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Fruit production from *Opuntia ficus-indica* ecotypes in comparison to commercial Italian clones

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Abstract

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Fruit production, as an elementary chemical characteristic of the fruit, was evaluated in 16 *Opuntia ficus-indica* Portuguese ecotypes cultivated in a marginal soil without tillage, in the second and third years after plantation. The *O. ficus-indica* ecotypes were compared with the Italian cultivars 'Bianca' and 'Gialla'. Significant differences were found among the *O. ficus-indica* ecotypes in biomass-related parameters and fruit yield, and different groups were established. Two spineless ecotypes (OFI-12 and OFI-13) had highest biomass production, with 9.9 Mg/ha dry matter on average. This was not significantly different from the 'Gialla' cultivar, which averaged 11.9 Mg/ha, for a density of 2,667 plants/ha, in the third year after plantation. Among Portuguese ecotypes, the fruit yields ranged from 2.4 to 10.1 Mg/ha fresh weight. The cultivars 'Gialla' and 'Bianca' had the highest fruit yield (13.8 and 13.6 Mg/ha fresh weight, respectively). The 'Gialla' cultivar and the group of ecotypes with orange pulp produced fruits of larger size and weight compared to the 'Bianca' cultivar and the group of ecotypes with white pulp.

Keywords: biomass; fruit yield; fruit size; prickly pear

The prickly pear, *Opuntia ficus-indica* (L.) Miller (OFI), is a long-domesticated cactus crop that is important in agricultural economies throughout arid and semi-arid parts of the world. It is a species of the Cactaceae family, and was originally domesticated in Mexico (Griffith 2004). The OFI has particular morphological and physiological characteristics that allow high water use efficiency. A specialised photosynthetic system in cacti, crassulacean acid metabolism (CAM), enables greater water-to-dry matter conversion than C3 and C4 photosynthetic pathways (Nobel 1988; Han, Felker 1997).

Prickly-pear cacti were brought to Europe by the first Spanish conquerors around the end of the 15th century and the beginning of the 16th century

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(Barbera et al. 1992). This species is an alternative to that cultured in the inland areas of the Mediterranean peninsula, where climate change is predicted to have a higher impact (Schröter et al. 2005).

Italy (mainly Sicily), with 7,400 ha and 78,000 t, is the main cactus pear fruit producer in Europe (Albano et al. 2015). At least 4,000 ha of specialised plantations produce 60,000 tons of fruits (Inglese et al. 2010), which corresponds to an average production of 15 tons per hectare. In Portugal, OFI is traditionally cultivated in non-irrigated conditions for edible fresh fruit production and the establishment of hedges, but recently some farmers have begun focusing on drip-irrigated OFI orchards for fresh fruit production, with a specific plant layout and spacing design. In 2016, the area occupied by specialised plantations was approximately 820 ha, with a likely increase in the near future. The local OFI ecotypes display variability in plant vigour and biomass production (Reis et al. 2018), and some producers have been using them in orchard plantations for fruit production.

The fruits of *Opuntia* spp. have nutraceutical benefits that are believed to stem from their antioxidant properties, which are related to ascorbic acid, phenolic compounds, including flavonoids and betalains, and a mixture of yellow betaxanthin and red betacyanin pigments (Galati et al. 2003; Stintzing et al. 2005).

Plant genetic resources play a significant role in the improvement of cultivated plants; however, germplasm utility depends on its evaluation. There is no data available regarding the fruit production potential of Portuguese OFI ecotypes. The main objectives of this study were to: (i) evaluate 16 Portuguese OFI ecotypes for their fruit production and the elemental characteristics of the fruit in the second and third years after plantation, in a marginal soil with no-tillage farming, (ii) evaluate the same OFI ecotypes for their biomass production in the third year after plantation and (iii) compare the results with two improved Italian cultivars, 'Bianca' and 'Gialla'.

