New Plum Varieties to Replace the Famously Known ‘Agen Prunes’

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Cover image
A snapshot of the potential varieties replacing ‘Agen prunes’ – Les prunes © Getty

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Abstract

The characterization of the French national plum collection maintained at INRAE Bourran, France is a necessary step to answer to the rising demand for new plum varieties adapted to climate change. In this study, I monitored 137 accessions of landraces on 33 different traits in order to evaluate their productivity, drying ability, resistance to pests and diseases and sensibility to physiological disorders. The French national plum collection has been monitored for two consecutive years and a database has been created and made available to plum and prune producers. The weather conditions in the last two years have been very different which allowed me to analyze their impacts on the traits monitored. High temperatures during mid-ripening stage stop physiological processes of fruits. It significantly reduces the average fruit weights and sugar content. Fungal diseases seem to take advantage of a rainy season while it negatively affect pests which find their life cycle disrupt by precipitations. The study of flowering dates suggests that early varieties are less likely to be damaged by late spring frosts. An evaluation and the selection of the 137 varieties were conducted using a qualitative multi-attribute model based on the DEX methodology. A decision support tree was developed in conjunction with producers. Eight cultivars stand out from the French national collection: ‘Mirabelle de Metz', ‘Datil', 'Perdrigon', ‘Saint Léonard’, ‘Reine-Claude d’Althan’, ‘Royale bleue’, ‘Marie Jouveneau’ and ‘Victoria’. More data would be needed to confirm these initial results and a slightly more precise calibration is required to fit producers demand.

Layman summary

France is the 3rd largest producer of prunes in the world behind the USA and Chile. Nearly 80% of the French production comes from the Lot-et-Garonne where the famous 'Agen prunes' are produced. Their gustatory and nutritional qualities are known and recognized beyond the French borders. This culture could nevertheless disappear. Indeed, the variety at the origin of these prunes ('Prune d'Ente') adapts with difficulty to climatic changes, to the appearance of new pests and diseases and to organic farming practices. It is therefore urgent to identify, characterize and select landraces already adapted to local conditions. That is why 137 varieties of the French National plum collection were monitored on 4 axes: productivity, drying ability, resistance to pests and diseases and tolerance to physiological disorders. A method to exploit the data was developed with the producers. It is based on the DEXi software, a program for multi-attribute decision making. Eight varieties emerged from the French National plum collection. Three of them, 'Datil', 'Perdrigon' and 'Saint Léonard' have particularly interesting characteristics.

Introduction

The fruit gene pool is undermined by conventional agricultural practices

Since the middle of the 20th century, a worrying loss of genetic diversity has been observed in orchards around the world and France is no exception (Lassois et al. 2016). With the rise of globalization in the 1950s, the industrially grown cultivars from the U.S replaced, bit by bit, the landrace cultivars, formerly grown. (Vetelainen et al. 2009; Martinez-Castillo et al. 2012). These new cultivars have been promoted by the plant nursery owner both for their ability to be intensively conducted and for their tradable characteristic. By doing though, the French orchards were completely reorganized. As was the case for corn and soybean, the orchards underwent an intensification of farming by increasing and specializing the cultivated area and using all kind of inputs (pesticides, insecticides, fertilizers ...).

Although the landrace cultivars, used until then, were particularly well adapted to the local soils and pedo-climatic conditions (Marchenay, 1981), they were not retained because they were less productive and they did not appear in the lists presented to the pomological congresses. In fact, those cultivars did not easily fit into the requirements of the elite varieties' lists. Since they generally were bred from random crossings and were propagated by grafting at the village or canton level (Marchenay, 1981), it is difficult to trace their origin (breeder, date of production and location of the mother tree). Moreover, those landrace cultivars are not well adapted to intensive cultivation (Lamine et al. 2014).

Agricultural industries have gone from a traditional system where fruits were harvested at maturity, carefully packed and sold straight after to consumers (Praly, 2010); to a system with so many intermediaries that it is necessary to harvest the unripe fruits several days before the sale. As a consequence, fruit industries have set up varietal selection programs that aim to improve yield and that target marketing criteria such as resistance to shocks, storage aptitude, preservation, appearance (mostly fruit caliber and color) and firmness (Lamine et al. 2014). The industrialization of agriculture and the selection of commercial traits therefore have led progressively to the decrease of genetic diversity within orchards letting them vulnerable to climate change and to various pests and diseases (FAO, 1996; Singh, 2002; Lamine et al. 2014).

A striking example of a product known to all: apples. Currently, 70% of the 25 to 40 phytosanitary treatments used annually on apple trees are intended to control diseases and are fungicides based (CRA-W (Walloon Agricultural Research Center) Gembloux, 2019; Codronet al. 2003). Without these chemical treatments, producers would lose between 90 to 100% of their production (CRA-W Gembloux, 2019). This vulnerability is partly explained by the much reduced genetic diversity of modern apple varieties. 'Golden Delicious' is the mother, grandmother and great-grandmother of most cultivars on the market. In 1980, it represented 70% of the apples marketed (Marchenay, 1981). This diversity drop applies to most of the fruit species: especially plums that will be the subject of this report, peaches, pears, hazelnuts and so on.

Global issues which act as eye-opener

In recent years, biotic (pests and diseases) and abiotic (climate change) pressures have dramatically increased on orchards. Jean Michel Legave, researcher at INRAE (French National Institute for Agriculture, Food and Environment) in Montpellier, explains that "*tree production is particularly exposed to adverse climatic impacts, particularly because of the perennial nature of most fruit species, but also because of the multi-year and cumulative effects*" (Bonnet, 2018).
The IPCC assesses in its newly published sixth report the impact of 1.5°C global warming and predicts an increase in extreme weather events: temperature and precipitation changes and intensification of droughts (IPCC, 2019). Climate warming leads to all sorts of undesirable effects on fruits given that commercial varieties are not adapted to it: early flowering (exposed to frost), poorer quality and duration of flowering, emergence of double fruit (not marketable), reduced chilling period etc (Bonnet, 2018; Quero-Garcia, 2009).
In addition, the IPCC also reports an increase in the number of diseases and pests epidemics and Bebber and al. (2013) showed the link between climate change and the emergence and spread of plant pests and pathogens. It appears that pests and diseases closely follow the latitudinal shift of temperature (Bebber et al. 2013). Since 1960, it is expected that temperature shift will move 27.3km per decades northward (Burrows et al. 2011) whereas pests and diseases have been reported to move 26.6km per decade (Bebber et al. 2013).For instance, the South West of France (Lot-et-Garonne) was in the past free of yellow prune tree sawfly (*Hoplocampa flava*) attacks but now, the damages caused by this pest are each year more important (Bonnet, 2018).
These findings reflect new needs and expectations.

An emerging awareness with organic farming

As shown previously, market traders impose diverse constraints regarding fruits' standards that are only reachable through high input agriculture. But since the last decade, consumers put pressure on the fruit sector and demand high quality product, respecting human health and environment (Lamine et al. 2014; FNAB, 2019). To meet this demand, the government and national organizations have jointly developed charters, laws and labels (integrated fruit production charter in 1997, Bio Coherence label in 2010, Eco responsible Orchards label in 2011, Zero Pesticides approach in 2014) with producers. The French organic label (AB: Agriculture Biologic), created in 1985, has seen its popularity soar among consumers and producers. Indeed, it offers to consumers a proof of sanitary security (through the prohibition of synthetic chemicals use) and interesting economic benefits to the producers (in 2019, the French organic market weighed 11.4 billion which is 2 times higher than 4 years ago (Renault et al. 2020)).

After having been for a long time almost entirely under the directives of technicians and phytosanitary firms, farmers can now regain control of their production thanks to these initiatives (Dubon & Lafitte2018; Appendix 1).These new approaches offer them the possibility to become again the masters of the fruit plant material and its evolution which has totally slipped from their grasp these last decades. Of course, the commercial varieties are adapted to an industrial management (large size, visual aspect of the fruit, productivity, adaptation to cold storage) but they do not answer the expectations, nor the needs of the producers who are looking for specific agronomic characteristics such as low alternation, strong rusticity or even an easier thinning.

The change of mindset of both producers and consumers as well as the climatic pressure testify that our current intensive agricultural methods are on their way out. The profession must evolve towards an agriculture that reduces inputs (phytosanitary products, water, fertilizer …), and this will only be possible with the evolution of fruit material and agriculture practices.

A glimmer of hope in the forgotten plum varieties that needs to be explored

Thankfully, since 1980s, firstly initiated by enthusiasts and then continued by conservatories and research institutes, a work of research and invetory of landraces has been carried out in order to save the heirloom varieties that could still be saved. The motivations were diverse but two of them united them all:

- Preserving the landraces with their good and fragrant fruits to be discovered by the new generation.
- Constituting a genetic pool of scientific interest. These varieties once appreciated and selected could have forgotten or ignored qualities that could be grown directly by producers or used as a genitor in a breeding program.

Although these approaches were initiated 40 years ago, little scientific knowledge of these ancient varieties has been accumulated. Even in the South-West of France (known for its prune production) the traditional plum varieties remain poorly characterized, thus "limiting their promotion in local markets, use for farm diversification, and exploitation for local gastronomic products" (Manco et al. 2019). Nevertheless, few characteristics have been documented. For instance, 'Reine-Claude Greengage', 'President', 'Stanley', 'Ruth Gerstetter' and 'Blue Free' have shown to be highly tolerant to European Stone Fruit Yellow (ESFY) (Jarausch et al. 2000).

Other plum varieties are considered tolerant to rust (*Tranzscheila spp*) such as 'Prune d'Agen', 'Stanley' and 'Tuleu Gras' as they express a significantly low infestation level (Bálint et al. 2016). The cultivar 'Jojo' carries a hypersensitivity resistance against the Plum Pox Virus (PPV) which makes it the first fully resistant genotype against PPV (Neumüller& Hartmann, 2008). This virus is known to transmit Sharka disease that can cause disastrous economic impact (Neumüller &

Hartmann, 2008). A non-exhaustive list of tolerant European plum cultivars against PPV can be found in Appendix (Neumüller, 2011). All these genotypes carry a tolerance or a resistance to a disease/pest but the mechanism behind it is not yet understood. In 2011, El-kereamy et al. discovered that "pathogenesis-related protein-5" activates the defense response pathway and enhances the resistance to fungal infection in plant (El-kereamy et al. 2011). 'Stanley' and 'Violette' produced high level of this protein and were, as a consequence, not very sensitive to brown rot (*Monilinia fructicola*) (El-kereamy et al. 2011). 'Anna Späth', 'Prune d'Agen', 'Blue Free' and 'Bonne de Bry' also seem to be quite resistant to *Monilinia fructicola* (Neumüller, 2011).

