Final Report

Improved Knowledge of Factors Contributing to Carrot Crown Rot

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Delivery partner:

Peracto Pty Ltd

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Improved Knowledge of Factors Contributing to Carrot Crown Rot – VG15066

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Content

Summary

Carrot crown rot disease was established as a major issue that could substantially reduce carrot packout. Investigations over two seasons in 2016-17 and 2017-18 showed that there were five different types of carrot crown symptoms that may affect carrot marketability. Four were carrot crown rots (ring crown rot, smooth crown rot, corky crown rot and soft watery crown rot) and one was a carrot blemish at the crown (black ring). Different soil factors and field conditions appeared to have a large influence on types of crown rot symptoms that developed.

Weather conditions and soil conditions appeared to be major factors in the incidence and severity of crown rots in carrots. Carrots produced in 2016-17 were sown under prolonged wet conditions in winter and spring, which caused soil compaction and soil crusting that were not ideal for carrot growing. Under these conditions, inadequate irrigation to prevent soil crusting during the early stages of carrot growth is believed to be a major causal factor in the development of crown rots as well as other defects in many crops. Approximately one third of 30 crops harvested and surveyed in 2017 had a high incidence of crown rots. In contrast, unusually dry weather conditions occurred in the 2017-18 cropping season. The drier soil conditions were easier to prepare, and soil conditions were ideal for carrot seed drilling and root growth. Crown rot incidence were very low in carrots harvested in 2018 and, when present, was often localised to small areas in the paddock where there was soil compaction, erosion or poor drainage.

Physical injury followed by fungal infections is believed to be the cause of most of the different crown rot symptoms observed. Ring crown rot symptoms develop just below the crown area within the top 25 mm soil profile. Early rubbing friction in dry soil crust under windy conditions is believed to be a pre-cursor to the development of ring crown rots. Smooth crown rot symptoms observed in some crops appeared to be associated with ring crown rot and their causal factors appeared to be similar. In some crops, high incidences of smooth crown rot were found in compacted soil that was prone to water-logging or in low lying ground. Corky crown rots were found in high levels in crops where the crowns were exposed and soils that have high levels of gravel or stones. High incidence of corky crown rots may also be related to exposure of carrot crowns to soil crusting and alternate wet/dry soil surfaces. Corky crown rot is believed to start as micro-cracks which become larger and develop into corky lesions as the carrot root expands in diameter. *Fusarium avenaceum* was almost always isolated from all the different types of crown rot symptoms and different crops. *F. avenaceum* is a common Fusarium pathogen in soil and carrot injuries that develop as described above are likely to pre-dispose them to infections by the pathogen. Other major defects such as misshapen carrots, carrot cavities and forked/stunted roots were also often related to soil factors that pre-dispose them to crown rots.

Soft watery crown rot and black ring appeared to be related to foliar diseases. Sclerotinia infections in tall dense crop canopy and cool wet conditions, particularly in crops harvested in autumn, could result in soft watery crown rots. Black ring describes carrots that have brown to black leaf tissues that could not be removed from the carrot crown after harvest and washing. Black ring is believed to be related to foliar diseases or any conditions that result in leaf damage and early leaf senescence. Practices that improve air flow and good management of foliar disease such as Alternaria, Cercospora or powdery mildew have been shown to reduce the incidence of black ring in carrot crops.

Carrot roots require constant soil moisture for ideal growth. Soil moisture is believed to play a critical role in carrot seedling establishment and root development. Based on field observations over many years by Serve-Ag agronomists, high incidence of crown rots and other carrot defects appear to occur when crops have infrequent irrigation during the crop establishment period followed by frequent irrigation during the late bulking stage. Early deficits in soil moisture may impact on root cell development and make them less able to cope with rapid root expansion in the root bulking stage. Uneven or fluctuating moisture levels in the top soil may impact on carrot crown growth and pre-dispose them to crown rots. In an irrigation study carried out within a commercial crop, a higher incidence of corky crown rot or corky ring crown rot was recorded in the trial block that had only 12 mm irrigation at the 6 to 9 leaf stages followed by 30 mm irrigation at 9 leaf until harvest at weekly intervals, compared to 25 mm irrigation at weekly intervals or twice per week from 6 leaf until harvest.

Public summary

This two-year investigative study showed that there were five different types of carrot crown problems that reduce carrot returns to growers: ring crown rot, smooth crown rot, corky crown rot, soft watery crown rot and black ring. All except black ring were major defects that will end up in waste bins. Carrots that have black rings in the crowns are downgraded to lower grade carrots and sold at less than half the premium grade carrot values. Soil environment has a major influence in crown rot disease development. Ground prepared and crops sown under wet weather conditions have increased incidence of crown rots as well as other major defects such as forked and misshapen carrots. High levels of stones, cloddy soil, poor drainage and soil crusting contribute to increased levels of ring crown rot and smooth crown rot. Corky crown rot appeared to be related to exposure of carrot crowns to fluctuating surface soil moisture and temperature. In a study on irrigation, low soil moisture (12 mm at weekly intervals) at the 6 to 9 leaf stages followed by 30 mm of irrigation at weekly intervals from 9 leaf to harvest increased crown rot incidence.

Keywords

Carrot; crown rot; ring crown rot, smooth crown rot, corky crown rot, black ring, disease; investigation; *Fusarium avenaceum*

Introduction

Carrot crown rot has been identified as a major constraint to carrot production in Tasmania. The Australian vegetable industry has identified the need for improved knowledge of factors contributing to carrot crown rot. In recent times, growers and packers have reported that carrot crown rot disease complex can result in crop losses of up to 25%. There is a rapid expansion in the production of fresh market carrots for domestic consumption in Australia and for export. The costs of grading out affected carrots after harvest is also a significant cost of production.

A previous industry project investigating carrot diseases in Tasmania (Project VG96015, 2001), clearly demonstrated that crown rot was the most important disease reducing carrot packout rates in Tasmania. To date, crown rot remains the most important carrot disease in Tasmania and in some cases, can lead to complete crop loss. Susceptibility of different carrot varieties has also been noted as an issue, whereby some varieties seem to be more susceptible than others. Sweeter carrot varieties such as Mojo are high in demand by domestic and overseas markets and these varieties are particularly susceptible to crown rots.

Apart from the presence of pathogens, agronomic conditions are believed to play a significant role in the development of many soil-borne pathogens. In potato crops, where there has been extensive research, soil moisture and agronomic practices that increase soil health are used to reduce disease levels and manage soil-borne diseases. In carrots, similar strategies are needed for growers to better manage carrot crown rot as well as other soil-borne diseases of carrots for sustainable production. However, there has been little or no established information on how soil environmental conditions and their management affect development of crown rot.

In previous survey-type projects conducted on all carrot diseases in Tasmania, crown rots had been found associated with Rhizoctonia and Sclerotinia diseases, which began as foliar diseases in the crop. Some species of Fusarium that may invade senescing leaves have also been shown to cause smooth crown rot (Project VG96015, 2001).

This project, conducted over two crop seasons in Tasmanian production regions, was aimed at gaining a better understanding of how crown rot disease develops through investigative studies with carrot sampling, field inspection and diagnostic examinations in commercial crops, especially those that have relatively high levels of crown rots. This project proposes to determine the causative agents of crown rot and conditions conducive to the development of crown rot disease complex in Tasmanian production regions.

Methodology

Samplings and diagnostic examinations of carrots sown in 2016 and 2017 were mainly carried out in February to May 2017 and 2018, the peak carrot harvest time in Tasmania.

Carrot samples were collected from three major fresh market carrot processors in Tasmania (Sumich, Harvest Moon and Premium Fresh Tasmania). Carrots that were rejects were sampled from processing lines at these three major fresh market carrot processors. The sample collections focused on carrot defects that developed in the field. Defects such as broken, bruising or splitting that occurred after harvest were not included in the sampling. Field samplings and inspections were also carried out in some of the crops to examine the influence of soil and field conditions that may contribute to crown rot developments as well as other field defects.

In carrot sampling examinations, carrots were sorted into various categories such as those affected by crown rot as well as other major defects. Carrots were closely examined to diagnose the primary cause of crown rot and other major defects. This included moist incubation, fungal isolations and DNA sequence analysis to identify fungal pathogens. Fungal pathogens that were isolated were identified to genus levels based on fungal taxonomy and then sent for species identification using DNA sequence analysis. Carrot samples that had cavities or forking were sent to SARDI in a collaborative study to develop tests for Pythium species (namely *Pythium sulcatum* and *P. violae* that are known to cause Pythium cavity spot) and plant parasitic nematodes.

