardonnay'/BN. Except for the last 2 years of observation, a grapevine was considered without symptoms (recovered grapevine) only if it did not show symptoms in the 2 following years. The average yield losses in symptomatic plants (I) were estimated on the basis of three damage ratings: 1 = light symptoms and almost normal yield (86% of a healthy plant), 2 = intermediate symptoms and partial yield (34% of a healthy plant), 3 = heavy symptoms and almost no yield (4% of a healthy plant) (Mutton *et al*., 2002). On the basis of the proportion of symptomatic grapevines belonging to the three damage ratings, the average yield losses in symptomatic grapevines were calculated (pYL). The yield losses occurring in the year of the first manifestation of symptoms (year N = 0) were not considered because these occur before, and then irrespective of, the decision whether or not to replace a symptomatic grapevine. In the first year of recovery the grapevines were assumed to have a yield loss still equal to one third of the yield loss of symptomatic grapevines, according to previous research (Credi, 1989; Garau *et al*., 2007; Morone *et al*., 2007).

The yield losses due to late replacement of dead plants (II) were estimated from a complete yield loss multiplied by the number of years that replanting was postponed at the net yield of the dead grapevines from year N = 1 to the year before death (e.g. if a plant dies in year N = 2, yield losses are equal to a complete yield loss multiplied by two at the net of yield of year N = 1).

Because the symptoms normally appear the year after inoculation (Cadwell, 1990), the yield losses due to newly symptomatic grapevines (III) were established on the basis of the NI index (the proportion of newly symptomatic grapevines / symptomatic grapevines in the previous year). The percentage of newly symptomatic grapevines was calculated with reference to the number of healthy vines in the previous year. NI was calculated as the average of 4 years data for all the three cultivars (four vineyards for 'Merlot' and 'Chardonnay' and one vineyard for 'Perera'). Always bearing in mind that the symptoms normally appear the year after the inoculation, the newly symptomatic grapevines in this first year (year N = 1) were not considered because these infections occur irrespective of the decision whether to replace the symptomatic grapevines in the previous year. In the following year (year N = 2) the newly symptomatic grapevines were calculated on the basis of the proportion of grapevines that were still symptomatic in the previous year (year N = 1). In year N = 3 and the following years they were calculated on the basis of the proportion of grapevines still symptomatic in the previous year, which included those symptomatic in year N = 0 and those newly symptomatic in the years from year N = 2 up to the current year. The newly infected grapevines were considered to have the same course of symptom expression and yield losses as the grapevines that showed symptoms in year N = 0.

$$MC_N = \left(\textstyle\sum_1^N YL\right)\cdot\left(YH\cdot GP\cdot GD\right)/N \tag{4}$$

$$\textstyle\sum_1^N YL = YL_1 + YL_2 + \dots YL_N \tag{5}$$

$$YL_N = YLSG_N + YLNSG_{N(>1)} \tag{6}$$

$$YLSG_N = \left(SG_N\cdot pYL\right)+\left(DG_N\cdot N\right)- -\left\{\textstyle\sum_1^N\left[DG_N\cdot\left(N-1\right)\right]\right\}\cdot\left(1-pYL\right) \tag{7}$$

$$NSG_{N(>1)} = (SG_N + CNSG_{N-1})\cdot NI \tag{8}$$

$$YLNSG_{N(>1)} = (NSG_N\cdot YLSG_0) + + (NSG_{N-1}\cdot YLSG_1) + \dots + (NSG_2\cdot YLSG_{N-2}) \tag{9}$$

MC_N = average annual cost of maintenance for different productive lifetimes of vineyards (N=number of years with 1=year of planting of the new grapevine)

$\sum_1^N YL$ = sum of yield losses from the year after the first manifestation of symptoms (year N=1) to the year of vineyard removal (N)

N = number of years following the first manifestation of symptoms (N=0) corresponding to productive lifetimes of vineyards

