Long-term graft compatibility study of peach-almond hybrid and plum based rootstocks budded with European and Japanese plums

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Abstract

The introduction of some new rootstocks requires knowledge of the potential ‘translocated’ and ‘localized’ graft incompatibilities before releasing these rootstocks into the market. Trials were established at the Aula Dei Experimental Station (Zaragoza, Spain) to assess graft compatibility between five European plum (*Prunus domestica* L.) and six Japanese plum (*Prunus salicina* L.) cultivars with thirty-eight rootstocks belonging to peach × almond hybrids, as well as slow-growing, fast-growing and interspecific hybrid plum groups. Some of these rootstocks are under process of selection and others are commercial rootstocks already introduced into the European market. External visual diagnosis of the scion-rootstock graft combinations was performed by observing symptoms of the ‘translocated’ incompatibility in the nursery. Visual symptoms of ‘translocated’ incompatibility were only found on the Japanese plum cv. ‘Golden Japan’ budded on the plum-apricot hybrid AP-45. The ‘localized’ graft incompatibility was assessed after internal macroscopically examination of graft unions. In the case of the European plum cvs., ‘President’ and ‘Reine Claude Tardive of Chambourcy’ exhibited good graft compatibility with all the tested rootstocks, with the exception of ‘President’ budded on the pentaploid plum hybrid rootstock Damas GF 1869. ‘Reine Claude Verte’ cv. showed ‘localized’ incompatibility with Myrobalan B and Myrobalan GF 3-1 since the second year after budding. ‘Stanley’ cv. showed ‘localized’ incompatibility with the six evaluated peach × almond hybrid rootstocks, although it was compatible with all plum based rootstocks. In the case of Japanese plums, four cultivars (‘Angeleno’, ‘Black Amber’, ‘Delbarazur’ and ‘Songold’) did not show any graft incompatibility, but ‘Friar’ showed ‘localized’ incompatibility on Myrobalan B. In the case of peach-almond and *P. cerasifera* based rootstocks (Adarcias, GF 677, Damas GF 1869, Myrobalan B, Myrobalan 29 C, Myrobalan GF 3-1 and Marianna GF 8-1), ‘Golden Japan’ trees showed similar symptoms

to those caused by TomRV in Myrobalan and peach rootstocks and ‘localized’ incompatibility. Finally, this study confirmed the interest of *P. insititia* specie as well as several interspecific *Prunus* hybrids as a good source of rootstocks for the plum industry.

Keywords: *Prunus domestica*, *Prunus insititia*, *Prunus cerasifera*, *Prunus dulcis* x *Prunus persica*, translocated incompatibility, localized incompatibility

Introduction

The orchard economic, longevity and environmental viability is linked to a proper cultivar and rootstock selection for a specific climate and soil conditions, together with its graft compatibility knowledge. The hexaploid European plums (*Prunus domestica* L.) and the diploid Japanese plums (*Prunus salicina* Lindl.) are among the most widely cultivated fruit species in temperate climates (Ferlito et al., 2015; Reig et al., 2018a). The commonly used rootstocks for European plum cultivars include different *Prunus* species such as *Prunus cerasifera* (Myrobalan or cherry plums, 2n=16), *P. cerasifera* x *P. munsoniana* hybrids (Marianna), *P. spinosa* (Sloe or blackthorn plums, 2n=32), *P. insititia* (Damson plums, 2n=48), and *P. domestica* (common plums, 2n=48). For Japanese plum cultivars, Myrobalan and Marianna are also commonly used, especially on orchards with poorly-drained soils and waterlogging conditions (Topp et al., 2012). To a lesser extent, interspecific hybrids of almond (*P. amygdalus*) and peach (*P. persica*) could be also used for European and Japanese plums to avoid iron chlorosis in calcareous soils and to have an adequate level of vigor on low fertility sites. Peach × almond hybrids have been successfully developed as rootstocks for almond and peach cultivars in Mediterranean countries (Mestre et al., 2015; Ben Yahmed et al., 2016). Nevertheless, they can exhibit graft incompatibility with some plum cultivars, especially with the European hexaploid plums (Moreno et al., 1995a). Most breeding programs, on diverse climate and soil conditions, aim to obtain commercial rootstocks with a wide range of cultivars compatibility (Moreno, 2004). However, the limiting factor for the widespread use of some *Prunus* spp. for plum production may be the occurrence of graft-incompatibility in the orchard.

Graft compatibility can be defined as the establishment of a successful graft union as well as extended survival and proper functioning of the composite grafted plant (Goldschmidt, 2014). Successful formation of graft depends on various complexes of biochemical and structural procedures, which includes callus formation, establishment of new vascular