Soil moisture is believed to have a major influence in the susceptibility of carrots to crown rot development. In 2018, an irrigation study was also conducted to investigate the effects of irrigation programs on crown rot incidence.

Outputs

Different types of carrot crown rots that occurred in Tasmania have been described.

Improved understanding of the influence of field and soil conditions on carrot crown rot development.

An industry review meeting was held on July 13th, 2017 at Peracto Meeting Room, 16 Hillcrest Road, Devonport to review and discuss project findings.

Presentation of project findings to Serve-Ag and E. E. Muirs agronomists at their review meeting on 5th September 2018.

Project findings will be extended through the regional vegetable network program (date TBA).

Final report of the project.

Outcomes

Carrot samplings and diagnostic examinations carried out over two seasons identified five different types of carrot crown symptoms that may affect carrot marketability. Four were carrot crown rots (ring crown rots, smooth crown rot, corky crown rot and soft watery crown rot) and one was a carrot blemish (black ring). All except black ring were major defects, where affected carrots will often end up in carrot waste bins. Carrots that have black rings in the crowns are still marketable but will be downgraded to lower grade carrots and sold for lower than premium grade carrots. Different soil factors and field conditions appeared to have a large influence on types of crown rot symptoms that developed.

Carrot crown rot disease was established as a major issue that could substantially reduce carrot packout. In a case study, a carrot crop sown in 4.5 ha had 69% packout, which gave a return that was $4824 less per ha than the seasonal average of 85% carrot packout. This gave a total reduction of $21,700 in expected return for the grower and crown rot disease was the cause of approximately 60% of the unmarketable carrots.

Weather conditions and soil conditions appeared to be major factors in the incidence and severity of carrot rots in carrots. Carrots produced in 2016-17 were sown under prolonged wet conditions in winter and spring, which caused soil compaction and soil crusting that were not ideal for carrot root growth. Under these conditions, inadequate irrigation to prevent soil crusting during the early stages of carrot growth is believed to be a major causal factor in the development of crown rots as well as other defects in many crops. Approximately one third of 30 crops surveyed in 2017 had a high incidence of crown rots. In contrast, unusually dry weather conditions occurred in the 2017-18 cropping season. The drier soil conditions were easier to prepare, and soil conditions were ideal for carrot seed drilling and root growth. Crown rot incidence was very low in carrots harvested in 2018 and, when present, it was often localized to small areas in the paddock where there was soil compaction, erosion or poor drainage.

Physical injury followed by fungal infections is believed to be the cause of many different crown rot symptoms observed. Ring crown rot symptoms develop just below the crown area within the top 25 mm soil profile. Early rubbing friction in dry soil crust under windy conditions is believed to be a pre-cursor to the development of ring crown rots. Smooth crown rot symptoms in some crops appeared to be associated with ring crown rot and their causal factors appeared to be similar. In some crops, high incidences of smooth crown rot were found in compacted soil that was prone to water-logging or in low lying ground. Corky crown rots had been found at high levels in soils that have high levels of gravel or stones. High incidence of corky crown rots may also be related to exposure of carrot crowns to hot dry soil surfaces. Corky crown rot is believed to start as micro-cracks which become larger and develop into corky lesions as the carrot root expands in diameter. Fusarium *avenaceum* was almost always isolated from all the different types of crown rot symptoms and different crops. *F. avenaceum* is a common Fusarium pathogen in soil and carrot injuries that develop as described above are likely to pre-dispose them to infections by the pathogen. Other major defects such as misshapen carrots, carrot cavities and forked/stunted roots were also often related to soil factors that pre-dispose them to crown rots.

Black ring or soft watery crown rot is believed to be related to foliar diseases or any conditions that result in leaf damage and early leaf senescence. Black ring describes carrots that have brown to black leaf tissues that could not be removed from the carrot crown after harvest and washing. Practices that improve air flow and foliar disease control have been shown to reduce the incidence of these crown symptoms.

Apart from crown rot disease, other common unmarketable carrot defects were physical, such as twisting, short stubby tap roots, growth cracks, cavities or forking. The crops that have crown rots tend to also have many physical carrot defects that are likely to be associated with poor soil conditions.

Evaluations and discussion

1. Seasonal weather and soil conditions

In Tasmania, the majority of carrot crops were sown in August to December and scheduled for harvest in February to March to meet demand over the summer period. Carrots were monitored over two cropping seasons for this project in 2016-17 and 2017-18. The weather conditions between the two seasons were vastly different: wet weather conditions with above average rainfall in 2016-17 and unusually dry weather conditions in 2017-18 (Figure 1.1). Crown rot disease was a major problem in 2016-17 but was negligible in 2017-18. Therefore, much of the information acquired to assist in our understanding on the development of crown rot disease were obtained in the 2016-17 season.

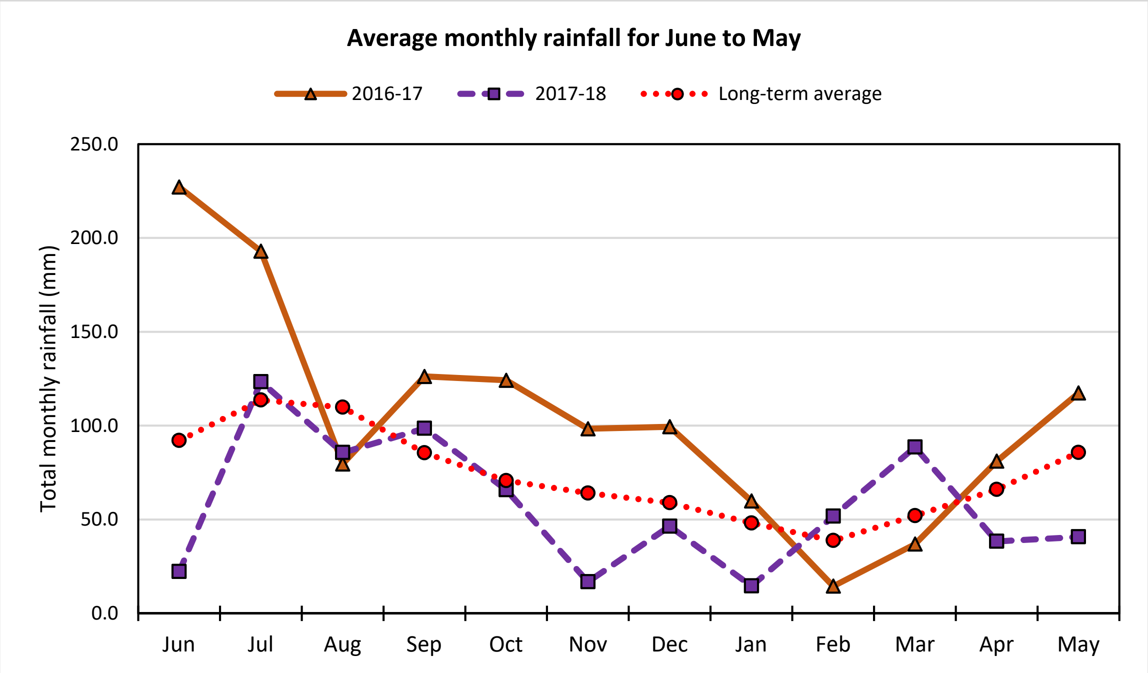

Figure 1.1: Average monthly rainfall for carrot crop season in Aug to May

In the 2016-17 season, in north-west Tasmania, where most of the carrot crops were located, in the winter months May to July the ground was wet, followed by frequent rainfall in spring and early summer from August 2016 to January 2017. These prolonged wet periods created challenging conditions for carrot ground preparation. In carrot production, sowing must occur as scheduled, even under unfavorable weather conditions, to ensure a continuous supply of carrots to the market. Therefore, many carrot crops in 2016 were sown under less than ideal soil conditions. Sub-soil compaction or cloddy soil were a common feature in many paddocks. Consequently, there were relatively high levels of carrot crown rots and other disorders. Many paddocks were bed-formed in wet ground and then had further heavy rain prior to seed drilling. In less forgiving soil types this led to consolidation of the beds, with crusting in the top 25 mm of the soil profile occurring. This crusting in some cases caused challenges at seed sowing and required frequent irrigation post planting to ensure satisfactory seedling establishment.