The major issue faced here is that most cultivars have only a single resistance, but, "*It is not enough to create varieties only with high tolerance to monilinia, we must work on the combination of factors in order to minimize the risks facing climate change.*"(Le Corre & Jean Marc Audergon, 2018). Few old cultivars with multi resistance have been documented. 'Húsos', a local cultivar from Romania, is resistant to PPV, tolerant to *P. rubrum*, to *Tranzscheila spp*, and to *M. laxa* (Bálint, 2016). Finally, two cultivars from Serbia, 'Zlatka' and 'Pozna Plava' show interesting resistance to various pathogens such as *Polystigma rubrum, Puccinia pruni-spinosae* and to *Monilinia laxa* (Glišić, 2016).

The literature doesn't cover French landrace cultivars which are most likely adapted to local climate and threats (Negri et al., 2009; Casañas et al., 2017). Here, in the South-West of France, producers are asking for new plum varieties better suited for their agricultural practices. Indeed, there is only one clone (clone 707) used to produce the famous Agen prune.

It is in this context that the project of the association "BioFruits Sud" intervenes. It is led by "Bio Nouvelle Aquitaine" (1) and aims to offer to organic arboriculturists of New Aquitaine and Occitania, a fruit plant material adapted to the practices of organic agriculture by promoting the creation of new cultivars, the exchange of knowledge, the participative selection, the experimentation and the production of tolerant plant material. To this end, the association has approached a fruit species conservatory, the CVRA (126 accessions of plum trees), the Prunus Biological Resources Center of INRAE, Bourran (350 accessions of plum trees), the ITAB (2) and the experimental station Invenio (3), in order to list the existing material and observe its behavior in organic practice.

The aim of the present report is to characterize plum varieties of INRAE Bourran (pedo-climatic conditions, pests/pathogens resistance and fruit quality) and identify the plum varieties best suited to an organically managed orchard in the South-West of France. This short listing is intended to be installed and observed more precisely in an orchard within Invenio's experimental stations. A new database gathering all the data available since 1970s will also be made available.

(1) Regional federation of organic agriculture which acts for the development of agriculture and food of general interest, the creation of economic, environmental and social values

(2) Institute of Organic Agriculture and Food is an applied research organization that aims to generate and share knowledge to improve organic production and processing

(3) Experimentation station of the fruit and vegetable sector in New Aquitaine. Created by and for producers, Invenio's mission is to meet their needs and provide them with real competitive advantages by improving their production and the quality of their products.

Materials and methods

Plant material and culture conditions

Plums and prunes (*Prunusdomestica*) were collected from the French national plum collection maintained in the INRAE *Prunus* BRC. This collection is planted in the 'A' plot orchard of the fruit tree experimental unit of INRAE at Bourran, France. The collection is divided in 20 rows with 15 trees per row for a total of 300 trees; 35 of them were already removed or dead before the start of this study. The 137 plum cultivars are represented in the orchard by 2 trees and grafted on 'Jaspi' rootstock (Figure 1). The north east side of the plot is defined by a hedge of pine trees and the south side by the main building of the farm. The orchard is located on a slope on a silty-clay soil (a porosity index of 0.4).This plot is run at a low input level. Three phytosanitary treatments were carried out before the beginning of the experiments (Appendix, table 2). The orchard is irrigated when needed (drought). The study was carried out for 2 growing seasons (years): 2020 (by Anne-Cécile Azam) and 2021(by Ivan Bigot).

Trees and their fruits were monitored between April and September for various traits regarding their **productivity** (tree vigor, average fruit weight, fruit yield), their **drying ability** (acidity, fruit size, adherence of the stone, sugar level, firmness), their **resistance to pests and diseases** (*Monilinia laxa & Monilinia fructigena, Hoplocampaflava, Cydia funebrana & Cydia lobarzewskii, Tranzscheliapruni-spinosae, Cladosporium carpophilum, Coryneum beijerrinckii, Barchycaudushelichrysi,* *Panonychusulmi and Tetranychusviennensis*) and their **sensibility to physiological accidents** (sunburn, fruit shattering, fruit fall before maturity, russeting, frost).
The protocols to assess productivity, resistance to pests and diseases and sensibility to physiological accidents have been created together with Invenio and follow both CEB (Commission on Biological Essays) and EPPO (European and Mediterranean Plant Protection Organization) standards and guidelines.

Productivity

- Tree vigor:
  Tree vigor was determined by measuring the diameter of the tree at a height of 20 cm above the grafting point. This practical work should have be done during the winter break but considering the time frame of the internship (April to September) it was performed in May.
- Fruit average weight:
  Mean fruit weight was calculated on the basis of a sample of 50 fruit randomly collected.
- Fruit yield:

The yield was assessed by counting the number of fruits harvested per tree, multiplying by the average weight of the fruit studied and by the number of trees/ha (667).

- Storage aptitude:
  25 fruits of each cultivar were stored in a 4°C cold room. The time of preservation (days) without rot spot determine the storage ability of the cultivar.

Drying ability

- Adherence of the stone
  The adherence was determined by eating the fresh or dry plum.
- Sugar content
  Sugar content was determined by squeezing 5 fruits and measuring the degree Brix with a refractometer (HI 96801) – HANNAInstruments (Padova, Italie).
- Firmness
  Firmness was assessed on 10 fruits on each side of the fruit with a durometer (130501) - Agro Technologie (Forges-les-eaux, France).
- Dryning protocol
  After being harvested, plums were dried in an oven (220V - 1250W) for 12h up to 24h depending on their size.

Resistance to pests and diseases

- On fruit: (Monilinia *laxa, Hoplocampa flava, Cydia funebrana, Cydia lobarzewskii, Cladosporium carpophilum)*
  Evaluation of 150 fruits/tree randomly harvested around the tree. Pests and diseases intensity was determined as the percentage of fruits infected per tree.
- On tree:*Coryneum beijerrinckii&Tranzscheliapruni-spinosae*
  Inspection of 50 leaves on the northern, southern, eastern and western sides of each tree (n=200 leaves/tree) to ensure the coverage of the whole tree. Diseaseintensity was assessed as the percentage of leaves infected per tree.
- *Barchycaudushelichrysi:*
  Assessment of plum aphids was performed at the beginning of an aphid wave before it was treated with limonene essential oil. The experiment consists in the examination of 5 to 10 shoots/tree (depending on tree size) on the northern, southern, eastern and western sides of each tree (n=20-40 shoots/tree) ensuring a descent coverage of the tree. Pest intensity was evaluated as the percentage of shoots attacked.

Sensibility to physiological accidents

- Sunburn, fruit cracking & russeting:

Examination of 150 fruits/tree randomly harvested around the tree. Sensibility intensity was determined as the percentage of fruits damaged per tree

- Fruit fall before maturity:
  Count of ripe fruits fallen before the harvest and establishing a percentage of loss.
- Frost:
  Assessment of frost damage was made by examination of 25 fruits on the northern, southern, eastern and western sides of each tree (n=100 fruits/tree) to limit plot effect. Frost damage was assessed as the percentage of frozen fruits (=dead fruit). The damage was classified into one of these percentage ranges: 0=no damage; 1=slight frost damage (0-33% of frozen fruits/tree); 2=moderate frost damage (33%-66% frozen fruits/tree); 3=high frost damage (66%-100% frozen fruits/tree). To counter the effect of the slope an index ranging from 0 to 2 was added. The score now range from 0 to 6 with 0=highly tolerant and 6=highly sensible. This index is not perfect and is not based on literature but it offers a quick way to compare the varieties between each other.

Data analysis

The evaluation of the studied varieties was done using a qualitative multi-attribute model based on the DEX methodology (Bohanec et al., 2000). The variety currently used to produce 'Agen prunes' ('Prune d'Ente 707') was used as reference. The model was developed together with the producers to perfectly fit their needs. The potential of a variety is evaluated according to 3 main criteria: fruit characteristics, resistance to pests and diseases, and sensitivity to physiological accidents. Each of these characteristics is divided into less complex traits that can be monitored in the field. These categories were weighted according to the needs and experiences of the growers (Figure 8). Three simulations were carried out for the fruit characteristics: 100% dry potential, 100% fresh potential and mixed potential. To narrow down our selection to a few varieties, the strongly weighted traits (*monilinia, C. funebrana, C. lobarzewskii*, rust, aphids, cracking and fall before maturity) were rated more harshly. Cultivars with more than 50% of damages on these traits were given a score of 1 which force DEXi to revaluate the other combination.

Results

Fruit producers need to evolve the current cultivars to meet the new needs imposed by organic agriculture and climate change. Knowledge on forgotten plum landraces is required so that they can be re-implanted and/or used in breeding programs. This is the second year that the 137 plum varieties from the French national collection maintained at the INRAE genetic resources center at Bourran, France is being monitored. This collection must be characterized and evaluated in a wide range of climatic conditions; hence, they can be wisely used to their fullest potential. Luckily, the weather of these last 2 years was completely different. While the spring and summer were long and hot in 2020, 2021 was punctuated by frosts in April and rains from April to August (Appendix, figure 1). These strong meteorological differences offer complementary and hitherto unseen information that deserves to be exploited. Large gaps of knowledge persist not only on the relevant traits to consider but also on the optimal way to evaluate the potential of a variety.

Early varieties are more tolerant to late frosts

In the Lot-et-Garonne, the spring of 2021 began with late frosts. A first frost episode occurred on the nights of April 7 and 8 with temperatures of respectively -2.2°C and -2°C, followed by a second episode on the night of April 13 reaching -1.5°C. Those frosts severely damaged plum orchards since they occurred during the flowering stages and the beginning of the fruit set. Some producers lost up to 90% of their harvest potential. The plum collection did not avoid it: 47% of the trees monitored lost at least 50% of their crop potential (Figure 1), the fruit being burned by the frost. Half of them were totally deprived of their fruits (100% loss). The most affected trees were located at the bottom of the plot (Figure 1, row K to O). Indeed, trees with losses greater than 50% represented more than 2/3 of the trees located at the bottom of the slope (Figure 1, row K to O) compared to 1/4 of the trees located in the upper third part (Figure 1 row A to E). In order to assess frost susceptibility, taking in account for this plot effect, an index has been added to the frost damage score (Figure 2). This new index allows comparing varieties between them and it highlights the varieties the most and the less adapted to late frosts (see materials & methods). Overall, 24 varieties were classified as sensitive to frost and 4 as very sensitive ('Prune Petite et Jaune', 'Monsieur', 'Reine-Claude d'Oullins' and 'De Montfort') while in the same time 18 seemed tolerant and 7 very tolerant ('Ama blanc', 'Prune d'Aste violette', 'Damas blanc', Prugnous de Munnick', 'Prune de Saint Leonard' and 2 unknown varieties). Surprisingly, the earliest varieties, which started flowering in mid-March (3 weeks before the frost), were the least damage varieties while the latest ones were the most sensitive as shown in the flowering graph (Figure 3).