tissue, and formation of an active vascular system across the graft interface (Martínez-Ballesta et al., 2010; Pina et al., 2012, 2017). The grafted partners often belong to the same species or genus, but the use of genetically divergent genotypes is also common (Usenik et al., 2006). Therefore, graft incompatibility occurs frequently, especially in the inter-species combinations, mainly because of the differences in anatomy, morphology and physiology between the graft components (Darikova et al., 2011). This is often the case when pear is grafted on quince, and apricot and peach on other *Prunus* species (Ciobotari et al., 2010; Zarrouk et al., 2006, 2010). Likewise, late graft rejection in fruit trees has been limited by plasmodesmal coupling at the time of grafting within one of the partners (Pina et al., 2009). To understand the mechanism responsible for graft incompatibility, Mosse (1962) described two types of graft incompatibility, ‘translocated’ and ‘localized’. The first one is characterized by visual symptoms in the tree (yellowing of leaves, which later became redder or more orange, premature defoliation, leaf wilting) and an earlier stop of tree growing and a radicular system not fully developed (Moreno et al., 1993; Hartmann et al., 2002; Zarrouk et al., 2006; Dogra et al., 2018). This type of incompatibility cannot be overcome by the use of an interstock (Hartmann et al., 2002). In contrast, ‘localized’ type is characterized by anatomical irregularities at the graft union interface accompanied by anatomical abnormalities of vascular tissue in the callus bridge (Hartmann et al., 2002) and by breaks in cambial and vascular continuity and poor vascular connections (Zarrouk et al., 2010). It can be overcome by the use of mutually compatible interstocks (Hartmann et al., 2002). These two types of incompatibility can present themselves jointly in a same graft combination, and neither of them is privative of determined species.

Breeding *Prunus* rootstocks studies are in progress at the Aula Dei Experimental Station for obtaining new *Prunus* rootstocks, with specific adaptation to Mediterranean environments (Font i Forcada et al., 2012; Mestre et al., 2015, 2017) and having a wide graft compatibility with different stone fruit species, including plum cultivars (Moreno, 2004; Reig et al., 2018b). Several graft compatibility studies were performed in plums budded on different plum based rootstocks (Mosse, 1960; Moreno et al., 1995b, 1995c). However, very few studies included peach × almond rootstocks (Moreno et al., 1995a; Duval, 2004) and new released rootstocks. Therefore, main objectives of the present study were: 1) to assess and determine the graft compatibility performance of European and Japanese plum cvs. budded on peach × almond hybrids, other interspecific hybrids and also on plum rootstocks recently released and/or in process of selection, and 2) to establish

comparisons in terms of graft compatibility with commercial rootstocks of different origins, introduced into the European market.

Material and Methods

Plant material

Five European plum cultivars ('President', 'Reine Claude of Bavay', 'Reine Claude Tardive of Chambourcy', 'Reine Claude Verte' and 'Stanley') and six Japanese plum cvs. ('Angeleno', 'Black Amber', 'Delbarazur', 'Friar', 'Golden Japan' and 'Songold') were T-budded *in situ* in summer and evaluated during 5 consecutive years on different *Prunus* rootstocks (Table 1). Approximately, at 15 cm from the ground, a T cut (approximately 1 cm width and 1.5 cm long) was made across the bark at each rootstock (one-year old tree, diameter $\approx$ 1 cm). For practical purposes, rootstock genotypes were divided into three different groups: (1) peach $\times$ almond hybrids (*P. amygdalus* $\times$ *P. persica*); (2) Slow-growing plums (*P. insititia* and *P. domestica*); and (3) Myrobalan-Marianna plums (*P. cerasifera* and interspecific hybrids having *P. cerasifera* as a parent). Among the thirty-eight rootstocks used in this study, the hexaploid plums 'Pollizo de Murcia' rootstocks and the interspecific hybrids Miral 3278 AD, PADAC 04-01 and PADAC 99-05 are under process of selection by the Aula Dei Experimental Station.

Rootstocks were propagated by hardwood cuttings treated with indole-3-butyric acid (indolebutyric acid) at 4 g L⁻¹ for peach $\times$ almond hybrids, other peach and almond hybrids and slow-growing plums rootstocks (Moreno et al., 1995b), and at 0.5 g L⁻¹ for Myrobalan-Marianna plum rootstocks (Moreno et al., 1995c). Stock-plants used for cutting production are routinely tested to maintain mother trees free of *Prunus* necrotic ringspot virus (PNRSV), Prune dwarf virus (PDV), Tomato ringspot virus (TomRV), Apple chlorotic leaf spot virus (ACLSV) and Plum pox virus, Sharka (PPV).

Trials were established in different nurseries at the Aula Dei Experimental Station (NE Spain; lat. 41° 43' 42.7 "N, long. 0° 48' 44.1" W), on heavy and calcareous soils with 29-30% total calcium carbonate, 7.4-7.6% active lime, water pH 8.0-8.5, and a clay-loam texture. The nurseries were level-basin irrigated every 12 days during the summer.

At each nursery, each scion/rootstock graft combination was replicated, in general, 10 to 30 times (trees) (10 trees per block) depending on the availability of plant material (previously rooted rootstocks). Consequently, not every scion/rootstock graft combination was available at each nursery. Ten replicates per combination were considered the minimum acceptable for assessment, although some combinations suffered field losses at

each block after several years of field-testing, but mainly due to the initial grafting process failure.

'Translocated' incompatibility evaluation

Firstly, the level of compatibility-incompatibility was mainly determined during the first two years after budding by visual diagnosis of the symptoms of the 'translocated' type of incompatibility in the nursery, e.g., leaf and wood yellowing and reddening, defoliation, tree vigour reduction, and death (Moreno et al., 1993). Moreover, a determination of leaf chlorophyll concentration using SPAD 502 m (Minolta Co., Osaka, Japan) was made on 2-year-old trees from the end of June to the beginning of July. This procedure was used as a potential tool to estimate the rate of 'translocated' graft incompatibility (Fig. 1). Measurements were made on fully expanded leaves of 10 trees per combination selected from the middle of the tree.