In the 2017-18 season, weather conditions were the reverse of that in the previous season, with below average rainfall in winter and average rainfall in early spring creating ideal conditions for ground preparation. Weather and soil conditions were also ideal for seed drilling. Unusually dry and warm weather in November to January were ideal for carrot root growth. There were few crops had that had serious crown rot levels, and other carrot diseases or defects were also minimal.

2. Diseases and disorders reducing carrot packout

Initially, carrot sampling was carried out in the field early in the crop establishment. There were negligible numbers of carrots with crown lesions at the early to bulking crop stage. Crown rot disease mostly became obvious close to harvest. Detecting low levels of crown rot in the field was also difficult due to small sampling size. Therefore, greater attention was made in sampling carrots at close to harvest and in collecting samples of rejected carrots from the carrot factory processing lines after the first wash. This allowed inspection of much larger samples to determine the levels of crown rots in the proportion of carrots that end up in the waste bins. Even though this project was aimed primarily to investigate carrot crown rot disease, other carrot diseases and disorders were also investigated as often the conditions that contribute to crown rot disease may also be linked to the development of other types of carrot diseases or defects.

In 2017 and 2018, carrots were taken from carrot waste samples from the processing lines at the three major carrot producers in Tasmania. The carrot waste consisted of carrots that were rejected after the first wash and from sorting in the processing lines. At least 200 carrots collected from each harvest were then sorted into various diseases and disorders. Field inspection and sampling of carrots were also carried out when possible to determine how the diseases or disorder may have developed. There were much higher levels of carrot waste in carrots harvested in 2017 compared to 2018. The obvious difference was due to vastly different weather and soil conditions as described above. Weather conditions were optimal for carrot growing in 2017-18, and there were low levels of carrot crown rots or other defects in carrots harvested in 2018. Therefore, this section will mainly discuss sampling of carrot crops harvested in 2017.

In 2017, carrot waste samples taken from 30 crops showed that the major causes of carrot defects that occurred in the field were misshapen carrots (including twisted, forked and stubby carrots), crown rot and cavities, in order of importance. Apart from crown rot, all the other defects (misshapen carrots and cavities) appeared to be related to soil compaction. Fungal pathogens were only isolated from crown rots. This indicates that crown rot is still a major disease issue for carrots in Tasmania. No fungal pathogen could be found in association with the other disorders. Often, field conditions that pre-dispose carrots to high incidence of crown rot were also associated with the other disorders. Therefore, in order to gain a better understanding of how carrot crown rots develop, the incidence and symptoms of all the other carrot disorders would also need to be considered.

2.1 Misshapen carrots

Twisted carrot is the most common misshapen disorder in carrot waste for many crops. This disorder describes carrots that were bent or twisted. This misshaping appeared to occur at late root bulking stage when roots twisted to grow around hard soil clods, stones or other physical barriers (Figure 2. 2). Field examinations indicate that twisting due to close plant spacing is rare. Narrowing or constrictions of the lower carrot roots was another common misshapen disorder (Figure 2.3). This appears to be related to soil compaction of the lower root zone or possibly soil moisture gradient at different soil depths. On rare occasions, obvious constrictions due to clumps of undecomposed roots from a previous crop may also distort root growth (Figure 2.4).

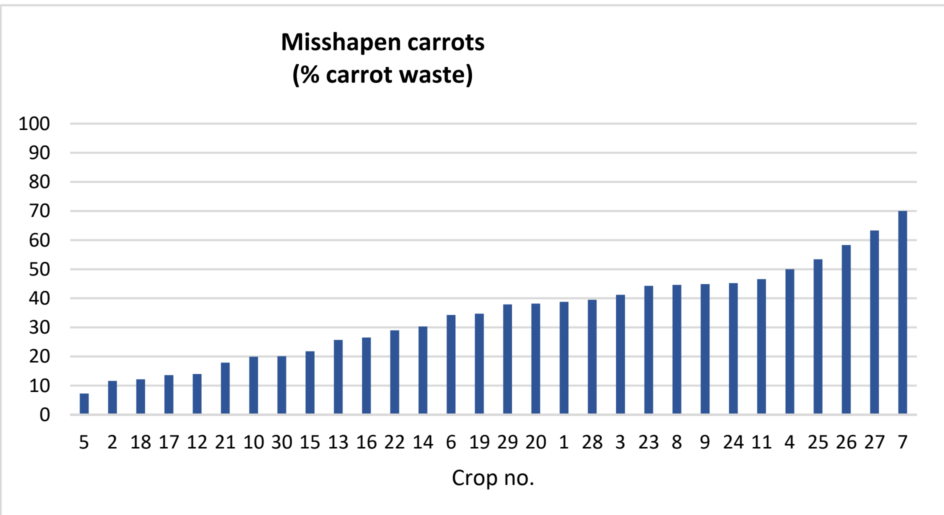

Figure 2.1: Misshapen carrots in crops harvested in 2017

Figure 2.2: Twisted carrots

Figure 2.3: Misshapen carrots due to root constrictions at a certain soil layer or depth

Figure 2.4: Misshapen carrots produced in undecomposed crop residue

Forked or stubby carrots

Forked carrots and stubby carrots were common in many crops harvested in 2017. When there was a high incidence of stubby or stunted roots, there was also a high incidence of forked roots. As the two symptoms often occurred together, their causal factors are likely to be related. Carrot roots will become forked or stunted and stubby when the root tips are damaged at the seedling stage. The root tips may be damaged by disease, nematodes or physical barriers. Often, growers will assume that root-knot nematode is the cause of forked carrots. Root tip damage may also be caused by Pythium infections. However, only in two crops, could root-knot nematode be confirmed as the cause of forked carrots. The root-knot nematode was identified as *Meloidogyne hapla* using DNA analysis. There was no evidence of root-knot nematodes or other pathogens in all the other forked or stubby carrots. Carrot peel tests carried out by SARDI also did not detect any root-knot nematodes or Pythium species. Often in the same crop, the depth at which the carrot root started to fork, and the carrot root became twisted, stunted or stubby, were similar. Physical barriers due to soil compaction, cloddy soil and inadequate soil moisture at the root tips at the critical root elongation stage are believed to be major factors in the development of forked or stubby roots.

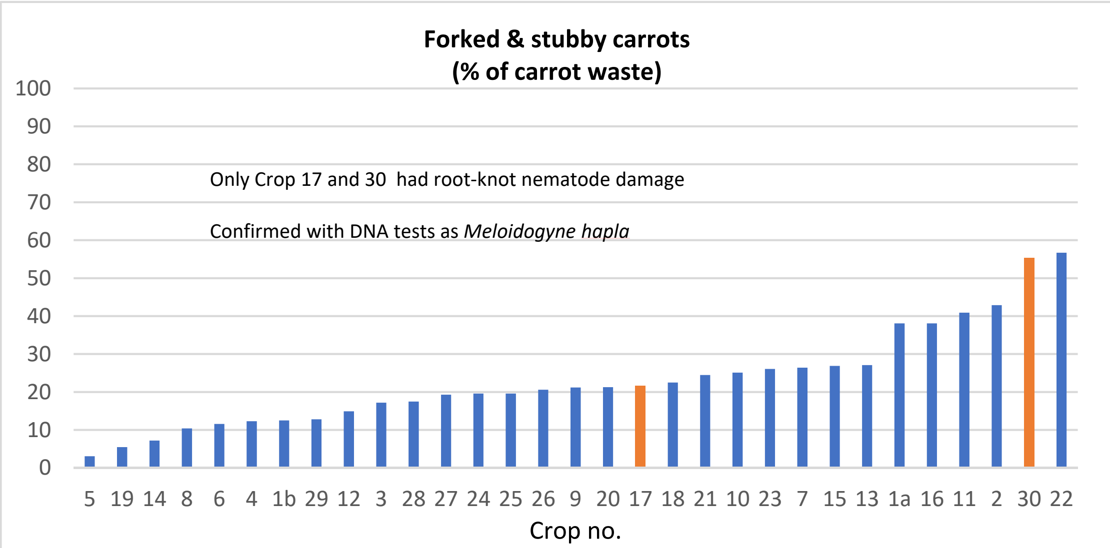

Figure 2.5: Misshapen carrots in crops harvested in 2017

Figure 2.6: Forked and stubby carrots

Carrot cavities

This disorder describes carrots that have small or large cavities (Figure 2.7). The cavities did not resemble cavity spots caused by Pythium. Many of these cavities occurred at the same depth where the tap root bends or constricts and typically occurs only on one side of the tap root. Many of these cavities appeared to begin as small cracks or splits in the side of the root that was slightly indented, flat or twisted and where root expansion may be restricted (Figure 2.8). These initial cracks or splits are likely to develop into large cavities following soft rot by soil bacteria under wet soil conditions. No fungal pathogens could be isolated from the cavities with fungal isolations. *Pythium sulcatum* or *P. violae* that had been associated with Pythium cavity spots on carrots were not detected in carrot peel tests in DNA analysis by SARDI conducted on samples from Crop 2, 28, 12 and 13. Other Pythium pathogens were also not detected in the carrot peel tests. Therefore, even though carrot growers in Tasmania often attribute such carrot cavities to Pythium cavity spots, findings in this investigation indicate that this disorder was separate to Pythium cavity spot disease.