High temperatures during mid-ripening stage stop physiological processes of fruits

As succinctly explained earlier, average maximum temperatures were higher throughout the 2020 season compared to 2021. The difference these two years almost reached 5°C in May (Appendix, figure 1B). At the highest, temperatures reached 40.1°C in 2020 compared to 34.3°C in 2021. Overall, the heat waves were significantly more intense and longer in 2020.
Figure 4 is a diagram of the 2020 and 2021 harvest dates. They are extrapolated as the dates of full maturity. Both years show very distinct harvest patterns. In 2020, harvest started 5 days earlier (data not shown here) and was characterized by two maturity peaks in mid-July and early August. These maturity peaks coincided with the extreme heat waves. The year 2021 was more homogeneous and stretched until September 14th.
Fruit weight and sugar content were not significantly different from one year to another (Figure 5). Nevertheless, in 2021, the fruit weights at the extremes (smaller and larger size) seemed to be more represented and the sugar content was slightly higher. Changes in these variables over time provide additional information (Figure 6). The 2020 and 2021 trend curves followed the same pattern for fruit weights and sugar content. The 2020 curve was higher than the 2021 curve at the beginning of the season until early August. But after the heat waves (of 2020), the 2021 curve exceeded the 2020 one's.
Maturity, sugar content and average fruit weight were significantly affected by temperature. At the beginning of the season, higher temperatures are beneficial to fruit development which explains their faster maturity, larger weight and greater sweetness observed in 2020. However, when temperatures reach extremes over several days, it becomes harmful to the fruit and fruit physiological processes are stopped, blocking fruit growth and sugar production.

Pests, diseases and physiological disorders are particularly influenced by climate conditions

Repeated and large amounts of rainfall throughout the 2021 season have resulted in an explosion of damage associated with fungi (Figure 7). *Monilinia* and *Coryneum* damages were significantly higher in 2021. Pests were negatively impacted by these poor conditions, as the numerous rains interfere with the reproduction stage (which is the period when the damages are produced) by disrupting their flights. This was particularly true for *C. funebrana*, which caused, on average, three times less damage this year. The very rainy years favor fungi to the detriment of insect pests which find their life cycle disrupted. Data on aphid attacks are not relevant considering that the orchard is not intensively cultivated. Thus, the production of young shoots is low which reduces the likelihood of aphid attacks.

Similarly, it is difficult to interpret the results for russeting because the identification of this physiological accident is quite personal and can therefore differ between observers. This might explain the variation observed between the two years. As expected, cultivars which were highly susceptible to cracking showed more damage in wet years.

Eight cultivars emerged from the French national plum collection.

Based on the DEXi method, a decision support tree was jointly created with plum growers. This tree is presented in figure 8. Each cultivar was evaluated on 3 major axis: fruit characteristics (fresh and dried), resistance to pests and diseases, and tolerance to physiological disorders. Each axis was divided into less complex variables. These variables were weighted by the producers in order to respond to both the reality of the market and the situations they experience in the field. For this reason, large fruit for fresh consumption was preferred (70%) over the yield (30%), and a higher yield (70%), with smaller fruit (30%), for making prunes.
The pressure induced by *Hoplocampa flava*, *Coryneum beyerinckii* and frost are, with some exceptions, generally low. Thus, they were weakly weighted at 10%, 20% and 20% respectively. On the other hand, monilinia, rust, aphid, cracking and fall before maturity were of major importance and were therefore weighted at 40%. Finally, 50% of the evaluation "resistance to diseases on fruit" was determined by the tolerance to *C. Funebrana* and *C. lobarzewskii*, as they have become an increasing threat in recent years.
This model analyzed 118 plum varieties as alternatives for new plum plantation. Overall, 8 cultivars outshined from the French national plum collection. A diagram of the main criteria (dry and fresh fruit characteristics, pest and disease resistance, and tolerance to physiological accidents) shows the strengths and weaknesses of each of these varieties (Figure 9). 'Prune d'Ente' is the cultivar almost exclusively grown in the southwest of France, so it will be used as reference. It is a variety with excellent fruit, both fresh and dried (4/5). However, it is moderately tolerant to diseases and physiological accidents (3/5 and 3/5), hence the need to find new cultivars. 'Mirabelle de Metz' is the variety with the best characteristics and could therefore be a candidate for planting although it does not target the same market. 'Datil', 'Perdrigon' and 'Saint Léonard' are cultivars with high potential. They are highly tolerant to pests, diseases (5/5) and physiological accidents (4/5). They also have very good drying qualities even if this is not obvious on the diagrams because they are strongly penalized by the low yields of the year 2021. Four additional cultivars harvested in 2020 stand out. 'Reine-Claude d'Althan' has similar characteristics as 'Prune d'Ente': high fruit potential both as fresh or dried plums but a slight sensibility to *C. funebrana* and *C. lobarzewskii.* 'Royale bleue', 'Marie Jouveneau' and 'Victoria' show an incredible resistance to pests and diseases (5/5) and have a particularly high tolerance to physiological accidents (4/5). Additional data are required to confirm those qualities but their current rusticity could make them ideal candidates for a breeding program.

Discussion

Climate change at the heart of varietal selection

Freeze damage is one of the major issues that need to be overcome in fruit production. It still causes more production losses than any other biotic or abiotic stress (Vitasse et al., 2018). What makes it particularly destructive is its impact both in the short and long term. Late spring frosts can have disastrous and immediate economic consequences. If they occur during flowering or fruit set, they can wipe out a whole harvest (Rodrigo, 2000). This was the case this year when some fruit growers lost up to 90% of their plum harvest because the frost was relatively late but especially very cold. The destruction of buds, leaves, flowers and fruits can also have unsuspected effects on the long-term health and production of trees. It reduces nutrient uptake and storage; it delays growth and leaf development, ultimately reducing the period during which the tree can build reserves (Vanoni et al., 2016). After a late spring frost the production of the following years is generally lower than an average year (Vanoni et al., 2016). As early as 1996 (Rodrigo et al., 2006), Rodrigo et al. confirmed that early varieties were more able to tolerate late spring frost. In a study on Apricot trees, they noticed that buds and flower structures were more fragile than small fruits. Nevertheless, these results must be nuanced. The frost of 2021 was an isolated and extremely late case. Our focus should not be on whether early varieties are more or less adapted to late spring frosts, but rather whether these late spring frosts are likely to become more common with climate change. This topic is the core of many unresolved debates.
However, a recent study spanning from 1975 to 2016 on both apple trees and cherry trees suggests that the risk of late spring frost damages has not increased nor decreased during the past four decades at low elevations (Vitasse et al., 2018). It is particularly true in warmer areas (including the south west of France) where the "safety margin against frost injury" increase because of the chilling and/or photoperiod limitation (Vitasse et al., 2018; Fu et al., 2015). These results suggest that late spring frosts should not become widespread in southwestern France. Therefore, in our case, this characteristic should not be considered as a main selecting criterion. However, having diversity on this criterion would make the system more resilient.

Heat waves and extremely high temperatures during summer have become widespread in the last decades and will continue to be more and more common. Our hypothesis that high temperature during mid-ripening may halt fruit physiological processes and thus stop sugar accumulation and fruit expansion/growth was supported by a study on grapevine (Greer & Weston, 2010). Potted vines Vitis vinifera L. cv. Semillon were grown in a controlled environment and transferred to a high temperature chamber (day/night: 40/25°C) at different developmental stages (veraison and mid-ripening) for 4 days. Fruit

growth, sugar accumulation and yield were evaluated at harvest time. After being exposed to high temperature at veraison and mid-ripening, berries growth stopped and decreased to about 9 mm in diameter at harvest (vs 14 mm for the control berries). This represents a 30% decrease in fruit volume which severely reduces fresh weight at harvest and therefore yield. At the end of the experiment, the average yield of the heat-treated vines ranged from 68g to 124g, depending on the stage to which they were exposed (fruit set, veraison, mid-ripeness). While it reaches 181g for the control plot. Similarly, sugar accumulation stopped after the heat treatment and slowly decreased until harvest, while it continued to increase for the control vines.
These brilliant results confirm that fruit size and yield are significantly affected by the heat treatment and that these high temperatures significantly disrupt the flow of sugar in the fruit, regardless of its stage of development (from veraison to mid-ripeness)
Greer and Weston also showed that there were varietal differences in responses to high temperatures stress. It would therefore be interesting to monitor the response to high temperatures of high potential varieties that we selected in order to eliminate the most sensitive ones. This characteristic could be even more important for plum growers because small size fruits are difficult to sell and can be only be sold at a low price. In addition, the sugar content is a criterion that allows producers to sell their production under the "Agen prunes" certification. This label offers them a more important and stable income.

Pests and diseases represent around 20-30% of worldwide agriculture production loss (Kashyap et al. 2018). Thus, it is one of the biggest challenges of this century considering that this pressure could increase with climate change. Firstly, as discussed earlier, climate change increase the range of distribution of pests and diseases. Secondly, the generalization of extreme weather events (heat wave, drought, frost, heavy rain ...) could provide new ecological niches for opportunistic pests and diseases (Rosenzweig et al., 2001). It is difficult to make projections about the evolution of pests and diseases in relation to climate change because many variables are involved: plants and pathogens life cycle, winter temperature, dry summer, presence or absence of dew, without forgetting the long term repercussions of such conditions, over several years. It is utopian to draw conclusions especially since the impacts can be different from one region to another. And as my results showed, no matter the climatic conditions of a year, they will always be pests and diseases thriving. Fungi will thrive during rainy years and insects will prosper during warm and dry summers (allowing additional reproduction cycles)
It is therefore essential to select multi-resistant varieties. This work can only be successful through breeding programs.