MATERIAL AND METHODS

Plant material and experimental design. The OFI plants were planted in a provenance trial at the School of Agriculture of Castelo Branco, Portugal (39°49' N; 7°27' W, elev. 365 m a.s.l.) in May 2012. Sixteen Portuguese ecotypes of *O. ficus-indica* and two improved Italian cultivars, 'Bianca' and 'Gialla', which were included for comparison purposes, were studied (Table 1). The plant spacing was 1.5 × 2.5 m (2,667 plants/ha). The experiment was run in a randomised complete block design, with three replicates and five plants in each replicate (2.5 × 1.5 × 5 = 18.75 m^2). The provenance trial was conducted in a marginal soil, with a reduced overall soil profile depth and low water holding capacity. The soil was granitic, with pH 5.9 and a low organic matter content. Nitrogen (N), phosphorus (P) and potassium (K) (40 kg/ha each) fertilisers were applied annually to reduce possible differences in soil fertility. Irrigation was applied during the summer period (approximately 60 mm). No tillage was used, and weeds were controlled by mechanical mowing. Cladode pruning and flower thinning were conducted, resulting in no more than six fruits on each fruit-bearing cladode.

The Köppen-Geiger climate classification of Castelo Branco is Csa. The average annual temperatures in 2014 and 2015 were 15.8 and 16.2°C, respectively. The driest and hottest months were July and August, with mean temperatures of close to 24°C and absolute values reaching 40°C. The coldest months were January, February and December, each of which had average temperatures below 10°C. The mean number of days with a temperature equal to or below 0°C was 30, with a range between 0 and –5.4°C. Rainfall was much higher in winter than in summer, which is typical for a Mediterranean climate, with the highest precipitation in October, November and December. The accumulated precipitation in 2014 and 2015 was 433 and 910 mm, respectively. These values were significantly different from the average over the last 30 years which is 735 mm. *O. ficus-indica* vegetative growth took place during the time of the year when the precipitation was lower.

Determination of pH, acidity, total soluble solids and dry matter of the fruit. Three replicates, including 10 fruits of each ecotype, were sampled. The peel was manually removed and the pulp was briefly homogenised in a kitchen-type blender. Afterwards, the pulp was separated from the seeds, portioned, and stored at –80°C until analysis. After defrosting, the juice was centrifuged at 14,000 rpm for 10 min and the supernatant was used for the determination of pH, acidity and total soluble solids (TSS, %). Total acidity was determined using a pH meter (after the titration of 10 ml of seedless pulp-juice against 0.01 N sodium hydroxide (NaOH) to

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Table 1. Identification, origin and morphological description of the *Opuntia ficus-indica* (OFI) populations

Population	Origin	Altitude (m)	Cladode shape	Spines	Petal colour	Fruit	
						shape	pulp colour
OFI-01	Alcochete	25	elliptic	many	scarlet	elliptic	white
OFI-03	Cascais	185	elliptic	intermediate	scarlet	elliptic	white
OFI-04	Portalegre	372	ovate	few	yellow	ovoid	pale yellow
OFI-05	Arronches	293	ovate	few	yellow	ovoid	orange
OFI-08	Melides	29	elliptic	intermediate	scarlet	elliptic	white
OFI-09	Santo André	25	elliptic	intermediate	scarlet	elliptic	white
OFI-11	Albufeira	61	elliptic	intermediate	scarlet	elliptic	white
OFI-12	Cacela-a-Velha	20	ovate	few	yellow	ovoid	orange
OFI-13	Monforte da Beira	260	ovate	few	yellow	ovoid	orange
OFI-14	Idanha-a-Velha	275	ovate	few	yellow	ovoid	orange
OFI-15	Ponte de Sor	125	elliptic	intermediate	scarlet	elliptic	white
OFI-16	Coruche	76	elliptic	intermediate	scarlet	elliptic	white
OFI-17	Castelo Branco	402	elliptic	intermediate	scarlet	elliptic	white
OFI-18	Reg. Monsaraz	223	elliptic	intermediate	scarlet	elliptic	white
OFI-19	Alvega	105	elliptic	intermediate	scarlet	elliptic	white
OFI-20	Madeira	116	ovate	few	yellow	ovoid	orange
OFI 'Bianca'	Italy	–	elliptic	intermediate	scarlet	elliptic	white
OFI 'Giala'	Italy	–	ovate	few	yellow	ovoid	orange

the end point (pH 8.2)), and the results were expressed as percentage citric acid. The total dry matter (DM %) was determined in three replicates of five fruits according to AOAC (2000). Triplicate readings were taken for each sample.

Morphological characterisation. A basic morphological characterisation of the plants was made using the following qualitative descriptors: cladode shape, number of spines, petal colour, fruit shape and pulp colour (Chessa, Nieddu 1997).

