Scientia Horticulturae 241 (2018) 29–40

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Spatial variation of root yield within cultivated carrot fields is strongly impacted by plant spacing

D'Hooghe Philippe[a,b,*], Diaz Dominique[c], Brunel-Muguet Sophie[d], Davy Maxime[b,e], Vial Franck[b], Dubois Jacques[b], Kauffmann François[a]

[a] Normandie Univ, UNICAEN, CNRS, LMNO, 14000 Caen, France
[b] Station d'expérimentation du Sileban, 19 route de Cherbourg, Gatteville-le-Phare, France
[c] Groupement Des Producteurs De Légumes De La Manche, route de Barfleur, Anneville en Saire, France
[d] Normandie Univ, UNICAEN, INRA, EVA, 14000 Caen, France
[e] Ctifl, Centre technique interprofessionnel des fruits et légumes, Centre de Carquefou, allée des Sapins, Carquefou, France

ARTICLE INFO

Keywords:
Carrot
Plant spacing
Spatial variability
Root size
Field
Competition

ABSTRACT

The establishment of yield in carrot fields should be determined by diverse factors. In order to identify the main factors involved in carrot growth variability under traditional producing conditions, spatiotemporal variability of yield and yield components was analyzed from raw observations acquired from three fields of carrot in the sandy soil of the western coast of Normandy (France). The three fields were cultivated strictly according to practices of the producers without any other intervention or controlled modalities. The relative position of carrots within harvested samples was investigated before winter mulching. The analysis revealed that total root yield and marketable root yield were both highly variable with coefficient of variations (CV) ranging [17.3%–32.2%] and [33.4%–46.8%] respectively. This showed that the potential for increasing carrots productivity needs to be investigated. Geostatistical analysis revealed that root yield was not spatially correlated, which means there was no effect of sample localization within cultivated fields. Individual root diameter showed high variability (CV ranging [19.1%–25%]) and was strongly related to the distance of the nearest neighbour. The number of carrots in marketable diameters and also total root yield were consequently impacted by the variability of plant spacing. To enhance both the total root yield and the number of carrots in marketable diameters, our results strongly suggest that efforts should be directed towards the control of average plant spacing and the reduction of plant spacing variability.

1. Introduction

Carrot (*Daucus carota* L.) is a biennial vegetable from the Apiaceae that produces leaves and a root mainly composed of C-rich assimilates which are stored in the first year of growth (Villeneuve and Leteinturier, 1992). Carrots production in France was 563 kt in 2015 from 8509 ha for fresh market and 3758 ha for processing (Source: Agreste, Ministry of Agriculture, Food and Forestry).

Management practices are key steps for improving soil water-holding capacity, nutrient retention and soil aeration and infiltration rates (Magdoff and Van Es, 2009). Carrots are sensitive to these fluctuations thus leading to negative impacts on root yield and quality (Batra and Kalloo, 1990). As in most crops, initial sowing conditions are also crucial for root size because they determine the environment of the belowground parts within the plots. Growing roots can be constrained by mechanical factors (e.g. high soil bulk density, presence of stone) and nutrient availability which can be both subjected to the heterogeneity of the soil. Carrot growth also undergoes the effect of neighbouring plant competition, thus highlighting the importance of plant spacing at sowing. Considering these aspects, the key challenge to improve carrot root yield and marketable value is the reduction of root size variability in carrot monocultures, which was the subject of several studies primarily based on top-down research approaches (i.e. based on experiments conducted with imposed modalities; Salter et al., 1981; Benjamin, 1982, 1984, 1988; Sutherland and Benjamin, 1993; Aikman and Benjamin, 1994; Li et al., 1996; Reid and English, 2000; Peach et al., 2000; Rajasekaran et al., 2006; da Silva et al., 2008; Lana, 2012).

Various factors that can influence carrot root size variability have

Abbreviations: CV, Coefficient of Variation; m_{row}, length of one row in meters

* Corresponding author at: Normandie Univ, UNICAEN, CNRS, LMNO, 14000 Caen, France.
E-mail addresses: philippe.dhooghe@live.fr (P. D'Hooghe), technique4@cgplm.fr (D. Diaz), sophie.brunel-muguet@unicaen.fr (S. Brunel-Muguet), davy@ctifl.fr (M. Davy), f.vial@sileban.fr (F. Vial), j.dubois@sileban.fr (J. Dubois), francois.kauffmann@unicaen.fr (F. Kauffmann).

https://doi.org/10.1016/j.scienta.2018.06.072
Received 30 January 2018; Received in revised form 31 May 2018; Accepted 25 June 2018

been identified. Individual root weight variability increases with plant density and can be partially reduced by increasing uniformity of i) the size of seeds, ii) sowing depth, iii) rooting medium and iv) time of seedling emergence (Salter et al., 1981). Although reduced, root weight variability remained high even by controlling these factors (Coefficient of variation, CV = 32%). Root size variation can also be significantly affected by the randomness of plant arrangement (Salter et al., 1981). Experiments from Benjamin (1982) investigating the effects of asynchronous seedling emergence, population density and seed size suggested that plant density was one of the main factor that impacts root weight variation and that the effect of an asynchronous seedling emergence was magnified under high density conditions. Differences in shoot height were also revealed to be an important component of inter-plant competition for carrots and then a source of root weight variability (Benjamin, 1984). Between line-spacing and harvest date also impact the recovery of Cenourete® from the cultivar Espanada and SugarSnax 54 (da Silva et al., 2008; Lana, 2012). Mathematical models have also been established on carrots from data obtained in variable controlled conditions in order i) to quantify the hierarchy in plant size induced by competition in monocultures (Benjamin, 1988), ii) to evaluate the increase in root weight with intra-row space (Sutherland and Benjamin, 1993), iii) to describe carrot growth assuming that it solely depends on competition for light (Aikman and Benjamin, 1994), iv) to describe both the asymptotic and the parabolic relationships between yield and density over time (Li et al., 1996) and v) to describe growth at uniform plant densities, without water or nutrient supply constraints and without unfavorable soil structure (Reid and English, 2000). Although relevant, the models developed are calibrated with dataset obtained with controlled and regular plant spacing, with very ordered spatial organizations at sowing (rectangular or hexagonal pattern) and for the former with too large spaces between carrots compared to field conditions (minimum carrot spacing is 5 cm in Benjamin, 1988). In a more recent field experiment both seedling rate and line spacing were revealed to impact significantly total root yield and recovery rate of roots with determined diameters (Rajasekaran et al., 2006). Moreover, the development of carrot roots and the establishment of marketable yield in fields may also be related to many other biotic (e.g. presence of weeds or pathogens) or abiotic (e.g. temperature, nutrients and water availability, soil bulk density) factors (Sri Agung and Blair, 1989; Hochmuth et al., 1999, 2006; Sultana et al., 2015; Agbede et al., 2017).