DEXi, a still imperfect but promising model

The development of the decision tree with the producers revealed some limitations. Few variables of interest are still lacking. The rehydration capacity of the prune, for example, is a crucial criterion for a successful commercialization of a new plum variety. But, it is tedious to evaluate in our current setup. We do not have a "standard" oven specifically used to dehydrate plum. Therefore, we used a small regular oven with its qualities and defects. Moreover, with more than 100 varieties, the sizes are not homogeneous and require different dehydration times, which is not possible in a standard oven at the present time. Other variables were discussed but not retained due to lack of data. The storage capacity of plums, their resistance to hail or the evaluation of rootstocks are variables that deserve to be taken into account in future research.

The calibration of the software also needs to be improved in order to respond perfectly to the needs of the producers and to display the varieties in the most representative way possible.

Despite these shortcomings, the results remain encouraging. Among the 8 varieties that are out of the lot, 3 of them, 'Datil', 'Perdrigon' and 'Saint Léonard' are coming back to the foreground. Saved by the conservatory of Montesquieu, 'Datil' is marketed again by the cooperative Prayssica in the South-West of France. It is reputed for its rusticity and its aromatic richness. It is even called the "plum caviar". For a few years now, Perdrigon has been revamped and is now available in a wide range of products: fruit jellies, jams, prunes, pastries in the South-East of France. Finally, 'Saint-Léonard' can be found on the markets of Limousin, France.

Towards a new agricutural paradigm

Breeding programs will not meet the challenges of the coming decades by themselves. It must be followed by an evolution of agricultural practices in orchards. Orchards should be thought of as natural, resilient and diversified ecosystems like a forest. Agroecology and agroforestry already offer practical and efficient solutions. Numerous systems are currently being tested (PRUMEL, circular orchard). Their objective is to mobilize functional biodiversity, in time and space, to limit the arrival of pests/diseases on the plot, their installation, development and the damage they cause. Several approaches are evaluated such as push and pull plants, natural edge creations, dilution and masking effects of fruit trees with a diversity of species, fruit varieties and associated plants. These innovative fields are waiting to be explored.

Figures

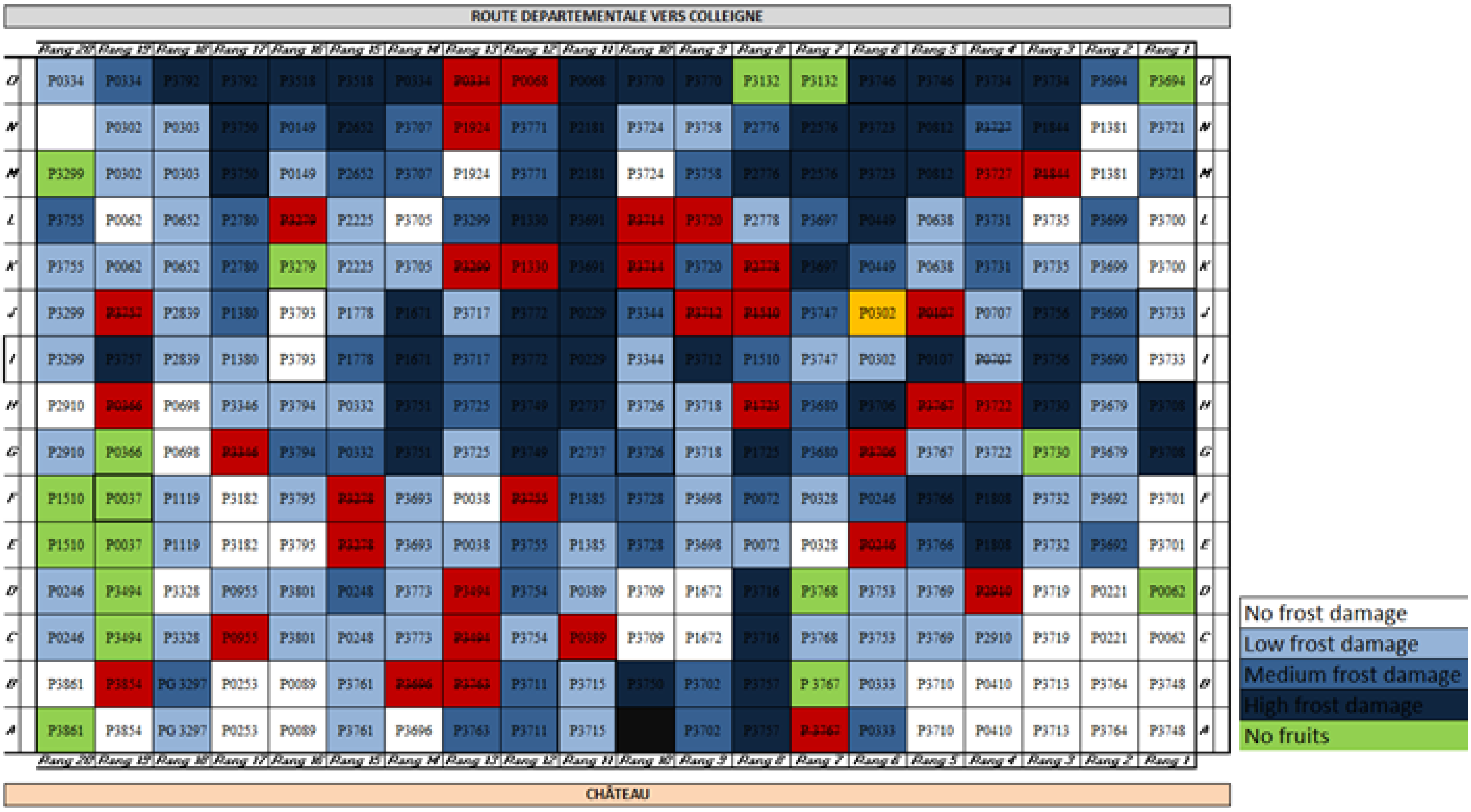


Figure 1: Extent of frost damages on the French national plum collection. Three late spring frosts occurred in 2021 on April 7th, 8th and 13th at respectively -2,2°C, -2,0°C and -1,5°C. Fruits were randomly collected and damages were evaluated on the field.

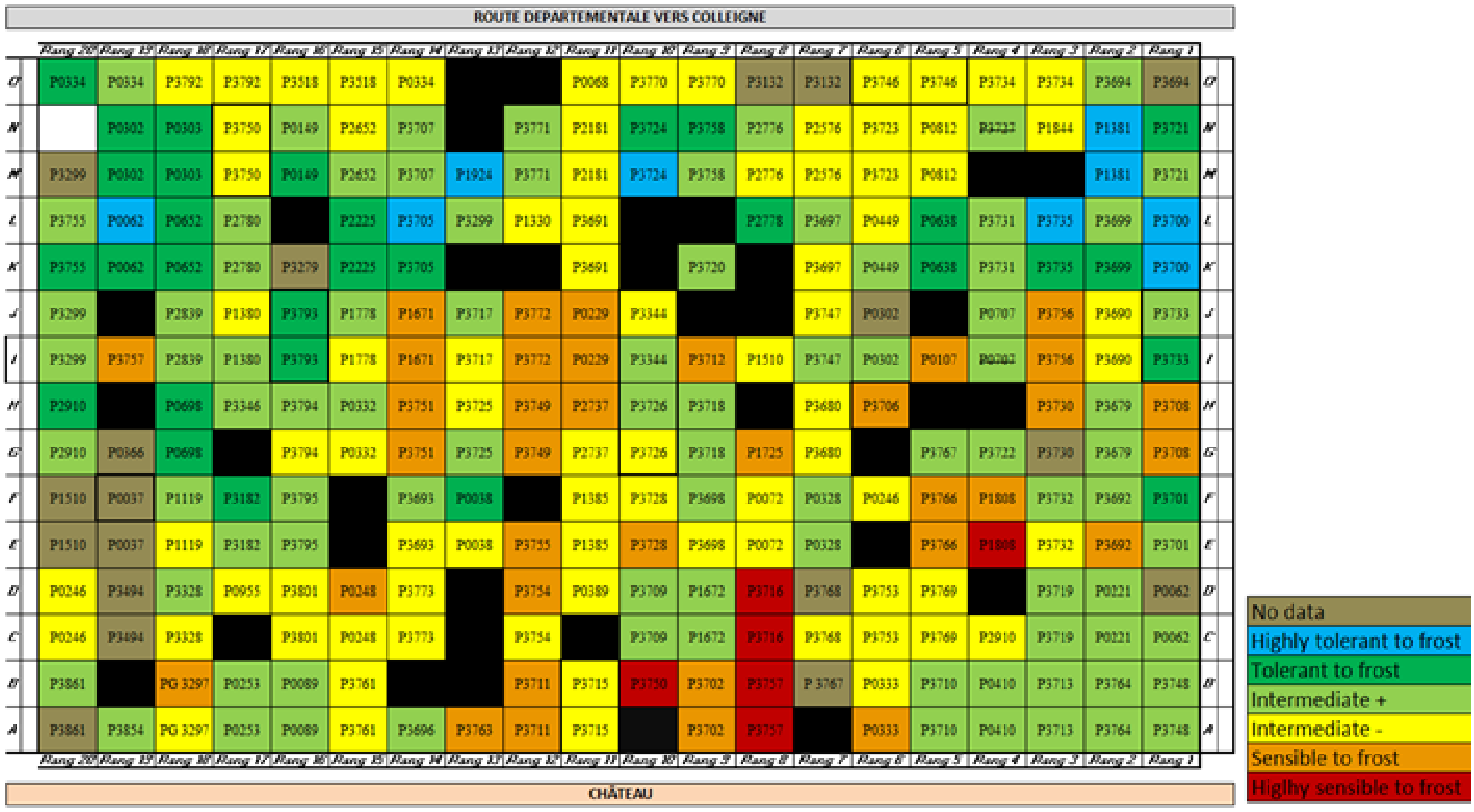


Figure 2: Estimated tolerance to late spring frosts based on the frost damages (%) and their position in the plot (on top of the slope vs at the bottom of the slop). The slope index adds up to the frost damages score from figure 1.