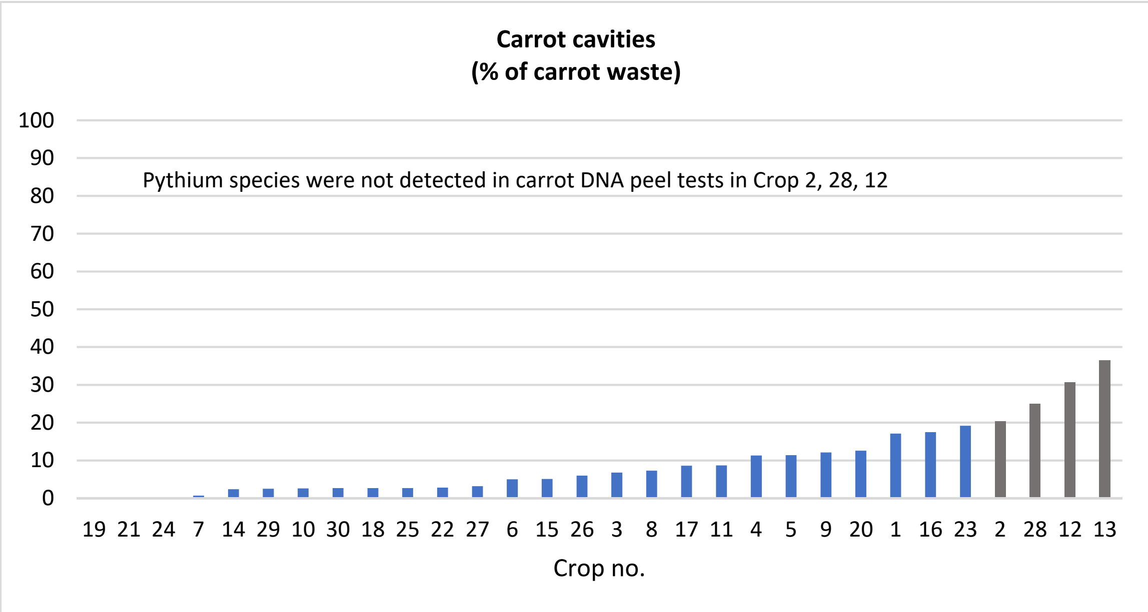

Figure 2.7: Carrot cavities in crops harvested in 2017

Figure 2.8: Large cavities (left) and small cracks or splits that developed at similar soil depth (right)

Carrot crown rots

In 2017, approximately one third of the crops inspected had a relatively high incidence of crown rots. Approximately 30% of the crops surveyed had 22% to 59% carrot waste due to crown rot. There were different types of crown rot symptoms: black ring, ring crown rot, corky dry crown rot, smooth black crown rot and watery crown rot. The symptoms appeared to be an indicator of how they develop and the influence of the soil conditions.

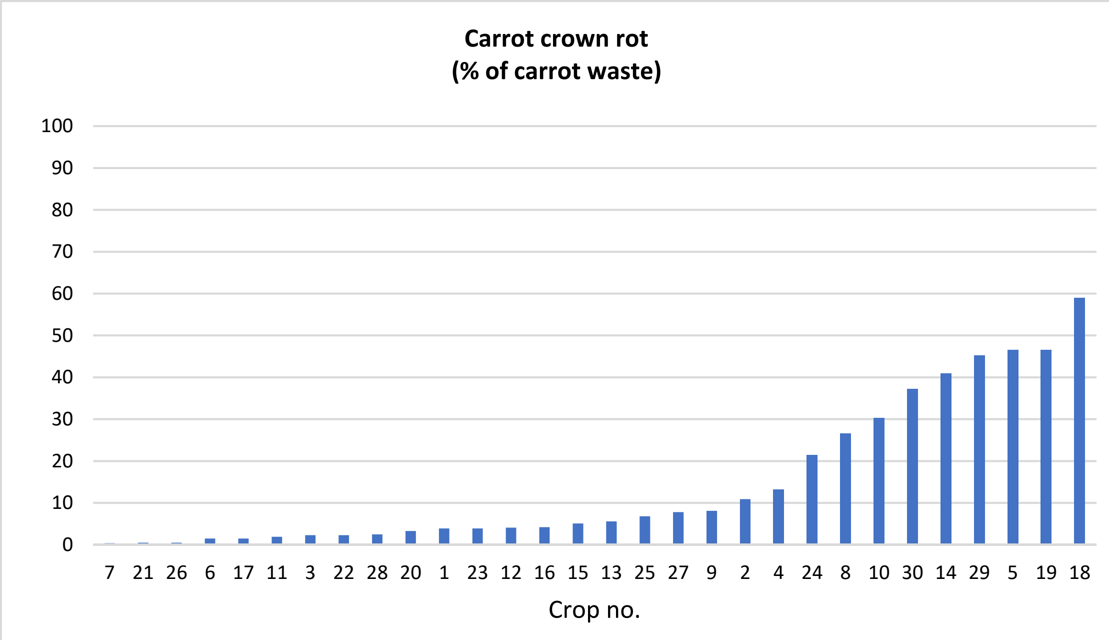

Figure 2.9: Crown rot levels in crops harvested in 2017

Ring crown rot

This symptom describes a partial or concentric ring that forms approximately 30 mm below the carrot crowns. Often there were constrictions around the affected area. The ring crown rot may be corky or smooth. Ring crown rot is believed to be due to physical injuries caused by the spinning and rubbing of carrot crowns at the early growth stages. The black ring symptom only became obvious at close to harvest following root bulking and fungal invasion of the damaged tissues. Only *Fusarium avenaceum* was consistently isolated from the black ring tissues, and it is believed to be a secondary invader.

Figure 2.10: Ring crown rot symptoms

Black smooth crown rot

This symptom describes black and smooth rot in the crown area (Figure 2.11). The black smooth crown rot may become sunken with increased severity and cracks may develop. Black smooth crown rot was often found in carrots grown in low lying ground or in compacted ground that may become water-logged. Only *F. avenaceum* was consistently isolated from the smooth crown rot tissues.

Figure 2.11: Black smooth crown rot symptoms

Corky crown rot

This symptom describes corky lesions in the crown area of carrots (Figure 2.12). These corky lesions tend to be shallow and do not deteriorate when stored over time in cold storage. Cracks may develop on the lesions at close to harvest as the root crown expands in circumference. Only *F. avenaceum* was consistently isolated from the smooth crown rot tissues. In crops that have high incidence of corky crown rot, there was also high incidence of green tops due to exposure of crowns to sun damage. This correlation suggests that carrot crowns not covered by soil or exposed to hot dry soil surfaces may be more prone to this type of crown rot. In some crops, very small cracks at the rim of the carrot crowns and small lesions at the base of leaf stems could be observed on the carrot crowns in early field sampling. Such micro-cracks and small lesions may become larger and develop into corky lesions as the carrot root expands in diameter. High incidence of corky crown rot and ring crown rot also occurred together, indicating that similar soil environmental conditions pre-dispose carrots to their development.

Figure 2.12: Corky crown rot symptoms

Figure 2.13: Micro-cracks and small lesions on carrot crowns

Soft watery crown rot

This symptom describes crowns affected by soft watery rot in the crowns. This symptom was often related to a dense and tall canopy and prolonged wet conditions beneath the crop canopy. Carrots harvested late in autumn under relatively cool and wet conditions are more prone to this type of crown rot. Damage to crown tissues due to foliar diseases such as Sclerotinia and Alternaria, followed by secondary bacterial and/or Fusarium invasion are believed to be factors involved. *F. avenaceum* was also consistently isolated and high levels of bacteria were detected in such types of rot after harvest.