The simulations on theoretical plant populations by the zone of influence (ZOI) model showed that increase in densities, asymmetric competition and randomness of spatial arrangement increased size variability and that these factors interact (Weiner et al., 2001). The authors discuss that the effect of spatial arrangement on size variation could be smaller in the field than in models because plasticity in growth can alter the spatial pattern and reduce the intensity of competition. Furthermore, competition for soil resources is apparently more symmetric than competition for light in which larger plants have a disproportionate advantage by shading smaller ones (For interaction between above and belowground competition see review of Casper and Jackson, 1997). Precision seeders used by producers still show strong variability in sowing uniformity, particularly with carrot seeds (Bracy and Parish, 1998; Bracy et al., 1999; Bracy and Parish, 2001). On three precision seeders evaluated with carrot seeds by Bracy and Parish (1998), none individualize or spaced seeds adequately and the average seed spacing was considerably lower than expected. In this context, plant spacing variability between carrots could be a major source of root size variability in cultivated fields under producing conditions. Sown at high densities in cultivated fields, competition within a carrot monoculture could then simply depend on the space available for root growth under non-limiting resources conditions.

In our study, we investigate the spatiotemporal variability of cultivated carrot fields under producing conditions. This bottom-up approach can contribute to a better understanding of the bio-physical processes involved in carrot growth and yield establishment and can be relevant in order to identify the main factor that impacts on root yield and root size variability. Therefore, the objectives of this study are (i) to identify the main factors impacting on the variability of carrot root yield and yield components under traditional producing conditions and (ii) to provide recommendations for commercial production. For these purposes, in situ measurements were acquired on three fields in different locations of the Normandy region (France) at three harvest dates to describe yield components in relation with two databases aiming at characterizing individual carrot position and individual carrot shape.

2. Material and methods

2.1. Growth conditions in fields

The experiment was carried out during the growing season 2016–2017 on three sandy soil carrot fields located in Pirou (49° 10' N, 1° 34' W), Créances (49° 12' N, 1°33'W) and Denneville (49° 18′N, 1°39′W) respectively named in the present study by their location. Over the past two growing seasons (2014–2015 and 2015–2016), fields were cultivated with leeks (2014–2015) and carrots (2015–2016) for Pirou, with carrots (2014–2015) and leeks (2015–2016) for Créances and with carrots (2014–2015 and 2015–2016) for Denneville. In our studied growing season (2016–2017), carrots were sown in June under the practices of the producers resumed in Table 1.

The cultivars used were Dordogne at Pirou and Maestro at Créances and Denneville, two carrot (*Daucus carota* L.) cultivars of the Nantes type. The fields located in Pirou and in Créances were sown using a vacuum vegetable seeder (Gaspardo) in three rows of three lines per 1.5 m large bed, adjusted to sow 68 and 63 seeds m_{row}^{-1} respectively according to the producers. The field located in Denneville was sown using a pneumatic seeder (Nodet-Gougis) that spreads seeds around three rows per 1.5 m large bed and adjusted to sow 70 seeds m_{row}^{-1} according to the producer.

Carrot samples (roots and shoots or roots only) were harvested in September 2016, November 2016 and February 2017 as indicated in Table 2. The harvest of September corresponded to carrots in growth and the harvests of November and February corresponded to full maturity before and after winter storage in fields. Temperature data were recorded throughout the crop cycle by weather stations located near the three fields. Thermal time from sowing was calculated from daily averaged temperatures with a base temperature (Tb) of 3.5 °C according to Tamet et al., (1996).

At each harvest date, 180 samples consisting of 30 cm row were collected per field, except in February at Denneville where one bed was missing for technical reason (prior quality check). As shown in Fig. 1, in November and February, three samples separated each by 30 cm were harvested per row on four plots previously defined 20 m away from each other on five beds separated each by two beds. In September, the samples were harvested on the same row 2.1 m apart (Fig. 1). Only roots were harvested in February since shoots were previously removed before the winter mulching carried out on the dates indicated in Table 1. The number of carrots within samples ranged from 3 to 36 in September, from 7 to 32 in November and from 3 to 32 in February.

2.2. Yield databases

2.2.1. Total and marketable yield of harvested samples

At each harvest and for each sample, carrots were washed, weighed fresh and manually classified according to the UNECE STANDARD FFV-10 (United Nations, New York and Geneva, 2010) that applies to carrot varieties to be supplied fresh to the consumer. Unmarketable carrots were manually classified into stained, non-uniform (i.e. too small, too large or misshapen) and attacked by carrot flies (*Psila rosae*) according to the main default. In November 2016 and February 2017, the marketable carrots, comprising "extra" class and class I carrots, were pooled