Evaluation of fruit and biomass production. All of the fruits from the 15 plants in each population were collected and weighed at full maturity by the end of August and beginning of September in 2014 and 2015 (780 and 1,140 days after plantation, DAP), respectively. The fruit production per plant (*FPp*, kg), the number of fruits per plant (*FNp*) and the distribution of fruits among two weight classes (*FWc*) were evaluated for each of the 18 populations.

In April 2015 (1,050 DAP), the cladode number per plant (*CNp*) was recorded in the 15 individuals from each of the 18 populations. The length (*L*, cm), maximum width (*W*, cm), mean thickness (*T*, cm), and the diameter of the neck (*D*, cm), were measured in all cladodes of the 15 individuals per population. The biomass production assessment was made by a determination of the cladode area (*CAp*, m^2), fresh weight (*FWp*, kg) and dry weight per plant (*DWp*, kg) using the following regression models (Reis et al. 2018):

1) $CAp = 48.13 + 0.75\ (L \times W)$, ($R^2 = 0.91$)
2) $FWp = 36.91 + 0.64\ (L \times W \times T)$, ($R^2 = 0.91$)
3) $DWp = 8.49 + 0.49\ (W \times T \times D)$, ($R^2 = 0.72$)

Statistical analysis. The data was analysed using one-way analysis of variance (ANOVA) followed by pairwise comparisons using the Tukey or the Games-Howell (in the absence of homoscedasticity) post hoc tests. Statistical significance was accepted, with a probability of a type I error of 5%, for both the omnibus test and the multiple comparisons. The statistical analyses were performed using SPSS Statistics software v.21 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Morphological characterisation

With regard to the morphological characteristics of the ecotypes, the cladode shape was elliptic or ovate, the number of spines could be categorised into one of three classes (many, intermediate

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or few), the flowers had two types of petal colour (scarlet or yellow), the fruit was elliptic or ovoid and the pulp colour was white, pale yellow or orange (Table 1). The ecotype OFI-01 corresponds to the *Opuntia ficus-indica* f. *amyclaea* (Ten.) Schell due to the high number of spines, while all the remaining ecotypes belong to the *O. ficus-indica* f. *ficus-indica* (L.) Miller according to previously published criteria (Kiesling 1995).

The ecotype OFI-04 differs from the others in the pulp colour, and in other morphological and chemical characteristics of the fruit. Based on the criteria that an *Opuntia* variety could be defined as one that is distinguishable from other strains based on the internal or external appearance of the fruit or overall plant morphology (Felker et al. 2005), the ecotype OFI-04 could be considered a new variety.

Elementary chemical characteristics of the fruit

The OFI populations were significantly different with regard to the DM content of the fruits, $F(17, 34.24) = 31.61$, $p < 0.05$, which ranged between 13.8% (OFI-20) and 17.9% (OFI-16) (Table 2). The DM of the fruits of the 'Bianca' and 'Gialla' cultivars were 15.6 and 16.1%, respectively. The average DM of the fruit in the OFI ecotypes of the provenance trial was 15.7%.

The TSS content of the cactus pears varied from 13.05% (OFI-20) to 15.63% (OFI-03) (Table 2) and significant differences were found among ecotypes, $F(17, 36) = 29.20$, $p < 0.05$. The pH ranged from 6.03 (OFI-13) to 6.47 (OFI-16), and the acidity values ranged between 0.05 and 0.07% citric acid (Table 2). The acidity values were determined by titration and the results are equivalent to citric acid. Among the entire OFI population, the average pH and acidity values were 6.23 and 0.06% citric acid, respectively. We can assume that the observed variations in the TSS and the other variables we studied reflected differences at the genotype level, because the ecotypes were grown under similar soil and climatic conditions, and the fruits were harvested when in the same physiological state. Among others aspects, the indicated maturity indices for cactus pear include TSS values of between 13 and 17%, pH between 6.0 and 6.5 and

Table 2. Fruit dry matter (DM %), acidity (% citric acid), pH and total soluble solids (TSS %) in the juice of the different cactus pear populations, n = 30, each sample was analysed in triplicate