$YLSG_N$ = yield losses in symptomatic grapevines in the years from N=1

$YLNSG_N$ = yield losses in newly symptomatic grapevines in the years from N=2

SG_N = still symptomatic grapevines in the year N among those symptomatic in the year N=0

pYL = proportion of yield loss in a symptomatic grapevine

DG_N = dead grapevines in year N among those symptomatic in year N=0

NSG_N = newly symptomatic grapevines in year N >1

SG_{N-1} = still symptomatic grapevines in year N-1 among those symptomatic in year N=0

$CNSG_{N-1}$ = cumulated still symptomatic grapevines in year N-1 among those newly symptomatic in the previous years

NI = index of new infections = NSG_N/SG_{N-1}

Results

Cost to replace symptomatic grapevines

The annual incidence of the replacement cost (RC_N) decreased as the productive lifetime of vineyards increased (Table 2). Comparing the three cultivars, a higher grape price determined a greater cost of replacement due to the higher value of the yield missed during the grapevine rearing period. A lower density of plants per hectare, assuming the yield per hectare is equal, increased the cost due to greater yield loss per plant during the grapevine rearing period, whereas a lower yield per hectare reduced the cost because the missed yield per plant decreased.

Cost to maintain symptomatic grapevines

In all the cultivars the proportion of symptomatic grapevines decreased in time due to both recovery and death of plants in the years following the first manifestation of the symptoms (year N = 0) (Table 3). Having assumed that grapevines in the first year of recovery have a loss equal to one third of the level of symptomatic grapevines, the proportion of plants on which yield losses was calculated decreased more slowly than the proportion of symptomatic grapevines. In the year N = 9, only a negligible proportion of grapevines still had symptoms. From year N = 2 to year N = 5 a high proportion of the grapevines was replaced because of death in 'Chardonnay'/FD (19%), 'Chardonnay'/BN (10%) and 'Perera' (67%).

The proportion of yield loss in a symptomatic grapevine (pYL) was on average 0.34 for 'Merlot', 0.56 for 'Chardonnay'/FD, 0.56 for 'Chardonnay'/BN and 0.81 for 'Perera'. Considering the pYL and the data on recovery reported in Table 3, a greater ability to recover appeared to be associated with lower yield losses in symptomatic grapevines. Comparing data collected for FD and BN on 'Chardon-

Table 2. Average annual costs of replacement "RC_N" (€/year/plant) estimated for three grapevine cultivars in relation to productive lifetime of vineyards, density of plants per hectare and yield per hectare. N = 1 is the planting year. Mer = 'Merlot'; Ch = 'Chardonnay'; Per = 'Perera'.

Productive lifetime of vineyards (No. years)	Density 3000 plants ha^{-1} Yield 13 t ha^{-1}			Density 1500 plants ha^{-1} Yield 13 t ha^{-1}			Density 3000 plants ha^{-1} Yield 8 t ha^{-1}		
	Mer	Ch	Per	Mer	Ch	Per	Mer	Ch	Per
5	1.64	2.06	3.72	2.34	3.17	6.50	1.38	1.63	2.66
10	0.82	1.03	1.86	1.17	1.58	3.25	0.69	0.82	1.33
15	0.55	0.69	1.24	0.78	1.06	2.17	0.46	0.54	0.89
20	0.41	0.51	0.93	0.58	0.79	1.62	0.34	0.41	0.66
25	0.33	0.41	0.74	0.47	0.63	1.30	0.28	0.33	0.53

Table 3. Proportion of symptomatic and dead grapevine plants from the year of the first manifestation of the symptoms. For FD after the 7th year the data were extrapolated on the basis of the trend. N. = 0 is the year of the first manifestation of symptoms; Sym = symptomatic grapevines; Dead = dead grapevines; Sym+1/3 = symptomatic grapevines increased by a third of recovered grapevines.