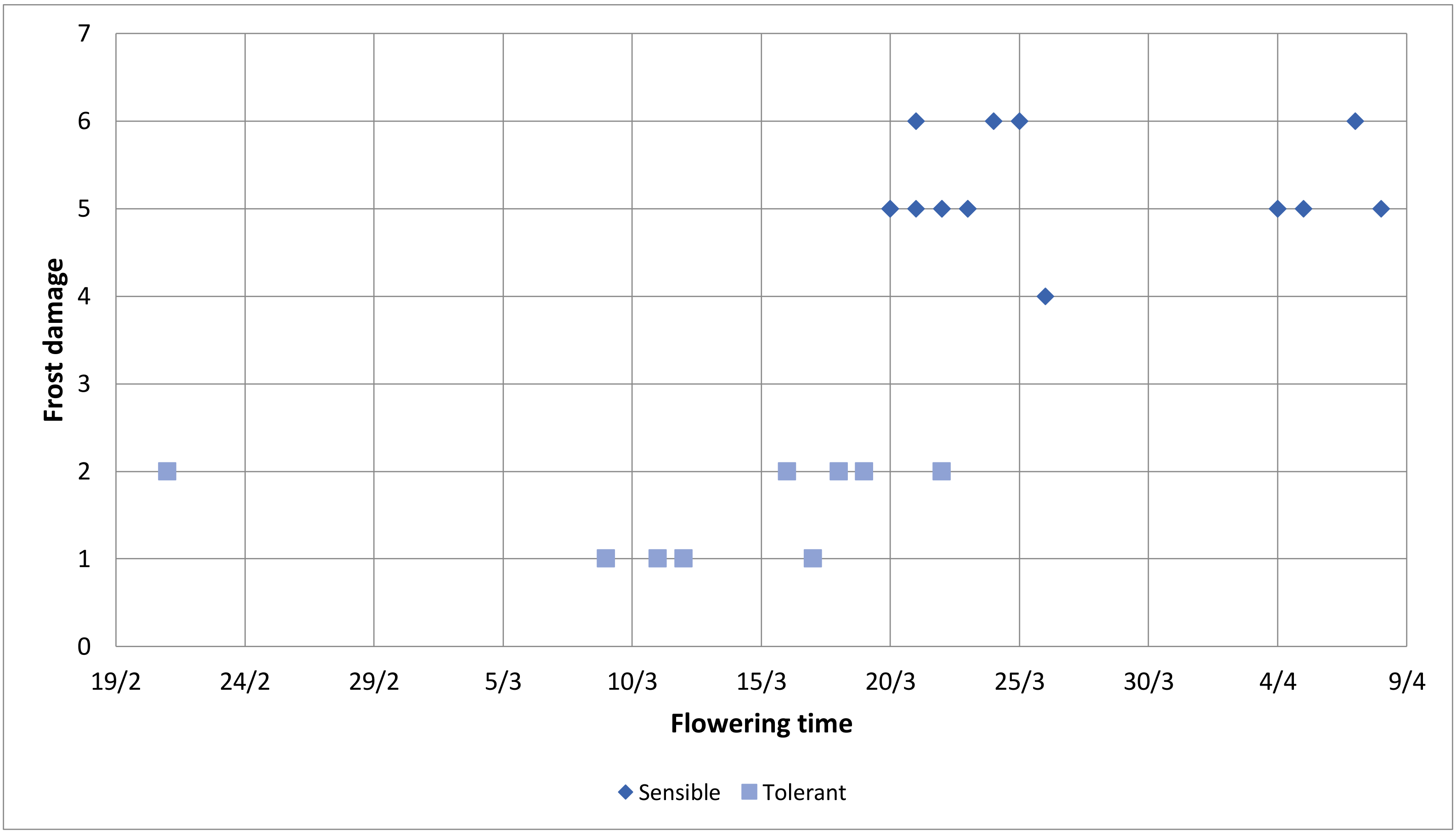


Figure 3: Correlation between frost damage and full bloom date. Only very frost tolerant and very frost sensitive varieties were considered here. The flowering dates were evaluated before and after the frost event

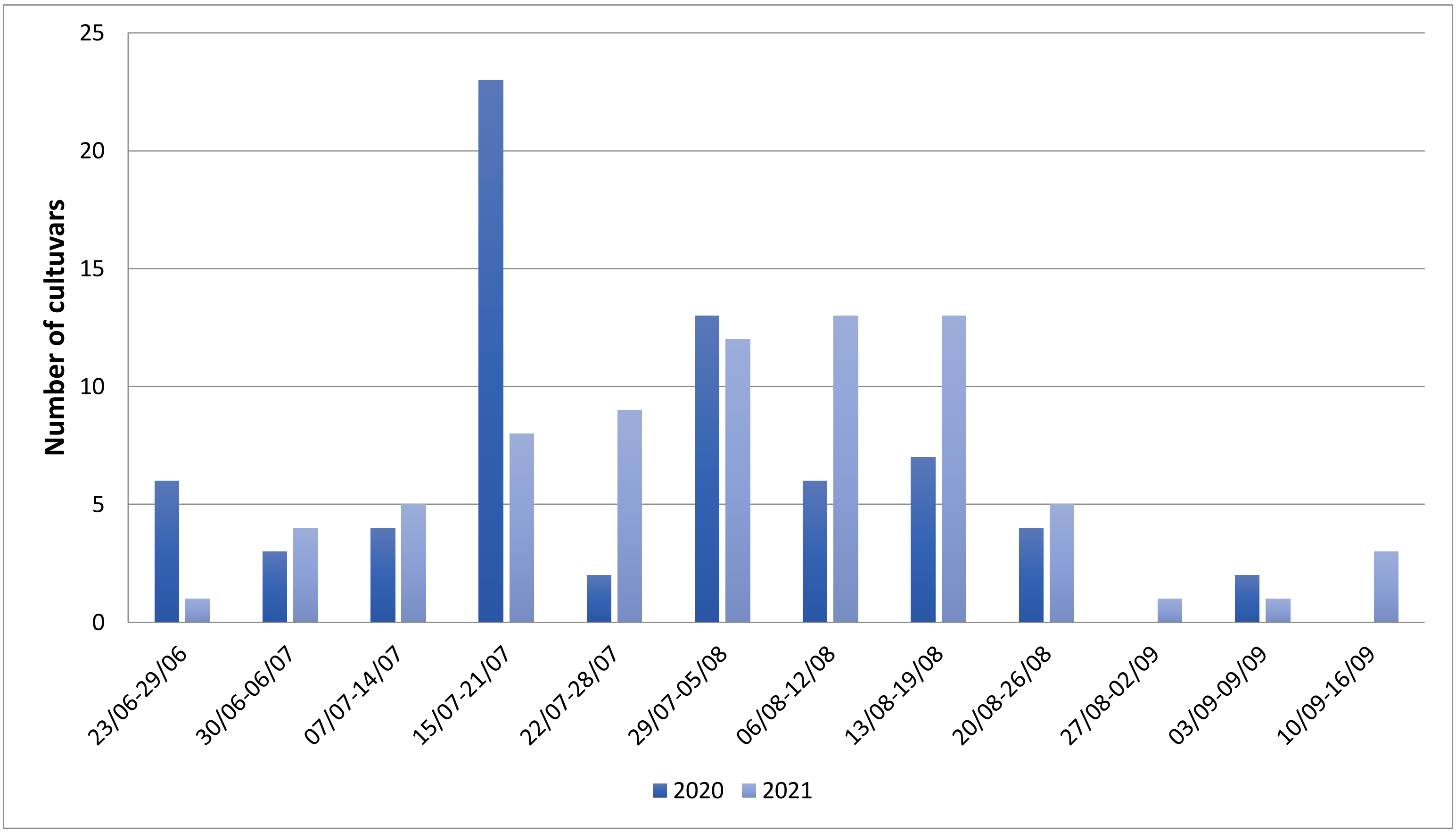


Figure 4: Harvest pattern of the French national plum collection during the 2020 and 2021 harvests.

The plum trees were harvested at full maturity. The year 2020 was very hot and was characterized by 2 heat peaks of 40°C over several days in mid July and early August. 2021 was very rainy and much more homogeneous in terms of temperatures. A weather report can be found in the appendix