Population	Fruit DM (%)	Juice		
		pH	acidity (% citric acid)	TSS (%)
OFI-01	15.87 ± 1.02	6.30 ± 0.00	0.05 ± 0.00	14.25 ± 0.28
OFI-03	16.31 ± 0.21	6.30 ± 0.00	0.05 ± 0.00	15.63 ± 0.15
OFI-04	16.53 ± 0.39	6.10 ± 0.00	0.05 ± 0.00	15.10 ± 0.10
OFI-05	16.17 ± 0.24	6.10 ± 0.00	0.06 ± 0.00	15.12 ± 0.28
OFI-08	15.92 ± 0.34	6.20 ± 0.00	0.07 ± 0.00	13.70 ± 0.15
OFI-09	14.96 ± 0.41	6.27 ± 0.06	0.06 ± 0.00	14.10 ± 0.41
OFI-11	14.72 ± 0.55	6.20 ± 0.00	0.06 ± 0.00	13.55 ± 0.35
OFI-12	16.46 ± 0.38	6.17 ± 0.06	0.05 ± 0.00	15.07 ± 0.31
OFI-13	15.98 ± 0.09	6.03 ± 0.03	0.06 ± 0.00	15.05 ± 0.28
OFI-14	16.16 ± 0.74	6.20 ± 0.00	0.06 ± 0.00	14.65 ± 0.09
OFI-15	15.25 ± 0.37	6.27 ± 0.06	0.05 ± 0.00	13.47 ± 0.08
OFI-16	17.90 ± 0.85	6.47 ± 0.06	0.05 ± 0.00	15.10 ± 0.26
OFI-17	14.77 ± 0.55	6.33 ± 0.06	0.05 ± 0.00	14.35 ± 0.30
OFI-18	15.00 ± 0.15	6.20 ± 0.00	0.06 ± 0.00	13.23 ± 0.12
OFI-19	15.41 ± 0.40	6.30 ± 0.00	0.06 ± 0.00	14.37 ± 0.34
OFI-20	13.81 ± 0.29	6.17 ± 0.06	0.06 ± 0.00	13.05 ± 0.13
OFI, 'Bianca'	15.63 ± 0.34	6.40 ± 0.00	0.07 ± 0.00	13.72 ± 0.20
OFI, 'Giala'	16.06 ± 0.44	6.10 ± 0.00	0.06 ± 0.00	14.67 ± 0.19

values are means ± standard deviation (n = 30, each sample was analysed in triplicate)