'Localized' incompatibility evaluation

Anatomic examination of each scion/rootstock union was carried out on 2 to 5 year-old budded trees. Each graft union was sawed by a radial-longitudinal plane, and each visual rating of 'localized' graft incompatibility (Fig. 2) was classified according to Mosse and Herrero (1951): 1) category A: Perfect unions (the line of the union between bark and wood is hardly visible); 2) category B: Good unions (the bark and wood are continuous although the line of union in the wood is often clearly distinguished by excessive ray formation); 3) category C: Unions with discontinuities in the bark (the bark tissues of rootstock and scion are separated by a dark brown layer of corky appearance); 4) category D: Unions showing vascular and wood discontinuities (the woody tissues of rootstock and scion are separated in many places by clusters of living, non-lignified parenchyma, whereas bark tissues are generally as category C); and 5) category E: Observed breakage of the tree at the graft union in the nursery or orchard. Categories D and E were considered 'incompatible' unions because breakage might occur caused by mechanical damage or wind.

Growth measurements

At the time of internal examination, stem circumferences at 5 cm above and below the graft union, and at the graft union itself were measured. This method enabled searching for correlations between growth characteristics and compatibility-incompatibility occurrence (Zarrouk et al., 2006).

Statistical analysis

Data from SPAD were evaluated by one-way variance (ANOVA) analysis with the software SPSS 21.0 (SPSS Inc., Chicago, USA). When the F test was significant, means separation were conducted using a Duncan test at $P \leq 0.05$. The analyses of Pearson correlation were carried out to study correlations between graft incompatibility occurrence and year after budding.

Results and Discussion

‘Translocated’ incompatibility evaluation

No visual symptoms of ‘translocated’ incompatibility were found on most of the plum graft combinations, with the exception of the Japanese plum ‘Golden Japan’ budded on the inter-specific hybrid plum rootstock AP-45 (Table 3, Fig. 1). During the second season of nursery growth, all trees of ‘Golden Japan’ budded on AP-45 (*P. besseyi* and *P. cerasifera* in its background) showed clear symptoms of ‘translocated’ incompatibility. The visual symptoms appeared in the form of leaf yellowing (Fig. 1), lower SPAD values and tree growth cessation (Figure 3). Zarrouk et al. (2006) reported that low SPAD values may be associated with the blockage of carbohydrate assimilates and nitrogen uptake in scion leaves. In addition, as the rate of shoot growth of incompatible graft declines, carbon export from the scion through the phloem to the rootstock has been reported to slow down and decrease nitrogen assimilation (Moreno et al., 1994). Although this type of incompatibility is usually expressed during the first year after grafting (Dogra et al., 2018), it is worth to mention that no trees from ‘Golden Japan’ / AP-45 combination developed incompatibility symptoms during the first year. Therefore, this combination showed a clear delay on the expression of this type of incompatibility. Finally, according to our knowledge, few studies have evaluated the ‘translocated’ incompatibility in *Prunus* spp., mostly in peach as scion (das Neves et al., 2017; Zarrouk et al., 2006).

‘Localized’ incompatibility evaluation

In terms of ‘localized’ graft incompatibility, all scion-rootstock combinations were, in general, compatible when plum cultivars were budded on the hexaploid slow-growing plum rootstocks (Tables 2 and 3), assessed by the five-scale categories described above. Among them, it is noteworthy the perfect unions observed with some ‘Pollizo de Murcia’ plums, Adesoto 101, PM 105 AD and PM 150 AD rootstocks, as previously reported in the case of Adesoto 101 (Moreno et al., 1995b).

Concerning the European plum cvs., the anatomical evaluation of unions indicated good compatibility of ‘President’ and the ‘Reine Claude’ cvs. on most of the tested rootstocks, with the exception of ‘President’ budded on the pentaploid hybrid Damas GF 1869 and

'Reine Claude Verte' budded on Myrobalan B and Myrobalan GF 3-1 (Table 2). Okie (1987) reported graft incompatibility between Myrobalan B and Myrobalan GF 3-1 and 'Reine Claude' cvs., in general. Moreno et al. (1994) already reported the good graft compatibility (category 'A') of the peach-almond hybrids Adafuel and GF 677 with 'President' cv. Similarly, Reig et al. (2018b) reported a good agronomic performance of the interspecific plum x almond hybrid Miral 3278 AD and the plums Myrobalan B and Myrobalan 713 AD with the European plums 'R.C. Bavay' and 'R.C.T. Chambourcy' in a long-term orchard trial. The graft combination 'President'/Damas GF 1869 exhibited 'localized' incompatibility (category 'D'), with presence of both necrosis and absence of lignified tissues in the graft plane of the wood. These results contrast with the expected good compatibility of Damas GF 1869 with European plum cultivars (Okie, 1987).