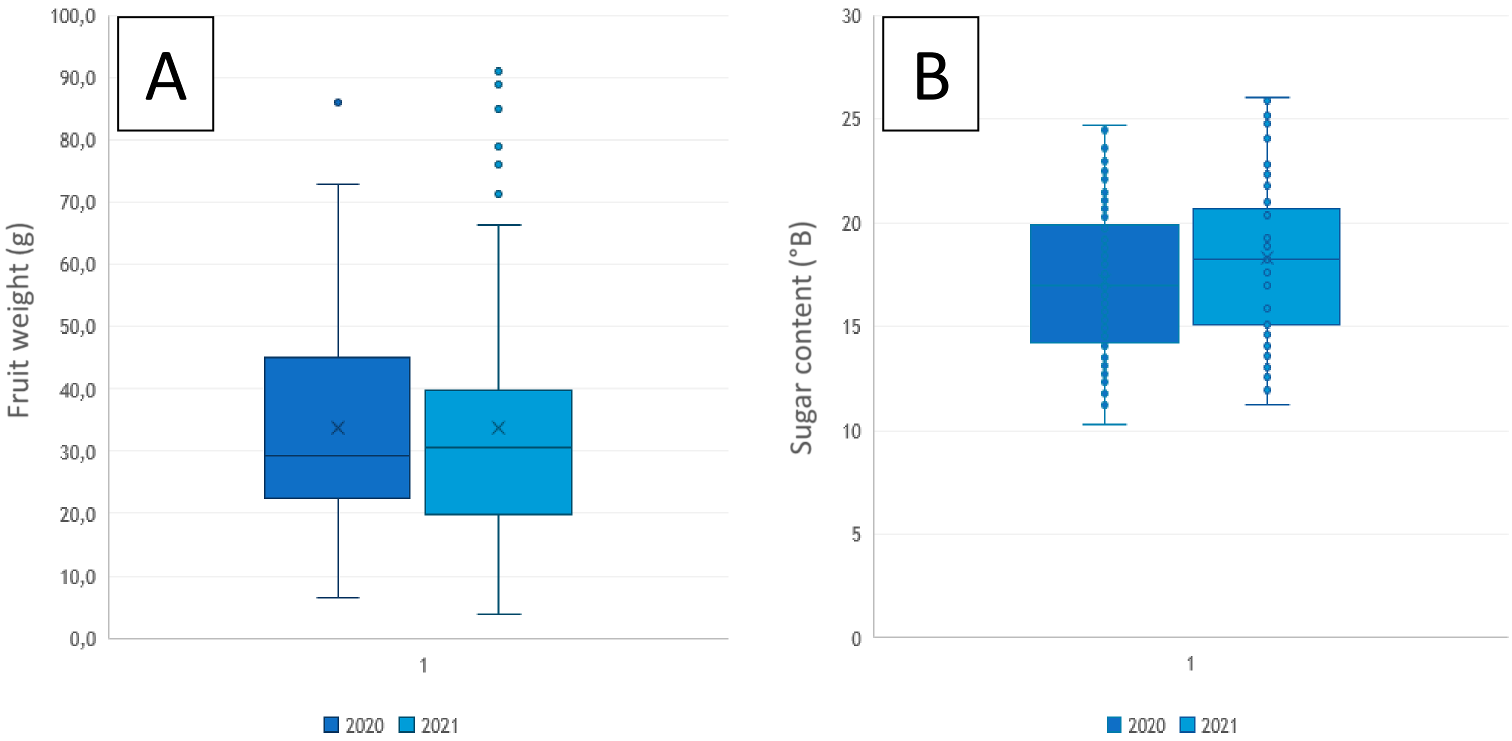
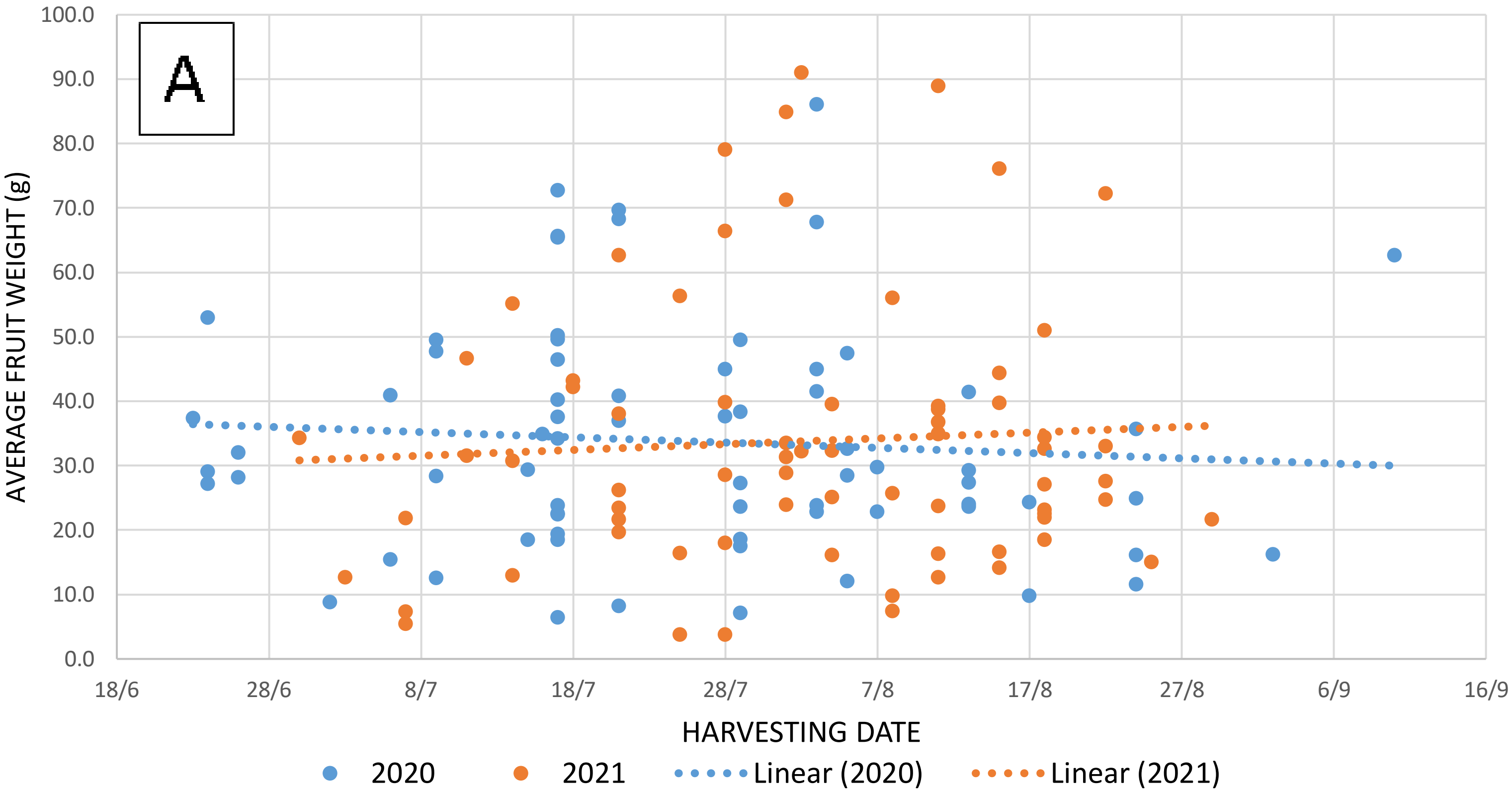


Figure 5: Impact of high temperatures (2020) on average fruit weights (A) and sugar content (B).
Only the varieties in common between 2020 and 2021 have been evaluated here.



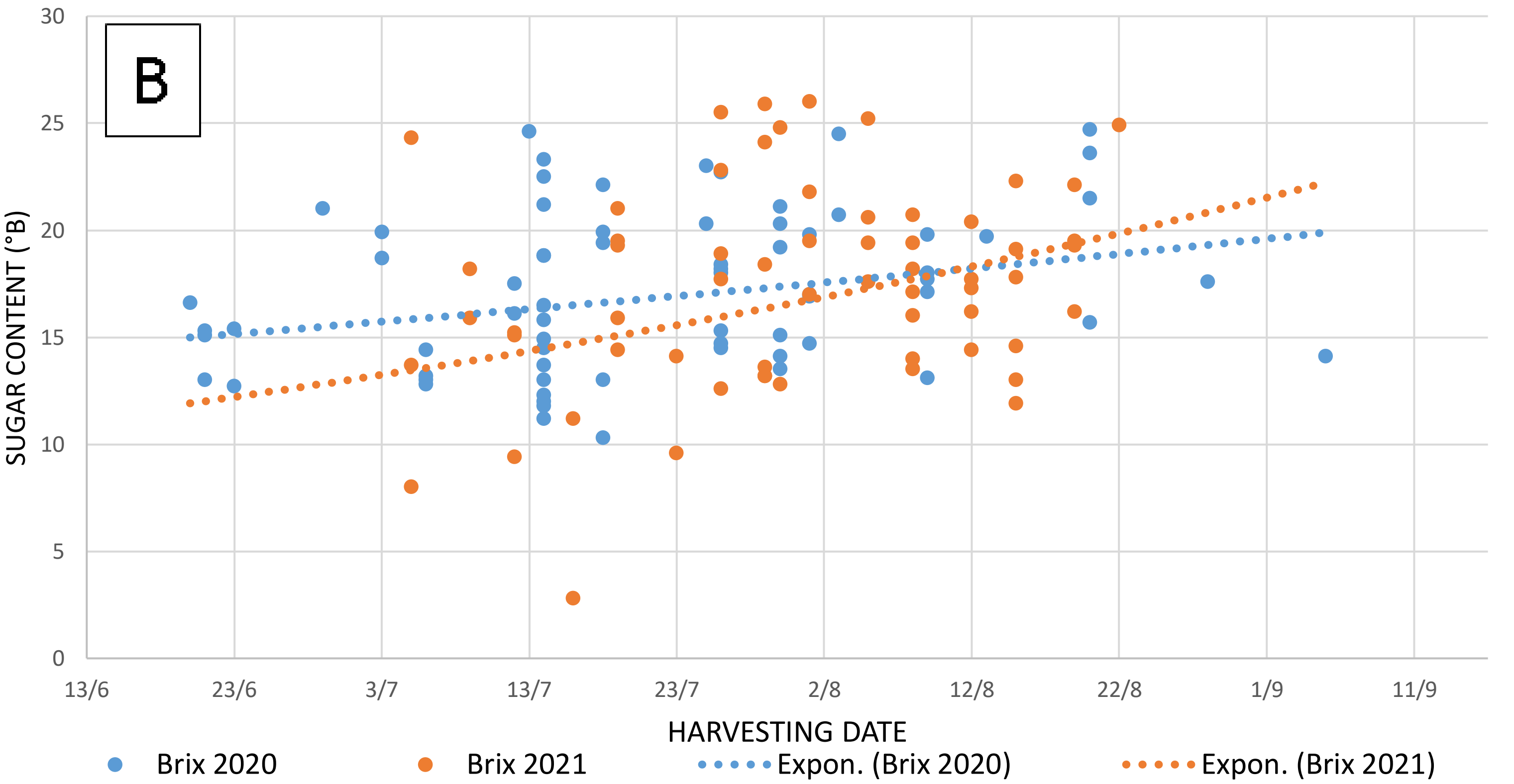


Figure 6: Evolution of average fruit weights (A) and sugar content (B) throughout the harvest season under high temperature (2020) and average summer temperature (2021).

Each point represents the value of a variety. Only the varieties in common between 2020 and 2021 have been evaluated here.