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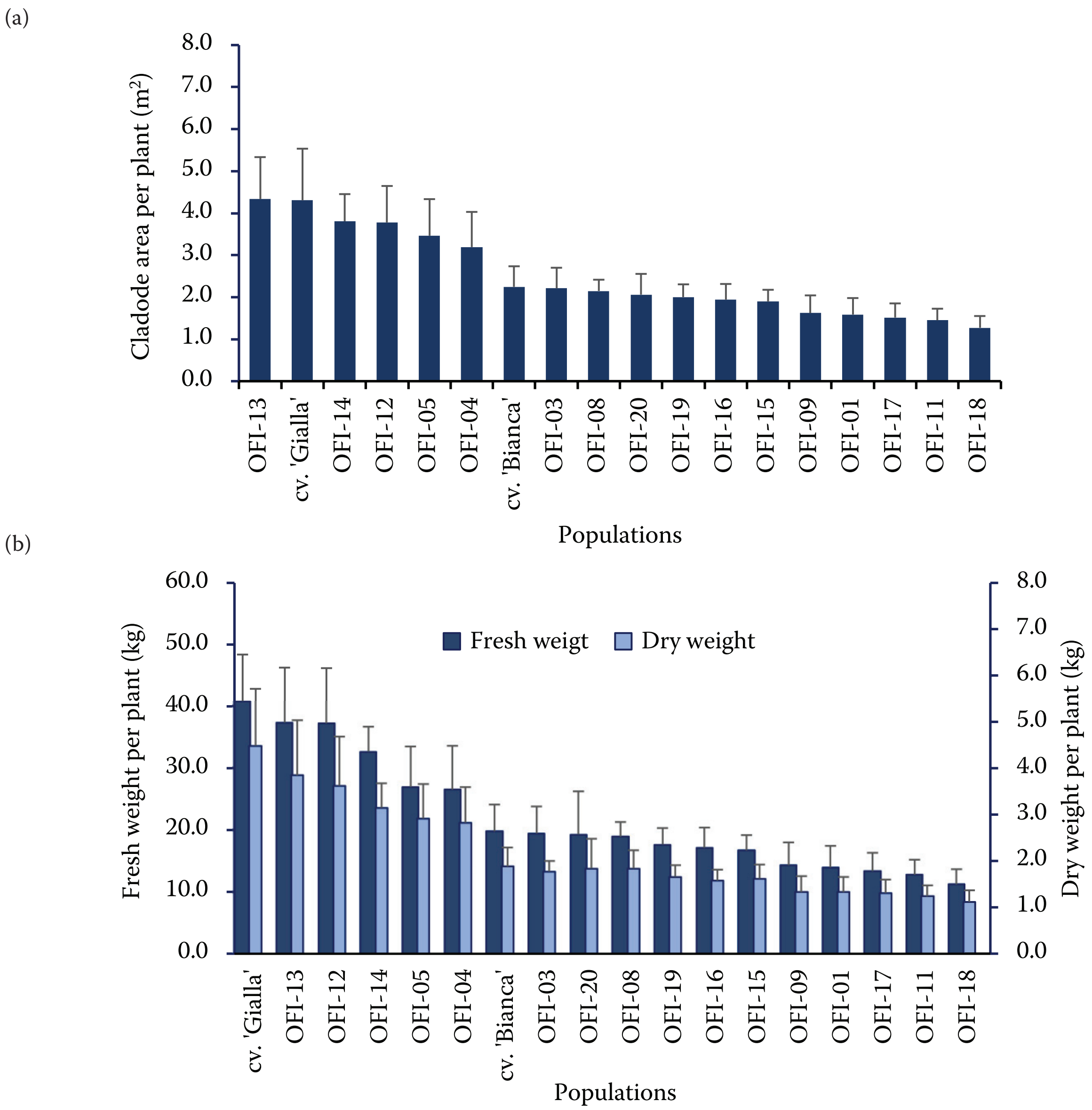

Fig. 1. Cladode area per plant (a) and fresh and dry weight per plant (b) in the 18 populations of *Opuntia ficus-indica* (OFI) studied, 1,050 days after planting (year 3) (n = 15 plants per population)

titratable acidity between 0.03 and 0.12%. (Inglese, Gugliuzza 2002; Inglese et al. 2002). All the ecotypes investigated in the current study had TSS values higher than 13%. The pH and acidity values were in agreement with those reported in previous studies (Medina et al. 2007; Albano et al. 2015).

Biomass production

The largest cladode area, *CAp*, was 4.34 m^2 in both OFI-13 and the 'Gialla' cultivar, and the lowest value of 1.27 m^2 was observed in the ecotype OFI-18 (Fig. 1).

The 'Gialla' cultivar had the highest fresh weight per plant, *FWp*, (40.79 kg) followed by the ecotypes OFI-13 and OFI-12 (37.32 and 37.19 kg, respectively), and the lowest value was found in the ecotype OFI-18 (11.21 kg) (Fig. 1). The 'Gialla' cultivar had the highest dry weight per plant, *DWp* (4.48 kg), followed by the ecotypes OFI-13 and OFI-12 (3.84 and 3.62 kg, respectively), and the lowest value was observed again in ecotype OFI-18 (1.12 kg) (Fig. 1).

The one-way ANOVA revealed significant differences among the 18 ecotypes for the three variables (*CAp*, *FWp* and *DWp*) (Table 3). The Games-Howell post hoc test revealed significant differences

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Table 3. Welch's analysis of variance (ANOVA) statistic for the area of cladodes (*CAp*, m^2), fresh weight (*FWp*, kg) dry weight (*DWp*, kg), fruit number (*FNp*) and fruit production (*FPp*) per plant

Biomass and fruit production parameters	Welch's statistic	df_1	df_2	Sig.
Area of cladodes per plant (*CAp*)	31.98	17	92.85	$p < 0.05$
Fresh weigh per plant (*FWp*)	40.63	17	92.84	$p < 0.05$
Dry weight per plant (*DWp*)	29.23	17	92.82	$p < 0.05$
Fruit number per plant (*FNp*)	35.26	17	13.29	$p < 0.05$
Fruit production per plant (*FPp*)	28.54	17	13.38	$p < 0.05$

among the OFI populations, with the group that included the 'Gialla' cultivar and the OFI-04, OFI-05, OFI-12, OFI-13 and OFI-14 ecotypes having a higher photosynthetic area compared to the other populations. For both the *FWp* and *DWp*, the Games-Howell post hoc tests revealed significant differences among the OFI populations, with the group constituted by the 'Gialla' cultivar and the ecotypes OFI-12, OFI-13 and OFI-14 outperforming the other populations.