In contrast to 'President', 'Stanley' budded on Damas GF 1869 did not exhibit graft unions included in the 'D' category even after examination of 4-year old trees (Table 2). In addition, 'Stanley' had good graft compatibility (category 'A') with all plum based rootstocks used in this study. However, 'localized' incompatibility (category 'D') was consistently observed when 'Stanley' was budded on almond $\times$ peach hybrid rootstocks, Adafuel, Adarcias and GF 677, as previously mentioned by Moreno et al. (1995a). It is interesting to note that this incompatibility was already observed on two year-old trees. The results also suggested good significant correlation between early and late graft-incompatibility incidence as reported by Mosse (1960), when graft incompatibility of two and ten-year-old trees of European plums trees budded on Myrobalan B was compared. In contrast to peach-almond hybrids, it is worthwhile to mention the good graft compatibility observed on Ishtara, despite of the *P. persica* parental background of the rootstock. Nevertheless, it has lower expected peach (up to 25%) and no almond in its genetic background as compared with peach-almond hybrids. Similarly, Reig et al. (2018a) reported a good agronomic performance of Istihara with 'R.C. Bavay' and 'R.C. GF 1119' (a selected clon from 'R.C. Verte') in a long-term orchard trial.

Besides of the 'localized' incompatibility, it is worth to mention that the visual examination of growth abnormalities at the nursery demonstrated high bud failure (> 30%) of 'Stanley' on Adafuel and GF 677. In addition, during the first vegetative period, more than 50% of the rest of the buds ceased their development at the rosette stage. This fact has been attributed in apricot cultivars to the presence of apple chlorotic leaf spot virus (ACLSV) (Desvignes and Boyé, 1988), although in this study the presence of viruses were not initially detected.

With regards to Japanese plum cultivars, visual observations in the nursery related to plant growth demonstrated, in general, a good bud take and normal development of trees for all graft combinations. The 'Angeleno' cv. showed good graft compatibility (category 'A') when 2 and 3-years-old trees were evaluated, including peach-almond hybrids (Table 3). Similarly, 'Black Amber', 'Delbarazur', 'Friar' and 'Songold' exhibited good graft compatibility (category 'A') when budded on peach $\times$ almond rootstocks. Good graft compatibility of 'Black Amber' and 'Friar' with GF 677 was already reported by Duval (2004). Nevertheless, two year-old trees of 'Black Amber' with Adafuel and Hansen 2168 (one for each rootstock) broke in the nursery (category 'E'). This could be attributed to graft incompatibility or to strong differences in vigor between scion and rootstock. Sometimes, the excessive growth rate of one of the two graft components during the first or second year after budding can cause breakage at the point of the union (Moreno et al., 2001). Nevertheless, examination of older trees from these combinations should be suitable before any recommendation for commercial use.

In the case of 'Golden Japan' cv., the graft compatibility response depended strongly on the rootstock genotype and its genetic background, having the peach $\times$ almond hybrids (Adarcias and GF 677), Damas GF 1869, Myrobalan B, Myrobalan 29 C, Myrobalan GF 3-1 and Marianna GF 8-1 more problems of bark and wood discontinuity (Table 3). These results contrast with the good compatibility found with younger trees of this cultivar on GF 677 (Moreno et al., 1995a). In the peach $\times$ almond hybrid group of rootstocks, American rootstocks Hansen 536 and Hansen 2186 exhibited only one tree classified as 'C' (discontinuity in the bark), whereas older trees did not show any discontinuity. When budded on the slow-growing plum rootstocks, the 100% of 'Golden Japan' trees exhibited good graft compatibility (category 'A'), with the exception of those budded on the pentaploid Damas GF 1869. In the case of peach-almond and *P. cerasifera* based rootstocks (Adarcias, GF 677, Damas GF 1869, Myrobalan B, Myrobalan 29 C, Myrobalan GF 3-1 and Marianna GF 8-1), 'Golden Japan' trees showed symptoms similar to those caused by TomRV in Myrobalan and peach rootstocks (Hoy and Mircetich, 1984), and 'localized' incompatibility. These trees exhibited a narrow strip of brown to dark-brown necrotic cambial tissue (prune brownline symptom, PBL), stem pitting, and discontinuities in the woody external cylinder at the junction of the scion and the rootstock, corresponding brownline to the inner bark removed from the graft union (Fig. 4). Okie (1987) reported prune brownline susceptibility for *P. cerasifera* and *P. persica* rootstocks, in general, and Myrobalan 29 C, in particular. However, as previously mentioned, TomRV has not ever

been detected in the assessed rootstocks and scions. In addition, the severe consequences of PBL symptom (decline and eventual death of the affected tree) described by Hoy and Mircetich (1984) were not observed in this study before sawing the assessed trees.

Modern Japanese plum cultivars are predominantly *P. salicina* but also include other species such as *Prunus simonii* Carr., *Prunus cerasifera* Ehrh., *Prunus americana* Marsh. and *Prunus angustifolia* Marsh (Topp et al., 2012). Different studies mentioned that ‘Golden Japan’ could be an open pollination of ‘Wickson’ (Goulão et al., 2001), a diploid plum resulted from the cross of Burbank (*P. salicina*) and Simon (*P. simonii*) (Boonprakob et al., 2001), but ‘Golden Japan’ could also have *P. cerasifera* in its ancestry (Duval, 1999). In addition, Hoy and Mircetich (1984) also reported that PBL results from the hypersensitive reaction of prune scions to TomRV infections in peach and Myrobalan rootstocks. The unclear parentage of ‘Golden Japan’ and the putative hypersensitivity of this cultivar to TomRV could help to explain the possible incompatibility (wood discontinuities) between ‘Golden Japan’ and peach and Myrobalan based rootstocks.