Figure 2.14: Soft watery crown rot symptoms

Black ring

Black ring describes carrots that have brown to black leaf tissues that remain in the carrot crown after harvest and processing. Carrots affected by black ring do not deteriorate over time in cold storage. Black ring is believed to be related to foliar diseases such as Alternaria, Cercospora or powdery mildew or any adverse conditions that result in leaf damage and early leaf senescence. Recently, practices that improve foliar disease control have been shown to reduce the incidence of black ring in carrot crops.

Carrots affected by black ring were not examined in the carrot waste because it is not regarded as a major defect and are still marketable. However, based on feedback from carrot packers, black ring is still a major concern to growers because affected carrots are downgraded to lower grade carrots. Growers will incur substantial loses as the values paid for lower 2nd or 3rd grade carrots are substantially lower than those of premium grade carrots.

Figure 2.15: Black ring in carrot crowns

Fungal isolations and identifications

Fusarium was frequently isolated from crown rots and almost all the Fusarium species isolated from different crops were identified as *F. avenaceum* using DNA sequence analysis. *F. avenaceum* is a known fungal pathogen that can cause seedling damping off and dry rot on carrots in the field or in storage overseas.

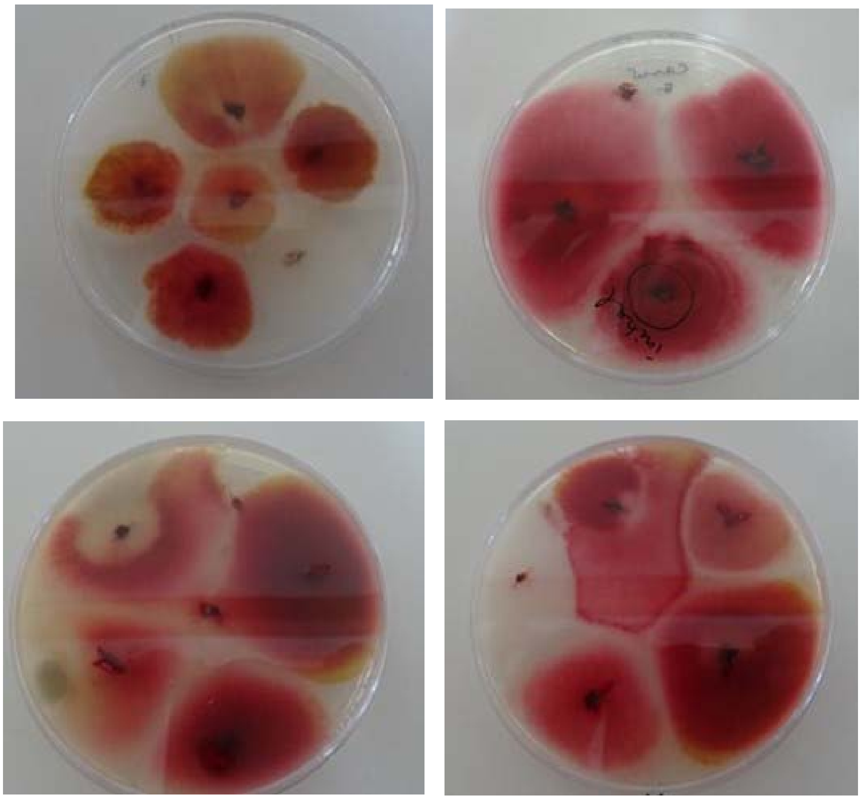

Figure 2.16: Isolations of *Fusarium avenaceum* from crown rot tissues from different crops

3. Economic impact of carrot crown rot in a case study of an affected producer

In a case study, crop 18 sown in 4.5 ha had a serious crown rot problem. This crop had 69% of the product packed for all categories, with 31% waste. Another crop from the same grower had no crown rot problem and it had 83% packout for all categories with only 17% waste. The return for crop 18 was $4824 less per ha than the seasonal average. When the carrot waste was examined after harvest, 59% of carrots in the waste bin was due to crown rot (Figure 4.2). There were two types of crown rot: crown rot in the crown area (18.9%) and black rot just below the crown area (40.1%). Other major defects that also reduced packout were forked carrots due to soil compaction (22.5%) and misshapen carrots (12.2%). Apart from major defects such as crown rot and misshapen carrots, there were also minor crown lesions in the crown areas that resulted in downgrading of carrots from high value premium grade carrots to lower value second grade carrots.

The two types of rot (smooth crown rot and ring crown rot) are believed to be inter-related. The carrot crop was sown in a 4 year rotation with other crops and was not known to have a history of crown rot. *Fusarium avenaceum* found in association with all crown rot lesions is a common soilborne pathogen and therefore there is limited scope in controlling this pathogen. There are indications that certain types of crop and soil conditions may cause damage to carrots and pre-dispose them to Fusarium infections and crown rot development. Currently, there is no effective method for reducing or preventing crown rot, as the interactions between the pathogen, crop and environment are not well understood. Therefore, it is necessary to gain a better understanding of the pre-disposing conditions and to understand why the disease develops in one crop and not another.

4. Detailed studies of carrot crops with high levels of crown rots

Carrot crops that have high levels of crown rots also tend to have many other carrot disorders such as misshapen carrots, forked, growth cracks or cavities. Therefore, a close examination of crown rots as well as all other carrot diseases and disorders in the same crop could provide insights on the field and soil environments. Details of a selection of 6 crops below (crop no. 18, 19, 5, 29, 30 and 10), where there were high levels of carrot waste and over 30% carrot rejects were due to crown rots as shown in Figure 2.9 have been examined in further details.

4.1 Crop 18

In field sampling, crop 18 had approximately 40% carrots that were unmarketable (Figure 4.1). Crown rot was the major cause of unmarketable carrots, followed by misshapen carrots and forked carrots. In the washing and sorting processing line, 59% of carrot waste was due to carrot crown rot (Figure 4.2). The main type of crown rot was ring crown rot with 40% carrot waste, followed by 19% of carrots affected by smooth crown rot.

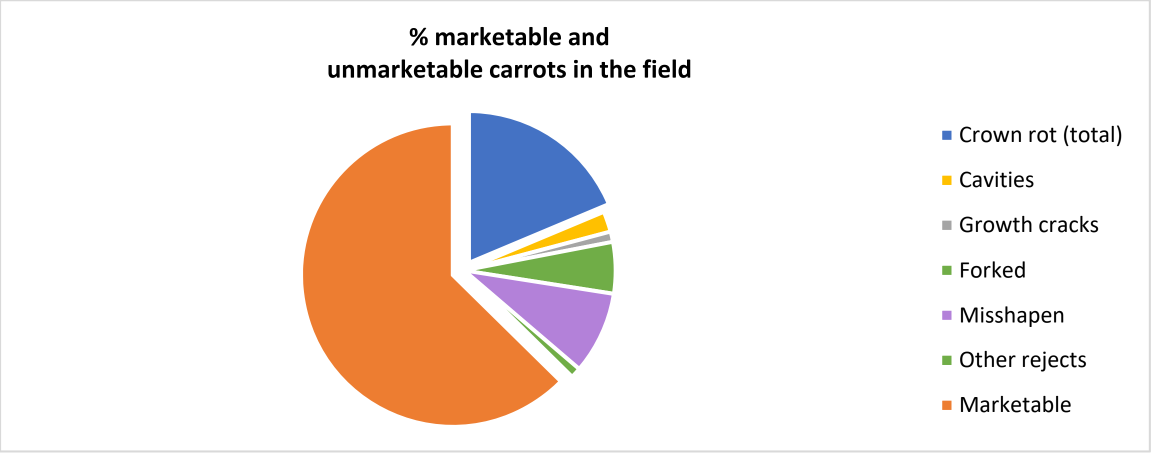

Figure 4.1: The proportions of marketable carrots and carrot disease and disorders in the field prior to harvest