The dry weight exhibited a significant correlation with the *CAp* ($r^2 = 0.984$) and *FWp* ($r^2 = 0.993$), while the *FPp* showed a significant correlation with the *FNp* ($r^2 = 0.941$).

A DM productivity of 11.95 Mg/ha, for a density of 2,667 plants/ha (0.27 plants/m^2), in the third year after planting, was obtained in the 'Gialla' cultivar based on the biomass of the cladodes. The ecotypes OFI-13 and OFI-12 did not differ significantly from the 'Gialla' cultivar, and DM productivity values of 10.24 and 9.65 Mg/ha was observed under the same conditions, respectively. Due to their spineless nature, they could be used to start a breeding program, deployed as material for animal feeding or for young cladode production.

Fruit production

The number of fruits and fruit production per plant (kg) in the second and third years after plantation are shown in Fig. 2. There was a marked difference in the number of fruits and in the production of fruits per plant when comparing years 2 and 3. In year 2, fruit production was negligible.

The number of fruits per plant ranged from 0.5 (OFI-14) to 8.5 ('Bianca' cultivar), and from 11 (OFI-14) to 68 ('Bianca' cultivar) in years 2 and 3, respectively (Fig. 2). Statistically significant differences were found among populations for the number of fruits per plant (Table 3). In the third year after planting, the Games-Howell post hoc test indicated significant differences among the OFI populations. The group including the 'Gialla' and 'Bianca' cultivars and the OFI-08, OFI-15 and OFI-19 ecotypes exhibited a higher number of fruits per plant than the remaining populations.

The 'Gialla' and 'Bianca' cultivars exhibited the highest production of fruits per plant, with 5.2 and 5.1 kg produced in the third year after plantation, respectively (Fig. 2). In the group with the 16 OFI ecotypes, the lowest values of fruit production per plant were found in OFI-03 (0.9 kg/plant) and OFI-14 (1.0 kg/plant), and the highest values were found in OFI-08 (3.8 kg/plant) and OFI-13 (2.9 kg/plant). The one-way ANOVA revealed the existence of significant differences among the 18 populations for the production of fruits per plant (Table 3). The Games-Howell post hoc test showed significant differences among the OFI populations. The group constituted by the two improved cultivars ('Gialla' and 'Bianca') and the OFI-08 ecotype did not differ significantly and outperformed the remaining populations concerning the fruit production per plant.

The distribution of the fruit across two size categories of fresh weight in the third year after plantation is displayed in Fig. 3. The populations with orange pulp fruits (OFI-5, OFI-12, OFI-13, OFI-14, OFI-20 and the 'Gialla' cultivar) had larger fruits than the populations with white pulp fruits (OFI-01, OFI-03, OFI-8, OFI-09, OFI-11, OFI-15, OFI-16, OFI-17, OFI-18, OFI-19 and the 'Bianca' cultivar). In the latter group, more than 60% of fruits had a fresh weight of lower than 80 g.

The Italian 'Gialla' and 'Bianca' cultivars had higher fruit yields compared to the Portuguese ecotypes. A fruit production rate of 5.2 kg/plant (13.9 Mg/ha fresh fruit for a density of 2,667 plants/ha, 0.27 plants/m^2) in the third year after planting was obtained in the 'Gialla' cultivar. The observed values

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(a)