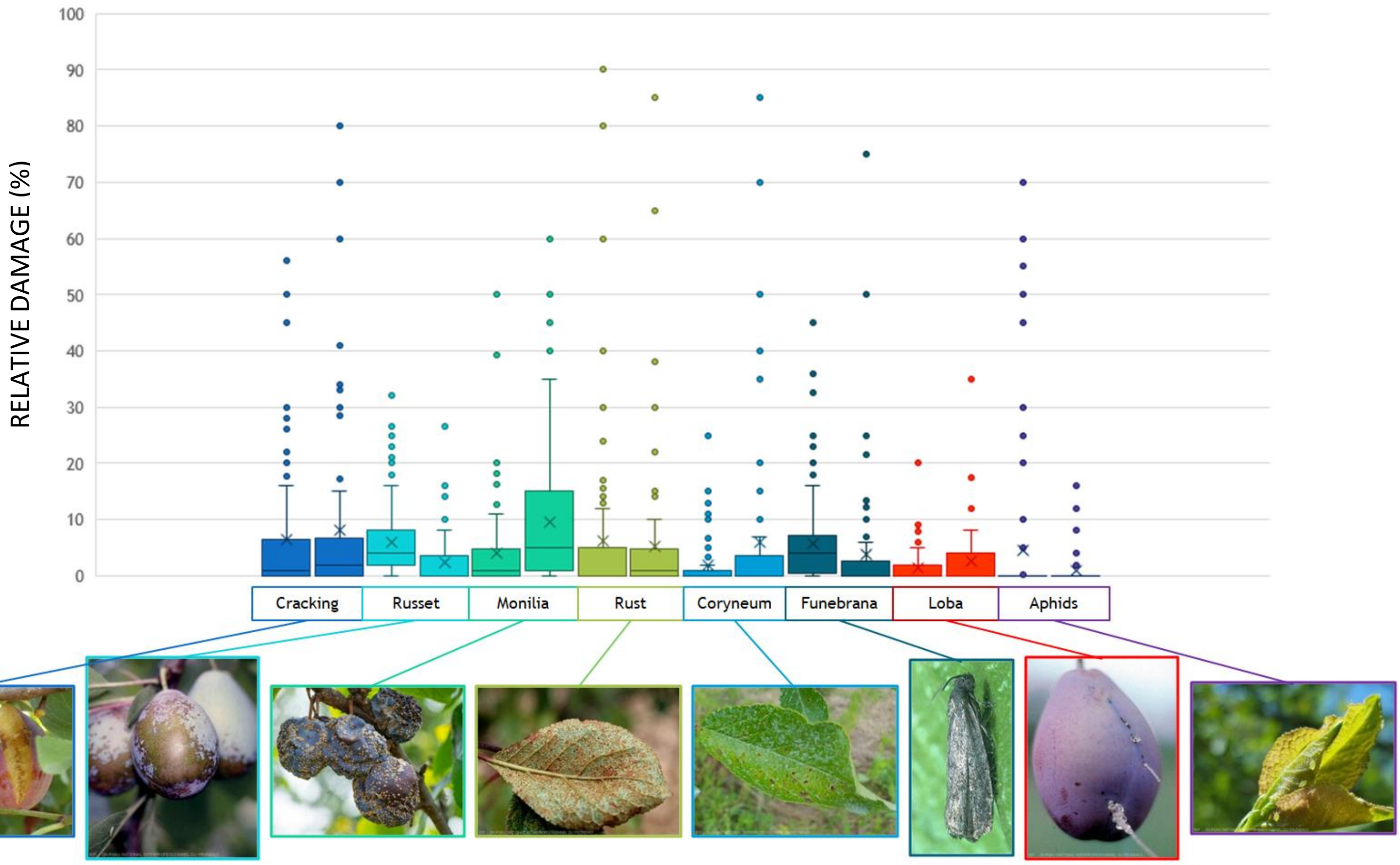


Figure 7: Relative damage (%) of 8 pests, diseases or physiological disorders (*C. funebrana, C. lobaezewskii*, aphids, *monilinia*, rust, *coryneum*, russeting, cracking) in 2020 (left bar) and 2021 (right bar).

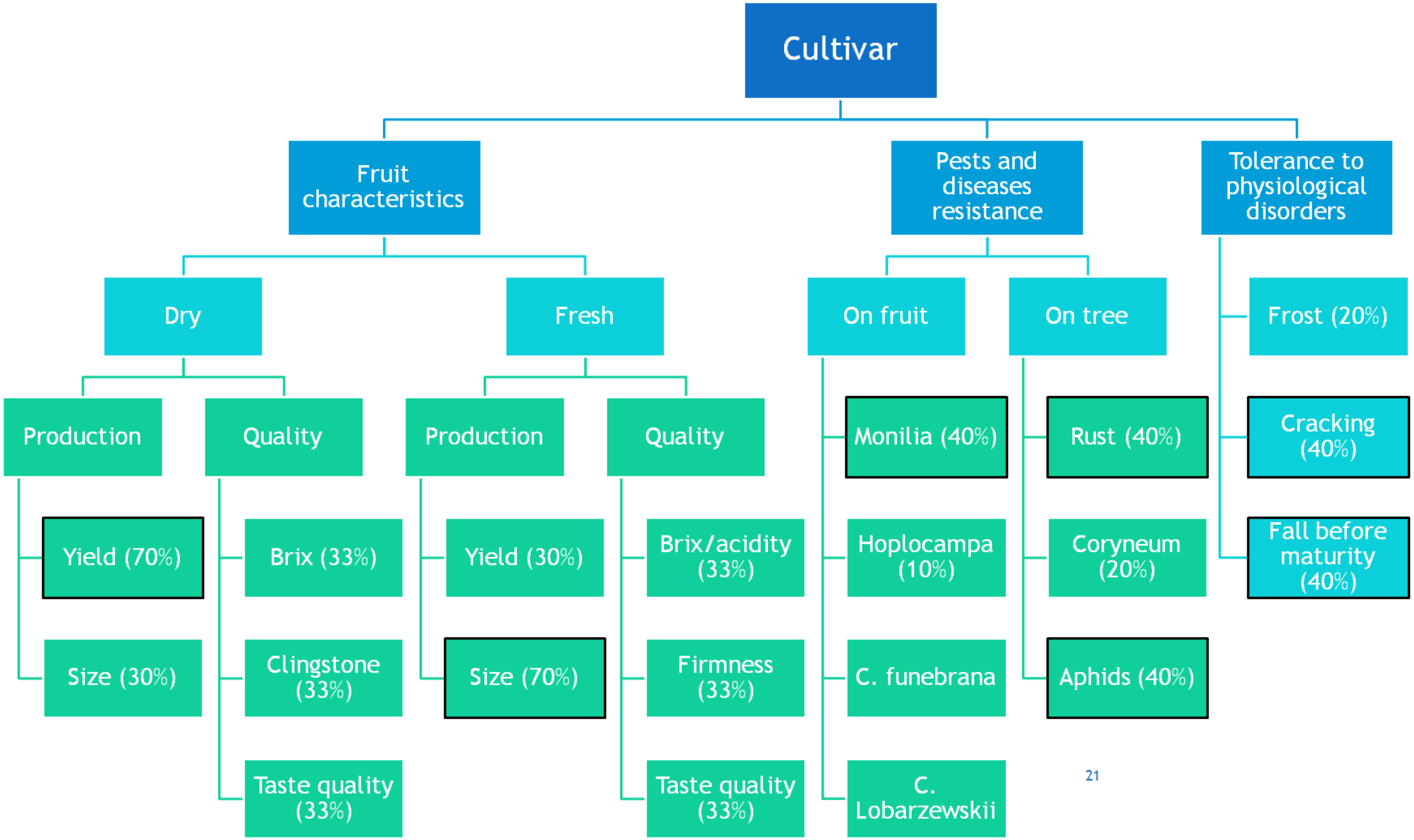
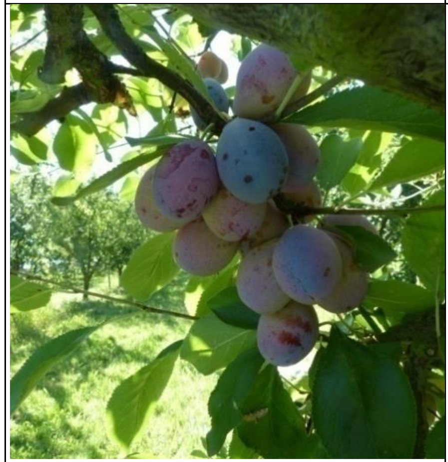
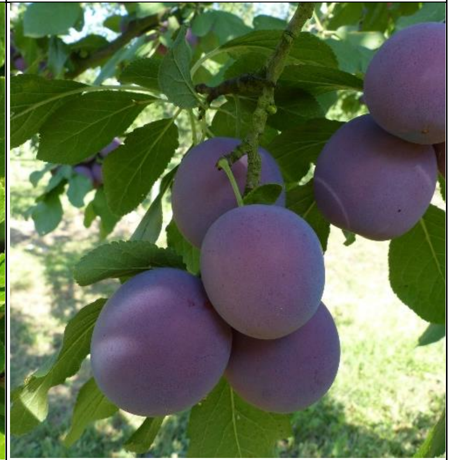
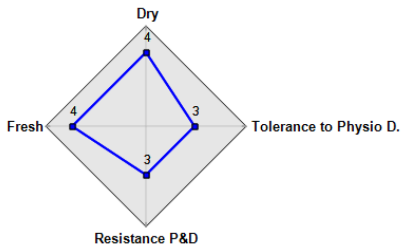
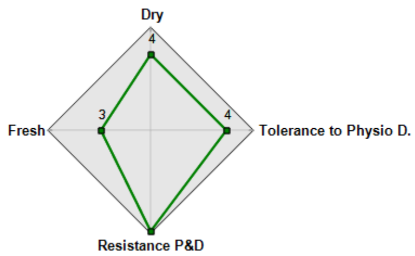
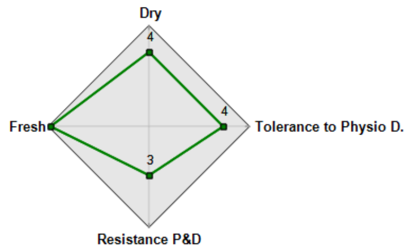
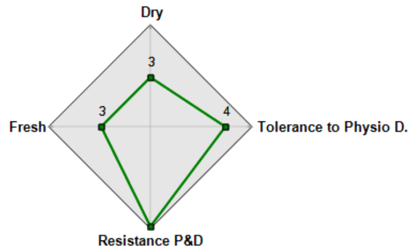
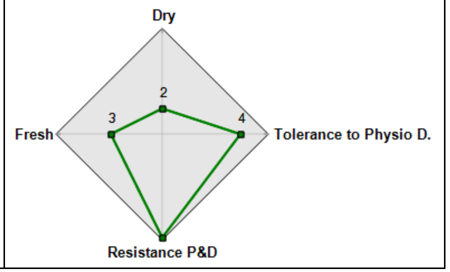


Figure 8 : The decision support tree based on the DEXi method, created and weighted with plum growers/producers

‘Prune d’Ente’	‘Mirabelle de Metz’	‘Reine-Claude d’Althan’	‘Datil’	‘Royale bleue’
				
				