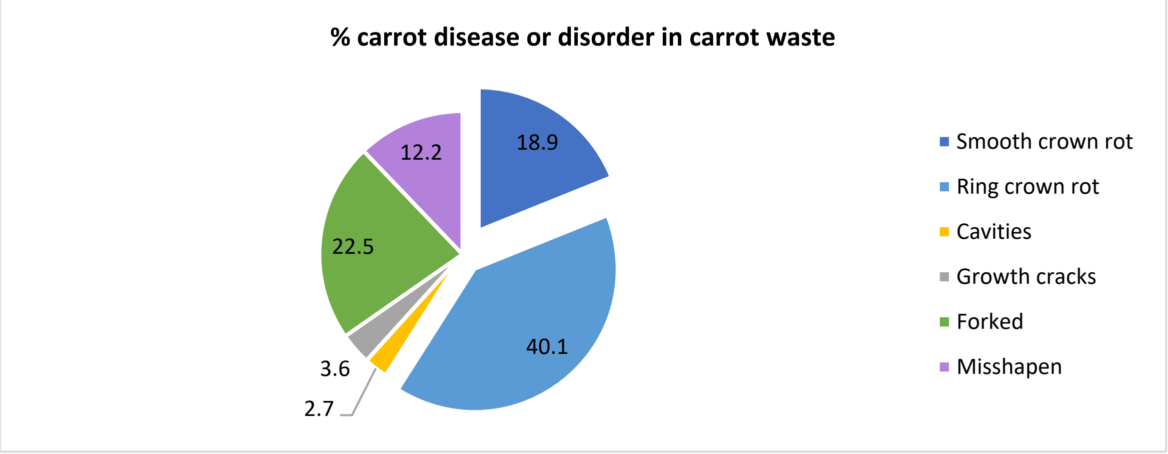

Figure 4.2: Proportions of carrot crown rot and other disorders in carrot waste in processing

Ring crown rot may be seen as a partial or full concentric black ring just below carrot crowns. The black smooth crown rot appeared to be related to the ring crown rot, with similar black lesions except that they occurred in the crown area. Soil crusting, soil compaction and wind damage to carrot tops are believed to be contributing factors to both the ring crown rot and smooth crown rot development in this crop. The combination of infrequent irrigation at crop establishment, soil crusting and rubbing frictions of carrot root tops on windy days may have caused epidermal tissue damage that only became obvious when roots started expanding in diameter. Apart from crown rots, misshapen carrots due to twisting of roots and forked or stunted carrots were also major causes of carrot waste that occurred in the field. It is noteworthy that the soil depth where carrots forked was similar to the depth where carrot twisting occurred. This indicates that root growth encountered impediments at a similar soil depth, except that forking of roots would have occurred early at the seedling stage, whereas twisting of roots occurred later at the bulking stage close to harvest.

Figure 4.3: Ring crown rot (top) and smooth crown rot (bottom) in carrots

Figure 4.4: Forked carrots (left) and misshapen carrots (right)

4.2 Crop 19

In field sampling, crop 19 had approximately 70% carrots that were unmarketable (Figure 4.5). Crown rot was the major cause of unmarketable carrots, followed by misshapen carrots. In the washing and sorting processing line, 47% of carrot waste was due to carrot crown rot (Figure 4.6). The main type of crown rot was black smooth crown rot accounting for 31% carrot waste, followed by 16% carrots affected by black ring crown rot.

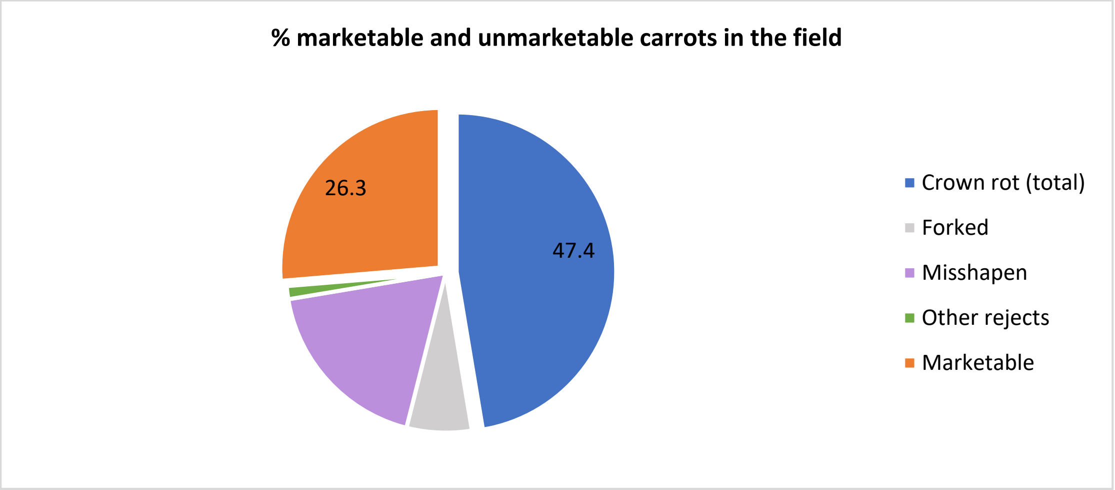

Figure 4.5: The proportions of marketable carrots and carrot disease and disorders in the field prior to harvest

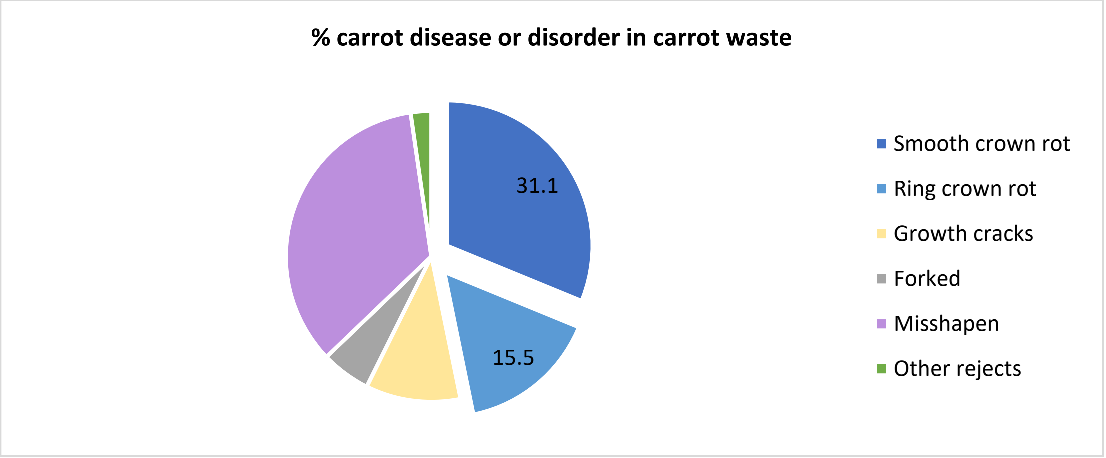

Figure 4.6: Proportions of carrot crown rot and other disorders in carrot waste in processing

Black smooth crown rots (31%) and misshapen carrots (35%) accounted for a large proportion of the carrot waste (Figure 4.6). In field sampling, the ground had a hard soil crust and soil was also very compacted and difficult to dig when dry. The ground was prone to water-logging when irrigated due to soil crusting and compaction. All these soil factors were likely to pre-dispose the carrots to smooth crown rot, ring crown rot, twisting of carrots as well as all other defects that developed in the field (Figures 4.7-4.9). There were also carrots that had unusual old growth cracks that appeared to develop early near the carrot crown and the wounds seemed to seal over (Figure 4.9).

Figure 4.7: Smooth and sunken crown rot (top) and ring crown rot (bottom) in carrots

Figure 4.8: Misshapen carrots (left) and forked carrots (right)

Figure 4.9: Carrots affected by growth cracks

4.3 Crop 5

Approximately a third of carrots harvested in crop 5 were unmarketable. Approximately 55% of carrot waste was due to carrot crown rots (Figure 4.10). The main types of crown rot were corky crown rot with 29% carrot waste, followed by 23% carrots affected by ring crown rot (Figures 4.11-4.12). Both types of crown rots were corky in their appearance and appeared to be related. Other types of major defects were carrots with large vertical growth cracks and carrot cavities (Figure 4.13).

There were high levels of rounded and sharp irregular stones in the harvest bin of carrots. Some of the sharp stones were embedded in carrots after washing, and these caused indentations and small cracks on the carrots. Damage due to stones appeared to be a major factor in the causes of crown rots as well as other defects. All the carrot cavities were likely to be initiated by small cracks due to stone damage that then were enlarged due to tissue breakdown by soil microbes (Figure 4.14). These cracks or cavities only occurred on one side of the affected carrots. No Pythium or other fungal pathogen could be detected in the cavities. There was also a relatively high incidence of carrots with old vertical growth cracks. All these symptoms seem to indicate that the carrots were exposed to fluctuations in soil moisture, possible very dry to very wet. Crown rots that were corky in appearance tended to occur under these fluctuating soil moisture conditions.