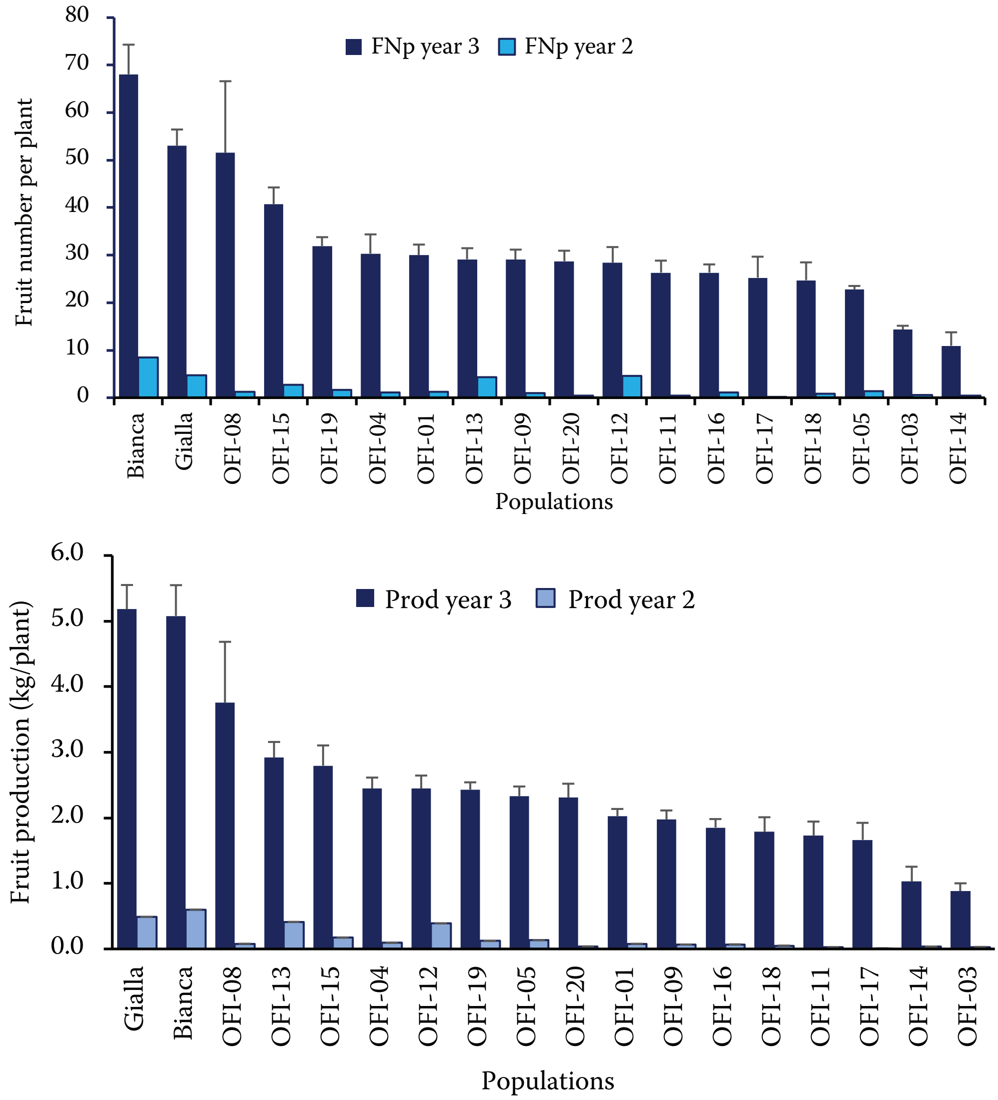

Fig. 2. Number of fruits per plant (a) and fruit production per plant (b) in the 18 populations of *Opuntia ficus-indica* (OFI) studied, in the second and third years after planting

were slightly higher than those previously reported by Caloggero and Parera (2004) who obtained a production rate of 3.7 kg/plant in the third year after plantation of the 'Gialla' cultivar. A fresh weight/dry weight ratio of 6.2 was observed for the fruit in this cultivar in the current experiment. With regard to cladode biomass and fruit production, a total DM productivity of 16.13 Mg/ha was obtained. The ecotype OFI-08 had a fruit production rate of 10.1 Mg/ha (3.8 kg/plant), while the ecotype OFI-13 had the highest production rate among the ecotypes with orange pulp fruits of 7.73 Mg/ha (2.9 kg/plant).

This is the first report of fruit yield and quality measurements from a field trial of Portuguese ecotypes of *O. ficus-indica*. The local OFI ecotypes displayed variability in biomass and fruit production, as well as in the shape of the cladodes, the presence or absence of spines and the colour of the corolla and pulp.