No. years	'Merlot'/FD			'Chardonnay'/FD			'Chardonnay'/BN			'Perera'/FD		
	Sym	Dead	Sym+ 1/3	Sym	Dead	Sym+ 1/3	Sym	Dead	Sym+ 1/3	Sym	Dead	Sym+ 1/3
0	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00
1	0.19	0.00	0.46	0.50	0.06	0.65	0.78	0.04	0.84	0.93	0.04	0.94
2	0.13	0.00	0.15	0.46	0.06	0.46	0.61	0.03	0.66	0.52	0.30	0.56
3	0.11	0.00	0.12	0.30	0.06	0.33	0.47	0.02	0.51	0.33	0.26	0.31
4	0.09	0.00	0.09	0.19	0.01	0.22	0.34	0.01	0.38	0.22	0.07	0.23
5	0.03	0.00	0.05	0.11	0.00	0.13	0.25	0.00	0.28	0.11	0.00	0.15
6	0.01	0.00	0.02	0.04	0.00	0.06	0.18	0.00	0.20	0.06	0.00	0.07
7	0.01	0.00	0.01	0.02	0.00	0.02	0.13	0.00	0.15	0.03	0.00	0.04
8	0.00	0.00	0.00	0.01	0.00	0.01	0.10	0.00	0.11	0.02	0.00	0.03
9	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.00	0.07	0.01	0.00	0.03

Table 4. Average annual costs of maintenance "MC_N" (€/year/plant) estimated for three grapevine cultivars in relation to different productive lifetimes of vineyards, density of plants per hectare and yield per hectare. Mer = 'Merlot'; Ch = 'Chardonnay'; Per = 'Perera'.

Productive lifetime of vineyards (No. years)	Density 3000 plants ha^{-1} Yield 13 t ha^{-1}				Density 1500 plants ha^{-1} Yield 13 t ha^{-1}				Density 3000 plants ha^{-1} Yield 8 t ha^{-1}			
	Mer FD	Ch FD	Ch BN	Per FD	Mer FD	Ch FD	Ch BN	Per FD	Mer FD	Ch FD	Ch BN	Per FD
5	0.09	0.98	0.53	2.70	0.18	1.95	1.07	5.41	0.06	0.60	0.33	1.66
10	0.06	1.18	0.32	3.55	0.11	2.36	0.64	7.10	0.03	0.73	0.20	2.19
15	0.04	1.08	0.22	3.39	0.08	2.15	0.44	6.79	0.02	0.66	0.13	2.09
20	0.03	0.91	0.16	2.69	0.06	1.83	0.33	5.38	0.02	0.56	0.10	1.65
25	0.02	0.77	0.13	2.15	0.05	1.54	0.26	4.30	0.01	0.47	0.08	1.32

nay', differences were not observed for pYL, whereas the percentage of dead grapevines was greater for grapevines affected by FD.

The index of new infections (NI) was on average 0.32 for 'Merlot', 0.43 for 'Chardonnay' and 0.50 for 'Perera'. The susceptibility of 'Chardonnay' was greater than 'Merlot' for all four vineyards where the two cultivars were simultaneously present (data not presented). Comparing 'Chardonnay' and 'Merlot', a positive association between susceptibility (NI) and sensitivity (pYL) was observed.

The cost of maintenance (MC_N) decreased as the productive lifetime of the vineyard increased (Table 4), even if for 'Perera' and 'Chardonnay' a momentary increase was observed for a productive lifetime of 10 years due to yield losses in newly infected grapevines resulting from the inoculum present in symptomatic grapevines. As a consequence of different susceptibility, sensitivity and grape price, the cost of maintenance for FD was highest for 'Perera' and lowest for 'Merlot'. A lower density of plants per hectare, with yield per hectare being equal, increased the cost due to the greater value of yield loss per plant, whereas a lower yield per hectare reduced the cost due to the lower value of the yield losses.

Comparison between replacement and maintenance costs

By comparing the costs of replacing and maintaining symptomatic plants, the profitability of replacing symptomatic grapevines varied among cultivars and within the same cultivar in relation to the disease considered (FD or BN) and agronomic/economic factors (Table 5).

BN affected vineyards

Replacement was clearly not profitable when the grapevines were affected by BN (Table 5). In some vineyards a small proportion of new grapevines (max 5%) showed symptoms within 3 years of replacement. Considering the actual data collected for the 10 vineyards of 'Chardonnay' (i.e. proportion of new grapevines that were replanted again due to failure to take root or grapevine phytoplasma occurrence, proportion of symptomatic and dead grapevines from the year of first manifestation of symptoms and pYL), the replacement would not be profitable for any vineyard when also considering a lifetime of 25 years (Figure 1).