The study of stem circumferences above, below and at the graft union did not shown any significant correlation with the ‘localized’ graft incompatibility occurrence (data not shown), in contrast with peach and apricot graft compatibility studies (Zarrouk et al., 2006; des Neves et al., 2017; Reig et al., 2018c).

The predominant type of incompatibility found in this study, mostly concerning the peach-almond hybrids and European plums (‘Stanley’ cv.), is an interesting result, as ‘localized’ incompatibility can be solved by the use of mutually compatible interstocks. Consequently, peach-almond hybrids could be used as rootstocks in calcareous soils, typical of the Mediterranean area, to avoid iron chlorosis in plum orchards, as also reported with cherries (López-Ortega et al., 2016).

Conclusions

In general, when graft incompatibility was early detected between European and Japanese plums and rootstocks, it also appeared continuously over the years of evaluation, with the exception of the Japanese cv. ‘Golden Japan’. Previous testing should be made when peach × almond hybrids rootstocks are going to be used with plum cultivars, as graft compatibility is strongly dependent on the budded cultivars. Japanese plums seem to be, in general, less exigent in terms of graft compatibility than European plums. However, special attention should be paid when they include in their genetic background other species than *P. salicina*, especially when budded on Myrobalan and peach based

rootstocks. In addition, this study confirmed the interest of *P. insititia* specie as well as several interspecific *Prunus* hybrids as a good source of rootstocks for the plum industry.

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Table 1. Rootstocks used for the plum graft compatibility study.

Rootstock ¹	Species	Ploidy level	Origin ²	Calcareous soil tolerance ³	Waterlogging tolerance ³	Root-knot nematodes resistance ³
Almond x peach hybrids						
Adafuel ¹	<i>P. dulcis</i> x <i>P. persica</i>	2x	CSIC, Spain	Highly tolerant	Susceptible	Susceptible
Adarcias ¹	<i>P. dulcis</i> x <i>P. persica</i>	2x	CSIC, Spain	Tolerant	Moderately tolerant	Susceptible
GF 557	<i>P. dulcis</i> x <i>P. persica</i>	2x	INRA, France	Highly tolerant	Highly susceptible	Resistant
GF 677	<i>P. dulcis</i> x <i>P. persica</i>	2x	INRA, France	Highly tolerant	Susceptible	Susceptible
Hansen 536	<i>P. dulcis</i> x <i>P. persica</i>	2x	UC, USA	Tolerant	Susceptible	Resistant
Hansen 2168	<i>P. dulcis</i> x <i>P. persica</i>	2x	UC, USA	Tolerant	Susceptible	Resistant
Slow-growing plums						
Adesoto 101 ¹	<i>P. insititia</i>	6x	CSIC, Spain	Highly tolerant	Highly tolerant	Immune
‘Pollizo de Murcia’: PM 44 AD, PM 95 AD, PM 101 AD, PM 105 AD, PM 137 AD	<i>P. insititia</i>	6x	CSIC, Spain	Tolerant	Tolerant	Immune
St Julien A	<i>P. insititia</i>	6x	INRA, France	Moderately tolerant	Tolerant	-
Constantí 1	<i>P. domestica</i>	6x	CSIC, Spain	Tolerant	Tolerant	Immune
RC GF 1380	<i>P. domestica</i>	6x	INRA, France	Tolerant	Tolerant	-
PP-1	<i>P. domestica</i> ?	6x	Oregon, USA	-	Tolerant	Immune
Penta	<i>P. domestica</i>	6x	CRA-FRU, Italy	Tolerant	Tolerant	Resistant
Tetra	<i>P. domestica</i>	6x	CRA-FRU, Italy	Tolerant	Tolerant	Resistant
Torinel	<i>P. domestica</i>	6x	INRA, France	Moderately tolerant	Tolerant	Resistant
Damas GF 1869	<i>P. domestica</i> x <i>P. spinosa</i>	5x	INRA, France	Highly tolerant	Highly tolerant	Resistant
Fast-growing plums and Inter-specific hybrid plums						
Adara ¹	<i>P. cerasifera</i>	2x	CSIC, Spain	Highly tolerant	Highly tolerant	Immune
Ademir ¹	<i>P. cerasifera</i>	2x	CSIC, Spain	Highly tolerant	Highly tolerant	Immune
Myrobalan B	<i>P. cerasifera</i>	2x	EM, UK	Susceptible	Tolerant	Moderately resistant
Myrobalan 713 AD	<i>P. cerasifera</i>	2x	CSIC, Spain	Tolerant	Tolerant	Resistant
Myrobalan 29 C	<i>P. cerasifera</i>	3x	GB, USA	Tolerant	Tolerant	Immune
Myrocal	<i>P. cerasifera</i>	2x	INRA, France	-	Tolerant	Susceptible
Marianna 2624	<i>P. cerasifera</i> x <i>P. munsoniana</i>	3x?	UC, USA	Tolerant	Tolerant	Immune
Marianna GF 8-1	<i>P. cerasifera</i> x <i>P. munsoniana</i>	4x	INRA, France	Tolerant	Tolerant	Resistant
Aprimed (AP-65)	[<i>P. armeniaca</i> x <i>P. cerasifera</i>] x <i>P. besseyi</i>]	2x	AI, Spain	Tolerant	Tolerant	Resistant
AP-45	[(<i>P. besseyi</i> x <i>P. salicina</i>) x <i>P. armeniaca</i>]	2x	AI, Spain	Susceptible	-	Resistant
Miral 3278 AD	<i>P. dulcis</i> x <i>P. cerasifera</i>	2x	CSIC, Spain	Tolerant	Tolerant	Susceptible
Myrobalan GF 3-1	<i>P. cerasifera</i> x <i>P. salicina</i>	2x	INRA, France	Tolerant	Tolerant	Resistant
Densipac (R-20)	<i>P. besseyi</i> x <i>P. cerasifera</i>	2x	AI, Spain	Tolerant	Tolerant	Moderately resistant
Ishtara ‘Ferciana’	(<i>P. cerasifera</i> x <i>P. salicina</i>) x (<i>P. cerasifera</i> x <i>P. persica</i>)	2x	INRA, France	Tolerant	Moderately tolerant	Immune
PADAC 04-01	[<i>P. cerasifera</i> x (<i>P. persica</i> x <i>P. dulcis</i>)]	2x	CSIC, AI, Spain	Highly tolerant	Highly tolerant	Immune
PADAC 99-05	[<i>P. cerasifera</i> x (<i>P. persica</i> x <i>P. dulcis</i>)]	2x	CSIC, AI, Spain	Highly tolerant	Highly tolerant	Resistant
Nanopac (R-40) ¹	<i>P. dulcis</i> x <i>P. cerasifera</i>	2x	AI, Spain	Tolerant	Highly tolerant	Moderately resistant
Replantpac (RR) ¹	<i>P. dulcis</i> x <i>P. cerasifera</i>	2x	AI, Spain	Highly tolerant	Highly tolerant	Resistant