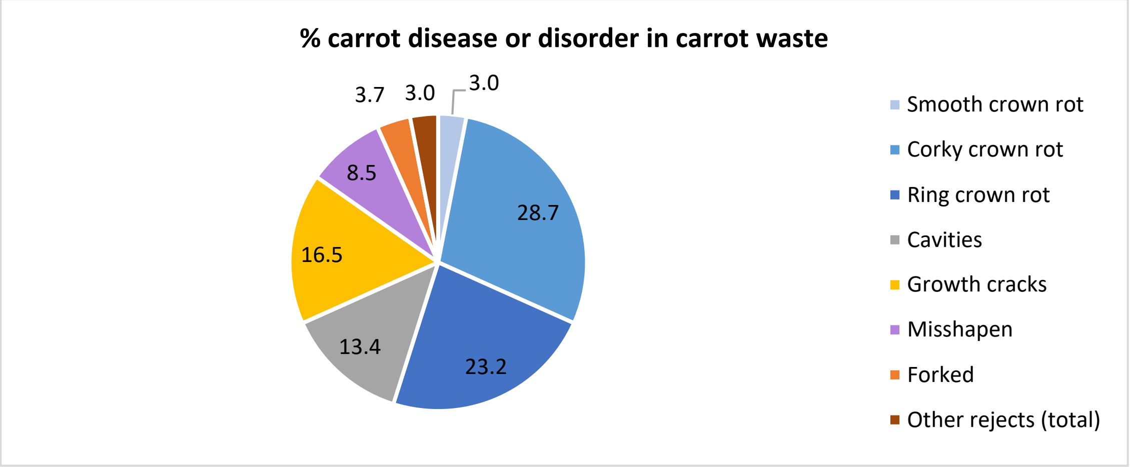

Figure 4.10: Proportions of carrot crown rot and other disorders in carrot waste in processing

Figure 4.11: Corky crown rot (top) and ring crown rot (bottom) in carrots

Figure 4.12: Ring crown rot

Figure 4.13: Carrot cavities (left) and growth cracks (right)

Figure 4.14: Indentations and cracks due to stone damage

4.4 Crop 29

The major cause of carrot waste in this crop was soft watery crown rot, misshapen carrots and forked carrots (Figure 4.15). This crop was harvested in May 2017, when soil conditions were wet and cool. White mould due to *Sclerotinia sclerotiorum* had been observed at the base of dense and tall carrot foliage in the field. After harvest, the watery crown rot had increased in severity and mainly bacteria were found in the rotting tissues (Figure 4.16). Sclerotinia rot was likely to be the primary cause of soft watery crown rot, followed by secondary bacterial rot.

Twisting of misshapen carrots and forking of carrots occurred at similar soil depths (Figure 4.17). There were no root-knot nematodes or Pythium found in association with the forked carrot roots. Damage to root tips and twisting of roots due to compacted soil may be a causal factor.

There was only low incidence of corky crown rot which were mainly small lesions with micro-cracks at the crowns. There was also a low level of carrots with small cavities, which were caused by small irregular stones responsible for indentations and small cavities (Figure 4.18). These root indentations may occur when soil moisture is low and root expansion may be impeded by even small gravel in the soil.

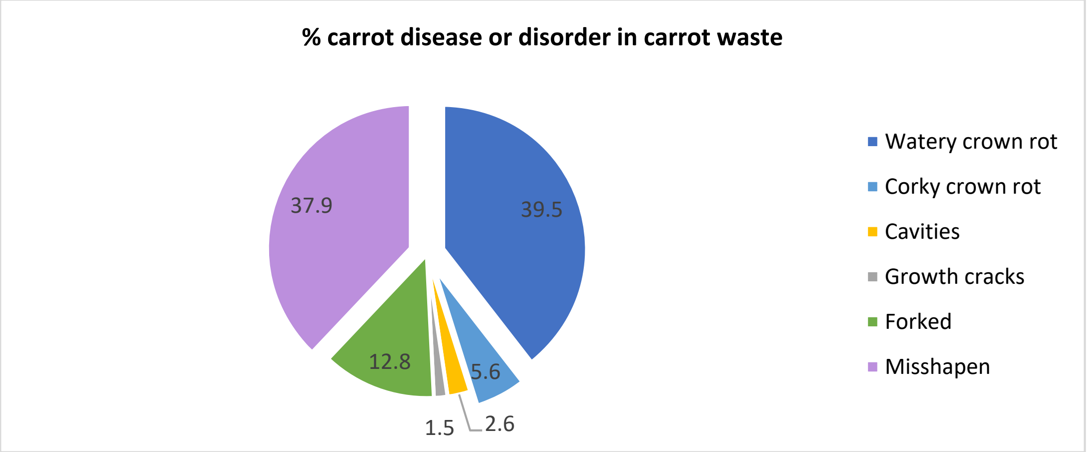

Figure 4.15: Proportions of carrot crown rot and other disorders in carrot waste in processing

Figure 4.16: Soft watery crown rot symptoms (top and bottom)

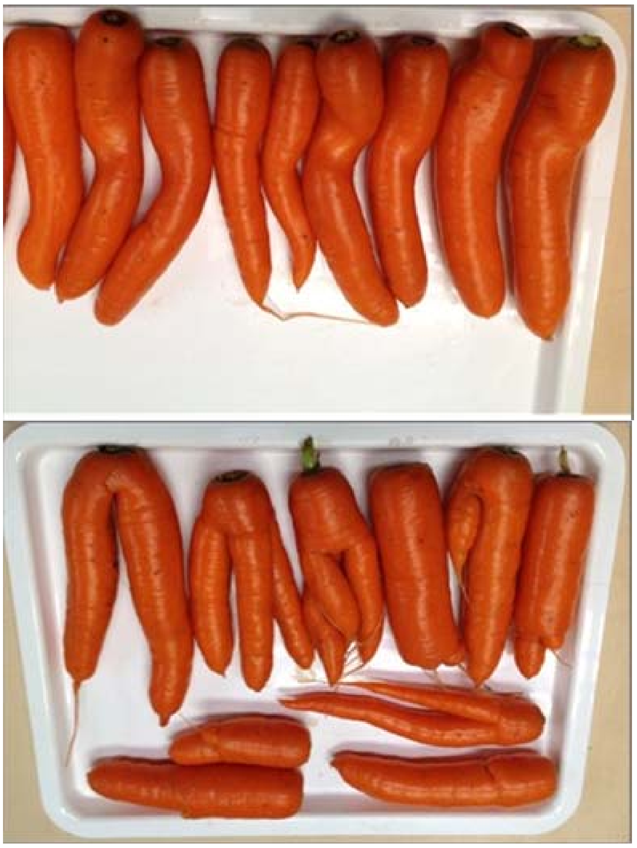

Figure 4.17: Misshapen carrots (top) and forked carrots (bottom)

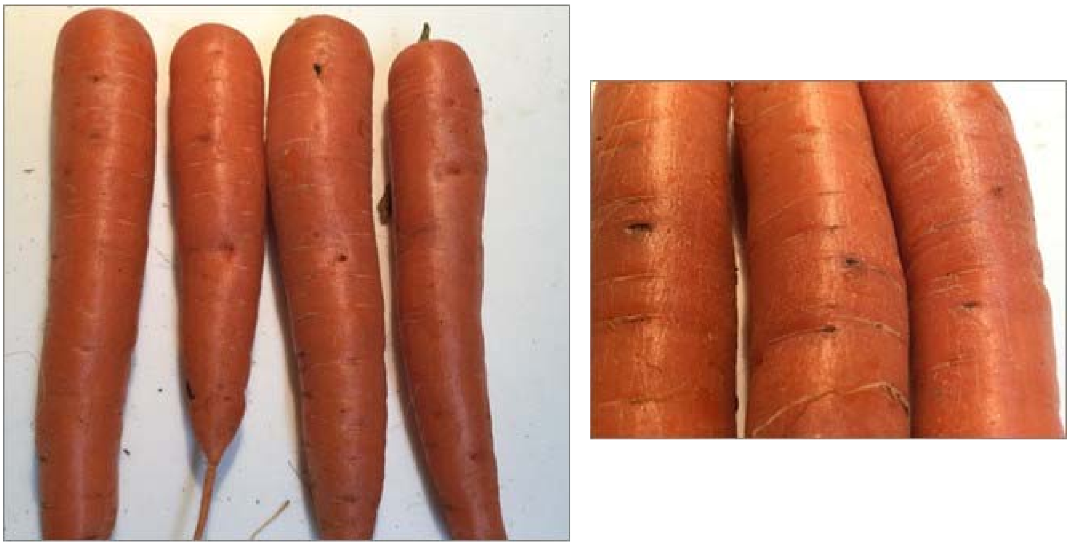

Figure 4.18: Indentations and small dry cavities due to stone damage

4.6 Crop 30

There were high levels of carrot waste due to forked or stunted carrots, corky crown rot and misshapen carrots (Figure 4.19). A high proportion of carrot waste had two or more disorders on the same carrot. The crop was sown in duplex soil with sandy topsoil and it was harvested in late April 2017. Corky type crown rot was prevalent, along with forked or stunted roots due to root-knot nematode damage. Root-knot nematode galls could be observed on forked or stunted carrot roots and the presence of *Meloidogyne hapla* was confirmed in carrot peel test using DNA analysis carried out by SARDI.