FD affected vineyards

The replacement of symptomatic grapevines was not profitable for the 'Merlot' cultivar, which was characterized by the greatest recovery, the absence of grapevine mortality and the lowest pYL and NI (Table 5). In the four vineyards of this cultivar a variable proportion of 0% to 3.8% of new grapevines showed phytoplasma symptoms within 4 years of replacement. Considering the actual data collected in the four studied vineyards (i.e. proportion of new grapevines that were again replanted due to the failure to take root or phytoplasma disease occurrence, proportion of symptomatic grapevines from the year of the first manifestation of symptoms, pYL and NI) the replacement would not be profitable for any vineyard when also considering a lifetime of 25 years (Figure 1).

In contrast, the replacement was very profitable for the 'Perera' cultivar, which showed the greatest levels of mortality and yield losses in symptomatic grapevines (Table 5). However, in the 'Perera' vineyard which was not treated against the vector, 39% of new grapevines showed symptoms within

Table 5. Differences between costs of replacement and maintenance "RC-MC" (€/year/plant) estimated for the three grapevine cultivars in relation to different productive lifetimes of vineyards, density of plants per hectare and yield per hectare. Positive and negative values indicate that maintenance involves gain and loss, respectively. Mer = 'Merlot'; Ch = 'Chardonnay'; Per = 'Perera'.

Productive lifetime of vineyards (No. years)	Density 3000 plants ha^{-1} Yield 13 t ha^{-1}				Density 1500 plants ha^{-1} Yield 13 t ha^{-1}				Density 3000 plants ha^{-1} Yield 8 t ha^{-1}			
	Mer FD	Ch FD	Ch BN	Per FD	Mer FD	Ch FD	Ch BN	Per FD	Mer FD	Ch FD	Ch BN	Per FD
5	1.55	1.08	1.53	1.02	2.15	1.21	2.10	1.09	1.32	1.03	1.30	0.99
10	0.77	-0.15	0.71	-1.69	1.06	-0.78	0.94	-3.86	0.65	0.09	0.62	-0.86
15	0.51	-0.39	0.47	-2.15	0.70	-1.10	0.62	-4.62	0.44	-0.12	0.41	-1.20
20	0.38	-0.40	0.35	-1.76	0.53	-1.04	0.46	-3.75	0.33	-0.15	0.31	-0.99
25	0.31	-0.36	0.28	-1.41	0.42	-0.90	0.37	-3.01	0.26	-0.15	0.25	-0.79