¹Protected grant by Community Plant Variety Office (CPVO) or the Spanish Plant Variety Office. ²AI= Agromillora Iberia S.L., private nursery, Spain; CRA-FRU= Centro di Recerca per la Fruticultura; CSIC= Consejo Superior de Investigaciones Científicas; EM= East Malling Research Station; GB= Gregory Brother’s, California; INRA= Institut

National de la Recherche Agronomique; UC= University of California. ³ Information obtained from different authors (Okie, 1987; Fernández et al., 1994; Bhutani and Joshi, 1995; Southwick and Weis, 1998; Pinochet et al., 1999; Moreno, 2004; Nyczepir and Esmenjaud, 2008; Jiménez et al., 2008; Pinochet et al., 2012; Byrne et al., 2012; Mestre et al., 2015, 2017; Reig et al., 2018a,b).

1 Table 2. Graft compatibility and internal examination of the graft unions between
2 European plum cultivars and different *Prunus* rootstocks.

Cultivar	Rootstock	‘Translocated’ incompatibility symptoms	‘Localized’ incompatibility Category ^z			
			2 nd year	3 rd year	4 th year	5 th year
			Number of trees			
President	Adafuel	N	30 A	30 A	10 A	10 A
	Adarcias	N	10 A	-	5 A	-
	GF 557	N	5 A	-	5 A	-
	GF 677	N	20 A	10 A	10 A	10 A
	Hansen 536	N	10 A	-	5 A	-
	Hansen 2168	N	10 A	-	5 A	-
	Adesoto 101	N	5 A	5 A	20 A	-
	Damas GF 1869	N	2 B; 8 D	1 A; 6 D	1 A; 9 D	-
	PM 105 AD	N	10 A	10 A	20 A	-
	St Julien A	N	5 A	5 A	10 A	-
	Constantí 1	N	10 A	10 A	10 A	-
	Adara	N	10 A	10 A	-	-
	Ademir	N	30 A	15 A	15 A	-
	Myrobalan B	N	9 A; 1 B	15 A	10 A	-
	Myrobalan 713 AD	N	20 A	10 A	10 A	10 A
	Miral 3278 AD	N	20 A	10 A	-	10 A
Reine	Adara	N	5 A	-	-	10 A
Claude de	Ademir	N	5 A	-	15 A	5 A
	Myrobalan B	N	5 A	-	20 A	10 A
Bavay	Myrobalan 713 AD	N	5 A	-	-	10 A
	Miral 3278 AD	N	5 A	-	-	10 A
Reine	Ademir	N	7 A	-	-	10 A
Claude Verte	Myrobalan B	N	9 A; 3 D	-	-	-
	Myrobalan 713 AD	N	12 A	-	-	-
	Myrobalan 29 C	N	39 A	-	-	-
	Myrobalan GF 3-1	N	8 A; 4 D	-	-	-
	Marianna 2624	N	17 A	-	-	-
Reine	Adafuel	N	10 A; 7 B	30 A	19 A	-
Claude	Adarcias	N	10 A	-	10 A	-
	GF 677	N	14 A	14 A	5 A	-
Tardive de	Adara	N	5 A	-	-	7 A
	Ademir	N	5 A	-	30 A	8 A
Chambourcy	Myrobalan B	N	5 A	-	20 A	4 A
	Myrobalan 713 AD	N	5 A	-	-	4 A
	Miral 3278 AD	N	5 A	-	-	8 A
Stanley	Adafuel	N	2 A; 3 B; 10 D; 3 E	10 D	10 A; 5 D	10 D
	Adarcias	N	1 A; 10 D; 5 E	10 D	10 D	5 D
	GF 557	N	10 D; 1 E	5 D	10 D	5 D
	GF 677	N	5 A; 2 B; 10 D; 3 E	5 D	10 D	10 D
	Hansen 536	N	5 D	5 D	10 D	-
	Hansen 2168	N	10 D	-	15 D	5 D
	Adesoto 101	N	5 A	-	10 A	-
	PM 105 AD	N	5 A	10 A	10 A	-
	St Julien A	N	5 A	5 A	10 A	-
	Constantí 1	N	10 A	10 A	10 A	-
	PP-1	N	10 A	-	-	-
	Penta	N	10 A	5 A	-	-
	Tetra	N	10 A	5 A	-	-
	Damas GF 1869	N	10 A	10 A	10 A	-
	Adara	N	10 A	9 A	-	-
	Ademir	N	10 A	15 A	-	20 A
	Myrobalan B	N	10 A	10 A; 2 E	15 A	-
	Myrobalan 713 AD	N	17 A; 3 E	20 A	20 A	-
	Ishtara® ‘Ferciana’	N	10 A	8 A	-	-
	Miral 3278 AD	N	15 A	13 A	-	-