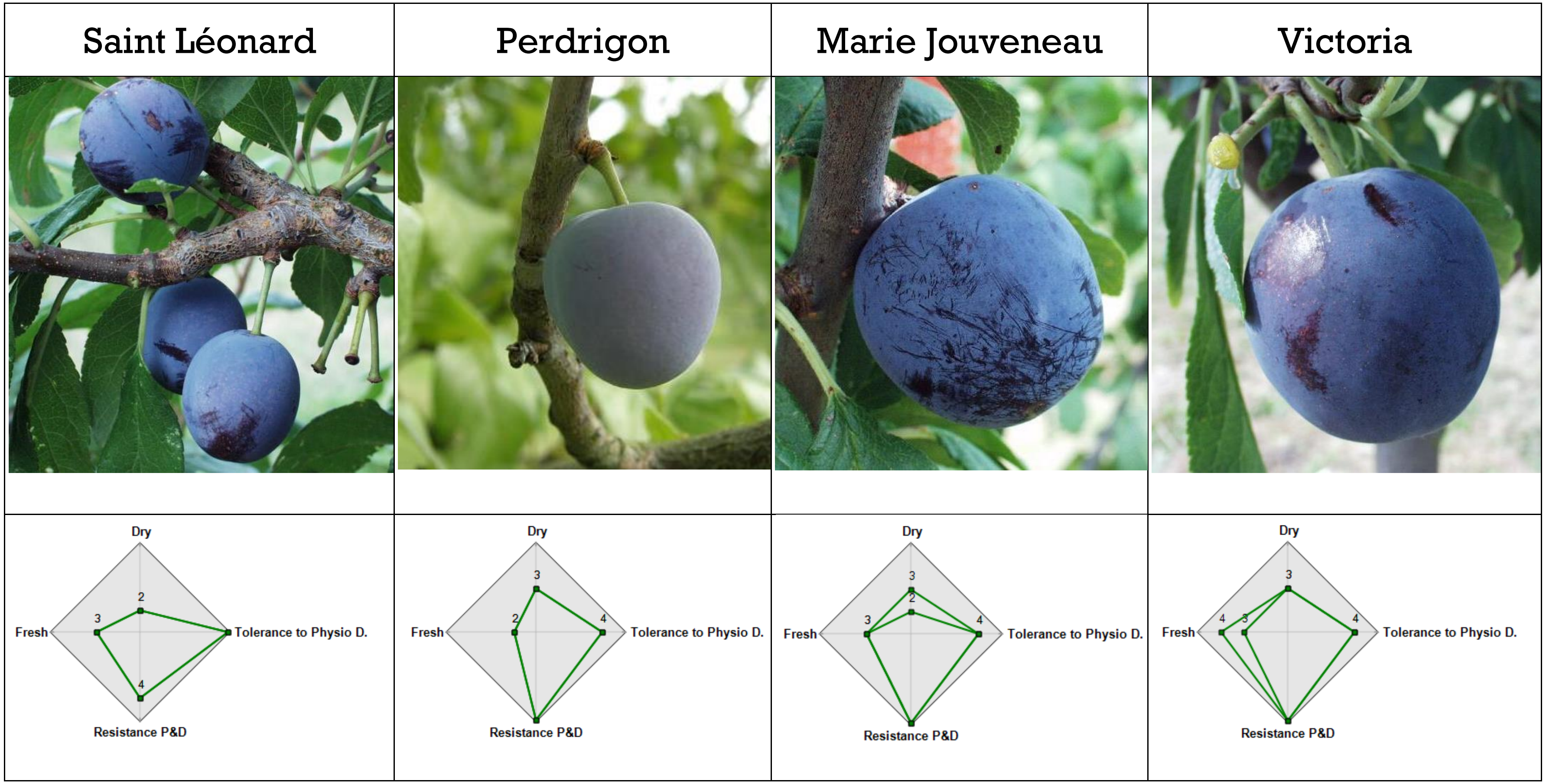


Figure 9: Summary of the shorlisting based on the DEXi methology. Three simulations were carried out for the fruit characteristics: 100% dry potential, 100% fresh potential and mixed potential. This figure shows the mixed potential varieties. Cultivars with more than 50% of damages on *monilinia, C. funebrana, C. lobarzewskii*, rust, aphids, cracking and fall before maturity were given a score of 1 which force DEXi to revaluate the other scores.

Appendix

Appendix 1 : Philipe Sfiligoï testimony

Formerly a conventional farmer, where he had little room for maneuver in the management of his farm, Philippe Sfiligoï, an organic apple producer in Lot-et-Garonne, has recovered a liking for his profession since he switched to organic farming 10 years ago: "For a long time, I thought that my conventional profession was leading us to ecological and economic dead ends. Today, with organic farming, I have regained control on my profession".

Table 1: Tolerance of some cultivars of European plum against PPV according to the symptoms on leaves and fruits (Neumüller, 2011)

Variety	Leaves	Fruits	Variety	Leaves	Fruits
Anna Späth	–	o	Katinka	–	+
Auerbacher	–	–	Victoria	–	o
Bühler Frühzwetsche	o	+	Mirabelle de Nancy	+	+
Čačanska najbolja	+	+	Jalomiţa	–	–
Čačanska rodna	–	–	Ontariopflaume	+	+
Čačanska lepotica	o	+	Opal	+	+
Čačanska rana	–	+	Ortenauer	–	–
Carpatin	–	+	Oullins Reineclaude	+	+
Centenar	–	+	Pitestean		+
Chrudimer	+	+	Presenta	–	+
Czernowitzer	+	+	President	o	+
Elena	–	+	Ruth Gerstetter	–	+
Ersinger	–	+	Sanctus Hubertus	o	+
Fellenberg	–	–	Stanley	o	+
Felsina	–	–	Tegera	–	–
German Prune	–	–	Topend	+	–
Green Gage	–	o	Tophit	o	o
Harbella	o	–	Topper	o	+
Haganta	o	o	Topfive	–	+
Hanita	–	+	Valjevka	o	+
Haroma	o	+	Valor	+	–*
Herman	o	o	Zimmers Frühzwetsche	–	–

– sensitive (strong symptoms on the leaves/fruits); o weakly sensitive/slightly tolerant; + tolerant (very few symptoms on the leaves/fruits); * During the 1980s, 'Valor' was considered to be fruit tolerant. During the last years, the variety suffers more and more from Sharka and shows symptoms on the fruits.

Table 2: Phytosanitary treatments carried out before the beginning of the experiments on plot A, Bourran, France

prunier RG A, C ,T, Botanique , tetard 3 HA			Prunier			
Date	**Produit**	**Cible**	**%**	**Dose**	**Segment**	**IFT**
17/02/21	BOUILLIE BORDELAISE RSR	Bactéries	100%	2.5 KG/HA	Fongicides bactericides	0.20
02/03/21	OVIPRON EXTRA	Stad. Hivern. Ravageurs	100%	15 L/HA	Biocontrole	0.75
15/03/21	CURATIO	Monilioses	100%	12 L/HA	Fongicides bactericides	0.31

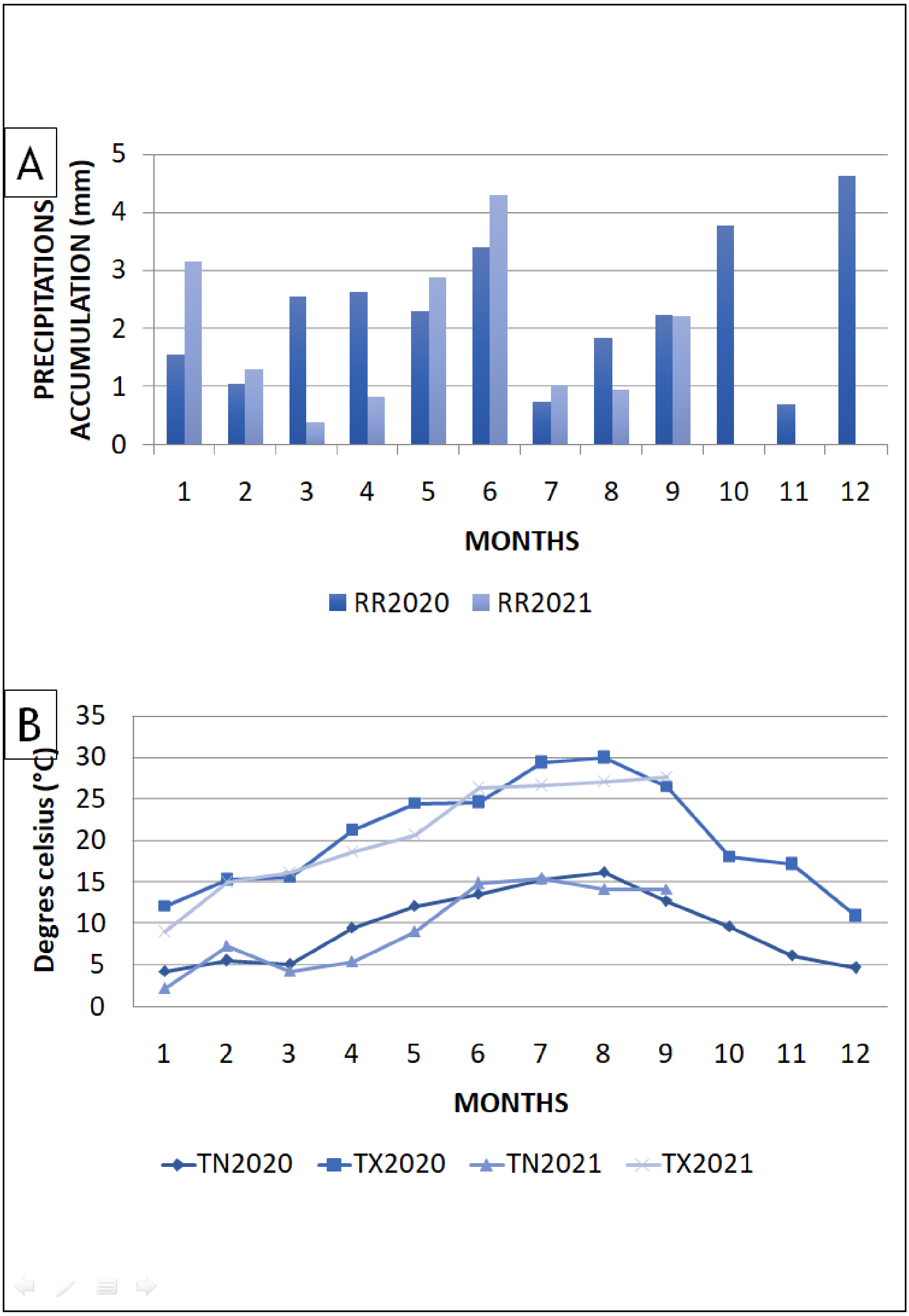


Figure 1: Precipitations accumulation (A) and minimum and maximum temperatures (B) of 2020 and 2021. The meteorological statements were carried out using the weather station which is on the site of Bourran, France. RR=precipitation accumulation; TN=minimum temperature and TX=maximum temperature.

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