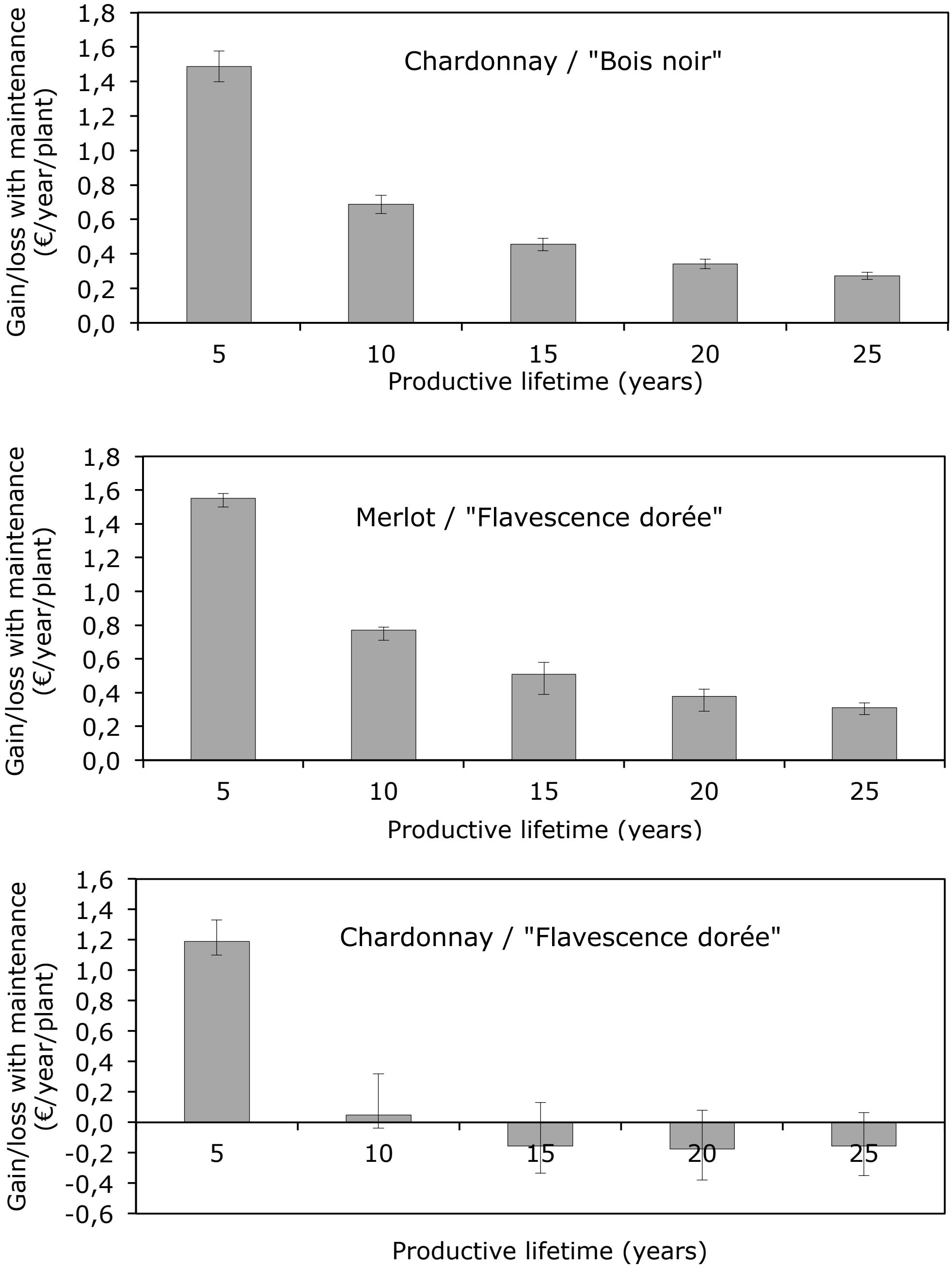

Figure 1. Average (max and min) gain or loss per year per plant for maintenance in comparison to replacement for the ten 'Chardonnay' vineyards affected by BN and for the four 'Merlot' and 'Chardonnay' vineyards affected by FD. Different productive lifetimes were considered.

3 years and would have required replanting. Considering this occurrence and also that 39% of these replantings would in turn have become infected, the replacement would not be profitable even for the 'Perera' cultivar. Only by adopting strategies to control the vector, thus reducing the infection in new grapevines, would the replacement of the infected grapevines of the 'Perera' cultivar be profitable.

For grapevines of the 'Chardonnay' cultivar the profitability varied according to the agronomic/economic variables, pYL and NI (Table 5; Figure 2). The longest productive lifetimes made the replacement more profitable. Productive lifetime being equal, a lower density of plants per hectare and an increase in the grape price made replacement relatively more profitable, whereas a lower yield per hectare made maintenance more profitable. A lower sensitivity (lower pYL) and a lower susceptibility (lower NI) made maintenance relatively more profitable. In two of the four considered vineyards some affected grapevines were replaced and in one of these, 9.1% (two out of 22) of the new grapevines showed phy-