3 ^zAccording to Mosse and Herrero (1951): A: Perfect unions; B: Good unions; C: Unions with discontinuities
4 in the bark; D: Unions showing vascular and wood discontinuities; and E: Observed breakage of the tree at
5 the graft union in the nursery or orchard. *Abbreviations*: N, visual normal trees.

7 Table 3. Graft compatibility and internal examination of the graft unions between Japanese
8 plum cultivars and different *Prunus* rootstocks.

graft cultivars and different P. ramis rootstocks.						
		‘Translocated’ incompatibility symptoms	‘Localized’ incompatibility Category ^a			
			2 nd year	3 rd year	4 th year	5 th year
Cultivar	Rootstock		Number of trees			
Angeleno	Adafuel	N	16 A	15 A	6 A	-
	Adarcias	N	15 A	15 A	-	-
	GF 557	N	10 A	3 A	-	-
	GF 677	N	10 A	3 A	-	-
	Hansen 536	N	10 A	12 A	5 A	-
	Hansen 2168	N	10 A	5 A	-	-

	Adesoto 101	N	5 A	10 A	-	-
	PM 44 AD	N	5 A	10 A	-	-
	PM 95 AD	N	5 A	10 A	-	-
	PM 101 AD	N	5 A	5 A	-	-
	PM 105 AD	N	5 A	10 A	-	-
	PM 137 AD	N	5 A	10 A	-	-
	St Julien A	N	5 A	10 A	2 A; 1 B	-
	Constantí 1	N	4 A; 2 B	10 A	-	-
	RC GF 1380	N	5 A	6 A	-	-
	Penta	N	5 A	6 A	-	-
	Damas GF 1869	N	5 A	5 A	-	-

	AP-45	N	-	5 B	-	-
	Aprimed (AP-65)	N	5 A	10 A	-	-
	Ademir	N	5 A	16 A	-	-
	Ishtara® ‘Ferciana’	N	5 A	6 A	-	-
	PADAC 99-05	N	5 A	10 A	-	-
	Miral 3278 AD	N	5 A	13 A	-	-
Myrobalan GF 3-1	N	15 A	-	-	-	
Replantpac (RR)	N	5 A	16 A	-	-	
Black Amber	Adafuel	N	15 A; 1 E	15 A	-	-
	Adarcias	N	15 A	12 A	-	5 A
	GF 557	N	10 A	-	-	5 A
	Hansen 536	N	10 A	15 A	-	5 A; 5 C
	Hansen 2168	N	10 A; 1 E	-	-	-
Delbarazur	Adafuel	N	7 A	10 A	-	4 A
	Adarcias	N	3 A	-	-	4 A
	GF 557	N	5 A	-	-	5 A
	GF 677	N	5 A	14 A	-	5 A
	Hansen 536	N	12 A	-	-	8 A
	Hansen 2168	N	6 A	-	-	5 A

	Constantí 1	N	5 A	22 A	-	-

	Adara	N	6 A	26 A	-	-
	Ademir	N	2 A	20 A	20 A; 2 B	-
Miral 3278 AD	N	20 A	18 A	-	12 A	
Myrobalan 713 AD	N	4 A	-	-	4 A	
Friar	Adafuel	N	20 A	40 A	17 A	3 A
	Adarcias	N	4 A	-	4 A	-
	GF 557	N	4 A	-	5 A	-
	GF 677	N	18 A	35 A	17 A	4 A
	Hansen 536	N	13 A	-	5 A	5 A
	Hansen 2168	N	8 A	-	5 A	5 A

	Adesoto 101	N	10 A	7 A	7 A	-
	PM 105 AD	N	20 A	13 A	18 A	-
	St Julien A	N	5 A	9 A	9 A	-
	Constantí 1	N	5 A	28 A	6 A	-
	Damas GF 1869	N	10 A	8 A	8 A	-