The main aim of the current study was the evaluation of a group of ecotypes for fruit production in the first years after plantation and the plant density (2,667 plants/ha) used was higher than the one usually used in commercial orchards. In Italy, the plant spacing of the orchards for fruit production ranges from 4 × 6 m (416 plants/ha) to 5 × 7 m (290 plants/ha). Usually, the plants begin to yield fruits two to three years after planting and achieve their maximum production six to eight years after planting (Inglese et al. 2002).

OFI-08, a white pulp ecotype, exhibited the highest fruit production among the studied eco-

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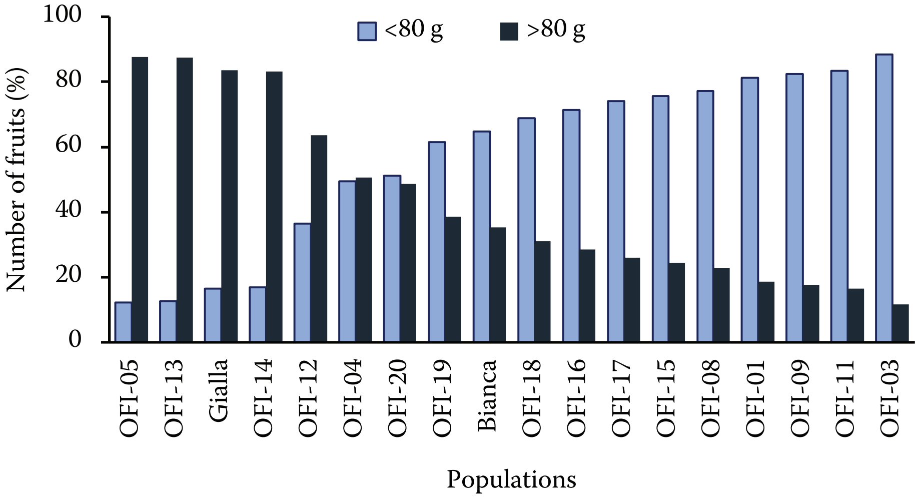

Fig. 3. Distribution of fruits of *Opuntia ficus-indica* (OFI) populations across two weight categories according to fresh weight, in the third year after planting

types; however, 77% of the total production had a small size and weight and was unsuitable for commercialization. White-flesh fruits are very sensitive to post-harvest handling and to specific pests, such as *Ceratitis capitate* (Inglese et al. 2002).

In Italy, the fruits are sorted according to their size and weight and according to a classification scheme: extra-large fruits are those over 160 g, first class is 120–160 g, second class is 80–100 g and third class describes fruits below 80 g (Barbera et al. 1992). According to Inglese et al. (2002), for export, the size of the fruit must exceed 120 g and it should have a minimum sugar content of 13%. Under the experimental conditions in the current study, the 'Gialla' cultivar and the group of ecotypes with orange pulp produced fruits of larger size and weight, and in all of them the sugar content was above 13%. In this group, the ecotype OFI-13 was the most promising because the majority (87.4%) of its fruits achieved the minimum size and weight for commercialisation. The best-appreciated fruits on international markets are those with yellow-orange flesh, such as the 'Gialla' cultivar. Fruits with white or greenish flesh are important only for regional or local markets, and their international trade is not relevant (Liguori, Inglese 2015).

The *Opuntia ficus-indica* is a multifunctional plant, even if cultivated for the main purpose of fruit production. The cladodes from pruning can be used as forage nutrition for ruminants and ultimately cactus pear plantations can contribute to the carbon stock for perennials.

A ranking of Portuguese accessions of OFI was made according to the biomass and fruit production per plant. Three OFI ecotypes did not differ significantly from cv. 'Gialla' in terms of biomass production. In terms of fruit production, the cultivars 'Gialla' and 'Bianca' clearly outperformed the Portuguese ecotypes, reflecting their origin as improved plant material. Among the 16 Portuguese OFI populations, variations in fruit yield and fruit distribution across the weight categories were found. The current study showed that OFI is a crop suitable for marginal soils, provided that high-yield cultivars and appropriate agronomic practices, i.e., pruning, fruit thinning, fertilisation and irrigation are applied.

Chemical composition as well as sensory attributes determine the fruit quality. The sensorial attributes of the cactus pear fruit should be further investigated. Therefore, the selection, training and validation of a panel should be carried out in order to determine the sensory profile of the different cultivars and ecotypes.

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