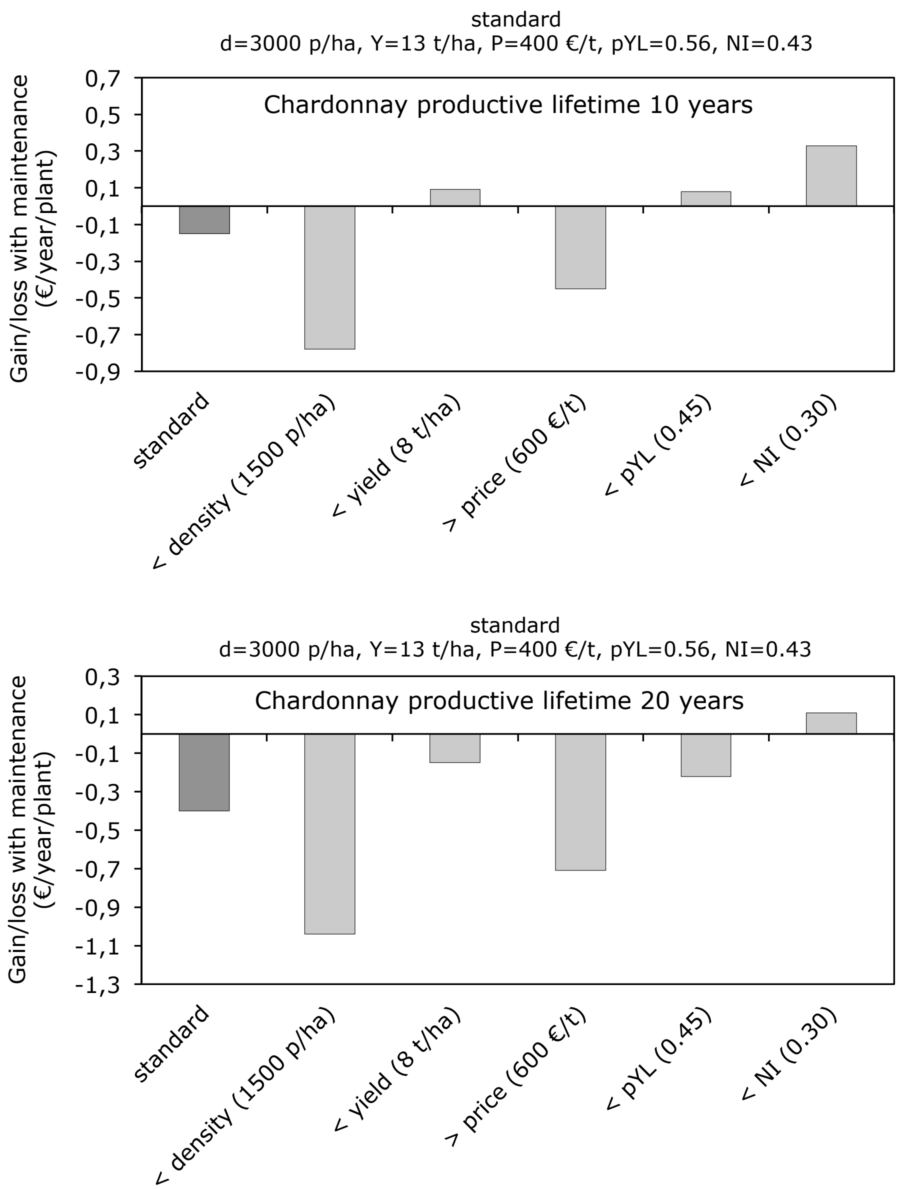

Figure 2. Average gain or loss per year per plant for maintenance in comparison to replacement for 'Chardonnay' infected by FD, assuming productive lifetimes of 10 and 20 years. The gain or loss obtained at standard conditions is compared with that obtained by increasing (>) or decreasing (<) some parameters.

toplasma symptoms within 3 years of replacement. Considering the actual data collected in the four studied vineyards (i.e. proportion of new grapevines that were replanted again due to failure to take root or phytoplasma occurrence, proportion of symptomatic and dead grapevines from the year of the first manifestation of symptoms, pYL and NI), the profitability of replacement started with a lifetime of 10 years for one of the four vineyards and with a lifetime of 15 years for two of the remaining vineyards (Figure 1).