	Adara	N	30 A	24 A	5 A	5 A
	Ademir	N	30 A	30 A	25 A; 1 B	10 A
	Miral 3278 AD	N	25 A	22 A	11 A	10 A
	Myrobalan 713 AD	N	16 A	4 A	6 A	4 A
Myrobalan B	N	6 A	24 A	5 A; 10 B; 5 C	4 D	
Myrobalan GF 3-1	N	1 A; 10 B	-	7 A	7 C	

9 Table 3. Continued.

Cultivar	Rootstock	‘Translocated’ incompatibility symptoms	‘Localized’ incompatibility Category ^a			
			2 nd year	3 rd year	4 th year	5 th year
Number of trees						
Golden Japan	Adafuel	N	5 A	20 A	22 A; 3 B	13 A
	Adarcias	N	10 C	5 A	10 A; 2 D	12 B; 2 C; 1 D ^b
	GF 557	N	5 A	-	5 A	10 A
	GF 677	N	5 A	5 A	10 A	12 A; 10 D ^b
	Hansen 536	N	5 A	-	4 A; 1 C	10 A
	Hansen 2186	N	10 A	-	4 A; 1 C	10 A
	Nanopac (R-40)	N	5 A	17 A	-	-
	Adesoto 101	N	5 A	10 A	10 A	-
	PM 44 AD	N	5 A	12 A	2 A	2 A
	PM 95 AD	N	5 A	19 A	4 A	-
	PM 101 AD	N	5 A	10 A	11 A	4 A
	PM 105 AD	N	10 A	10 A	10 A	-
	PM 137 AD	N	5 A	9 A	11 A	6 A
	St Julien A	N	14 A	11 A	5 A; 1 B	12 A; 4 B
	Constantí 1	N	16 A	20 A	26 A	-
	RC GF 1380	N	5 A	8 A	3 A	-
	Penta	N	5 A	7 A	6 A	-
	Tetra	N	5 A	-	-	20 A
	Torinel	N	5 A	4 A	5 A	10 A
	Damas GF 1869	N	5 A	18 A; 2B	10 A; 2 B; 6 D ^b	-
	Adara	N	30 A	30 A	-	10 A
	AP-45	Ab	2 B	13 B	-	-
	Aprimed (AP-65)	N	5 A	16 A	-	-
	Ademir	N	40 A	15 A	20 A	30 A; 2 B
	Densipac (R-20)	N	5 A	17 A	-	-
	Myrobalan B	N	5 A; 8 B; 4 C	25 A	20 A; 7 C	8 C; 7 D ^b
	Ishtara® ‘Ferciana’	N	5 A	11 A	2 A	6 A
	Miral 3278 AD	N	30 A	20 A	20 A; 1 B	20 A; 4 B; 3 C
	Myrobalan 713 AD	N	10 A	5 A	22 A	20 A
	Myrobalan 29 C	N	10 A	-	-	2 C; 9 D ^b
	Myrobalan GF 3-1	N	10 A	5 A	3 C	10 A; 1 C; 3 D ^b
	Myrocal	N	5 A	-	9 A	11 A
	Marianna 2624	N	10 A	-	-	11 A
	Marianna GF 8-1	N	10 A	-	-	3 C; 8 D ^b
	PADAC 99-05	N	5 A	13 A	6 A	7 A
	PADAC 04-01	N	5 A	16 A	-	-
	Replantpac (RR)	N	5 A	17 A	-	-
Songold	Adafuel	N	10 A	6 A	-	-
	Adarcias	N	10 A	7 A	-	-
	GF 557	N	10 A	5 A	-	-
	GF 677	N	10 A	10 A	-	-
	Hansen 536	N	10 A	5 A	-	-
	Hansen 2168	N	10 A	7 A	-	-

^aAccording to Mosse and Herrero (1951): A: Perfect; B: Good unions; C: Unions with discontinuities in the bark; D: Unions showing vascular and wood discontinuities; and E: Observed breakage of the tree at the graft union in the nursery or orchard.

^bNarrow strip of brown to dark-brown cambial tissue (brownline) together with stem pitting in the wood cylinder at the junction of the scion and rootstock.

Abbreviations: N, visual normal trees; Ab, abnormal scion behavior, reduction in vigor, leaf yellowing.

23

24 Figure 1. 'Translocated' graft incompatibility symptoms in 'Golden Japan' budded on AP-
25 45 (irregular growth) compared with 'Golden Japan' budded on Aprimed (good and
26 uniform tree development).

27

Figure 2. Longitudinal sections through different scion-rootstock graft unions for each category (A, B, C, D and E) according to Mosse and Herrero (1951).

Figure 3. SPAD (grey bars) and trunk cross sectional (TCSA) (green line) values of ‘Golden Japan’ budded on plum-based rootstocks. IT: translocated graft incompatibility. Duncan test ($P \leq 0.05$) was performed for SPAD (uppercase letters) and TCSA (lowercase) values. Data followed by the same lowercase or uppercase letter are not significantly different.

Figure 4. Narrow strip of brown to dark-brown cambial tissue (brownline), stem pitting, and discontinuities in the woody external cylinder at the junction of 'Golden Japan' and Myrobalan GF 3-1.