Discussion

Bois noir

For BN in northeastern Italy the replacement strategy is not profitable in relation to the 'Chardonnay' cultivar. The fact that the vector, *H. obsoletus*, does not acquire the phytoplasma from symptomatic grapevines, at least on the basis of the present knowledge (Maixner, 2010), seems to be a decisive factor because the roguing of symptomatic grapevines does not reduce the probability that other plants become infected. Because the healthy plants are often inoculated by vectors moving into vineyards from outside, as shown by the spatial distribution of both the vector and the disease (Bressan *et al.*, 2007; Mori *et al.*, 2008), there is a high risk that the replantings can, in turn, also be infected. This occurrence is still more probable if cultivars more susceptible than Chardonnay are considered. Because greater susceptibility is associated with greater incidence of mortality in infected grapevines, the replanting of dead grapevines would be less profitable if it was not accompanied by the removal of local herbaceous plants, which are sources of infected vectors (Maixner, 2007; Mori *et al.*, 2008, 2012; Stark-Urnau and Kast, 2008). If the removal of these herbaceous plants is not possible, less susceptible grape cultivars should be planted.

Flavescence dorée

For FD, the replacement of symptomatic grapevines is to be encouraged if they are mostly destined to die, because a delayed replacement represents a cost and the symptomatic plants are sources of FD phytoplasmas. This strategy was rightly adopted for Garganega in northeastern Italy (Posenato and Girolami, 1994; Posenato *et al.*, 1996). However, the success of the strategy requires: (i) chemical control of *S. titanus* that might have acquired the phytoplasma inside the vineyards, and (ii), roguing of abandoned vineyards and American grapevine spontaneously established in woodland, which can be sources of infected vectors (Caudwell, 1981; Pavan *et al.*, 2005).

If a cultivar shows high recovery, as observed for 'Merlot' in this study, it is not profitable to replace the symptomatic grapevines. The maintenance of symptomatic grapevines associated with insecticide treatments against *S. titanus* was successfully adopted for Prosecco in northeastern Italy (Pavan *et al.*, 1997; Osler *et al.*, 2002).

For intermediately sensitive cultivars, the profitability of replacing symptomatic grapevines varies according to factors independent of grower activity (e.g. yield losses in symptomatic grapevines, recovery incidence, grape price) and factors on which farmers can act (e.g. density of plants per hectare, yield per hectare, vector control). In particular, a greater density of plants per hectare reduces the profitability of replacement because the economic value of yield losses due to grapevine phytoplasma diseases is greater when the same yield per hectare is spread over a few plants. Effective chemical control of *S. titanus* reduces the negative effect of non-rogued symptomatic grapevines as potential sources of FD phytoplasmas. Data collected in north Italy demonstrated that when insecticide treatments are applied, the incidence of newly symptomatic grapevines decreases drastically, even without the roguing of symptomatic grapevines (Pavan *et al.*, 2005; Morone *et al.*, 2007). In some cases the incidence of newly symptomatic grapevines does not decrease, in spite of the insecticide treatments, but in these situations external sources of infected vectors should be considered, as suggested by the existence of gradients of the disease from infected abandoned vineyards (Pavan *et al.*, 2010). If it is not possible to remove these external sources, the susceptible/sensitive cultivars need to be substituted with non-susceptible/non-sensitive ones.

In most cases of the more susceptible cultivars, there is a high risk that replanted grapevines will be infested by *S. titanus* and that they will need to be replaced again, thus reducing the profitability of replacement. On the basis of the vineyards monitored during the present study, the incidence of infestation was low if the vineyards were treated with insecticides against the vectors (i.e. 'Merlot' and 'Chardonnay' vineyards), but it was high if the vineyards were not treated (i.e. the 'Perera' vineyard). Therefore, replacement needs to be associated with vector control strategies.

The replacement of symptomatic grapevines, even when not profitable at farm level, could be necessary for general reasons. FD is a quarantine disease and if grapevines with symptoms are found in areas with nursery activity, they must be removed. The replacement of FD affected grapevines has to be recommended also in areas of new introduction, to reduce the inoculum of the disease to low levels.

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