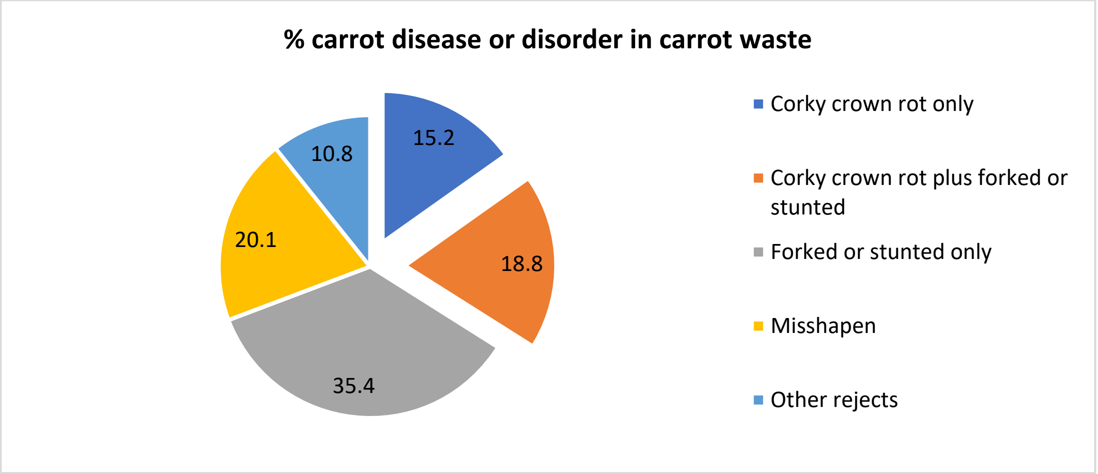

Figure 4.19: Proportions of carrot crown rot and other disorders in carrot waste in processing

Figure 4.20: Corky crown rot (left) and forked or stunted carrots (right)

Figure 4.21: Misshapen carrots

4.7 Crop 10

Almost all carrot waste in Crop 10 had corky crown rot (Figure 4.22). A high proportion of carrots affected by corky crown rot also had other types of defects such as forked, misshapen, growth cracks or green tops (Figures 4.23-4.25). There were high levels of rounded stones in harvest bins. The relatively high incidence of carrots with green crowns indicated that the crowns were exposed to sunlight. The presence of green crowns, growth cracks and corky crown rot suggests that carrots may have been exposed to fluctuating wet and dry top soil conditions.

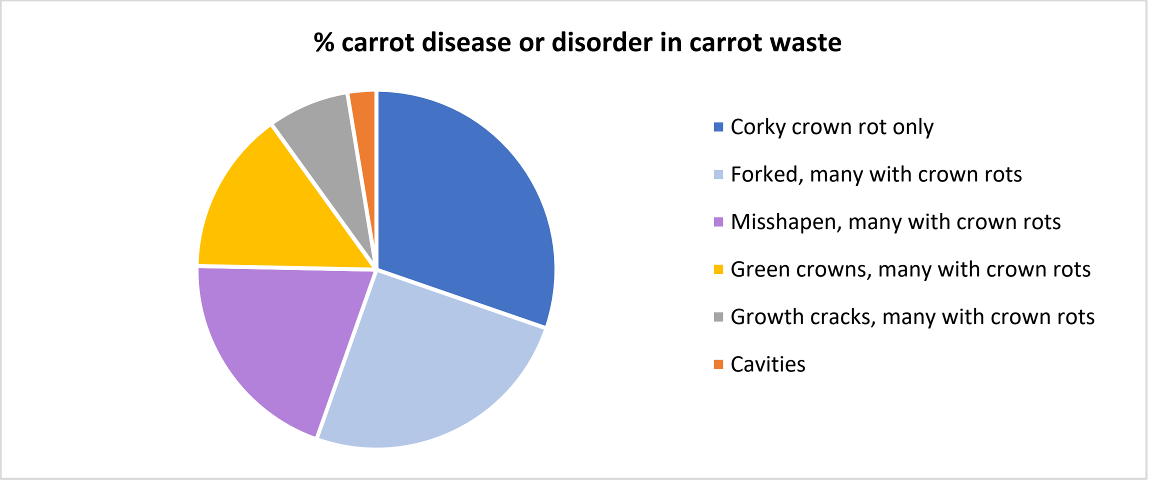

Figure 4.22: Proportions of carrot crown rot and other disorders in carrot waste in processing

Figure 4.23: Corky crown rot only (top) and corky crown rot and green crowns (bottom)

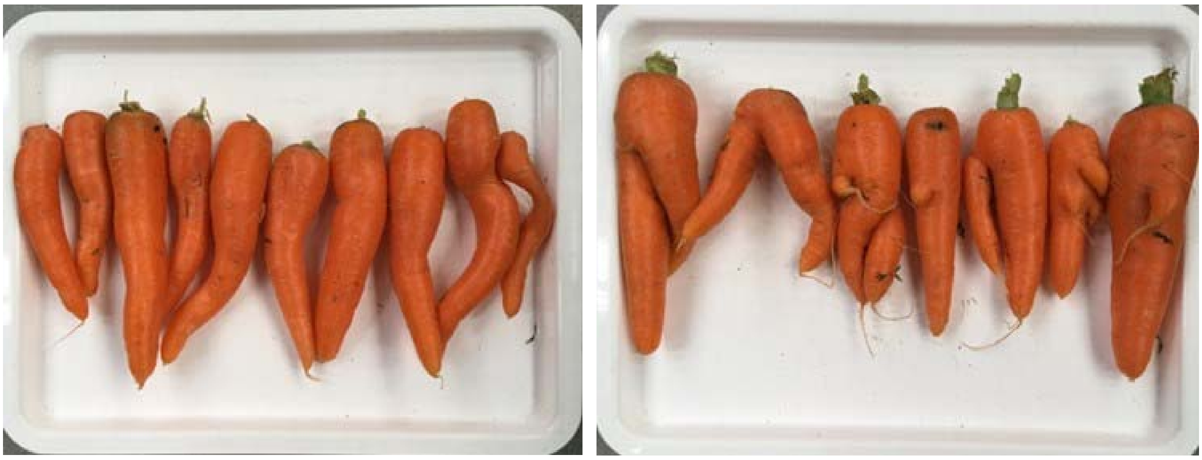

Figure 4.24: Misshapen carrots (left) and forked carrots (right)

Figure 4.25: Corky crown rot and growth cracks

5. Soil moisture and irrigation effects

Soil moisture is believed to play a critical role in carrot seedling establishment and root development. Based on field observations over many years by agronomists, high incidence of crown rots and other carrot defects appear to occur when crops have infrequent irrigation during the crop establishment period followed by frequent irrigation during the late bulking stage. Carrot roots require constant soil moisture for ideal growth. Early deficits in soil moisture may impact on root cell development and make them less able to cope with rapid root expansion in the root bulking stage. Uneven or fluctuating moisture levels in the top soil may impact on carrot crown growth and pre-dispose them to epidermal tissue damage and crown rot development. Therefore, a non-replicated demonstration type study was set up at TIA Vegetable Research Facility to examine the effects of irrigation programs on crown rot incidence. The irrigation programs were as described in Table 5.1. The study was set up within a commercial crop that was sown on 5th December 2017 using a 40 m x 40 m trial block for each irrigation program. Each plant bed was 2.1 m wide and irrigation was applied using fixed overhead sprinklers starting on 5th February 2018. Fertiliser treatments were also applied once on 22 February 2018 as foliar sprays followed by irrigation in a 2.5 m bed within the irrigation blocks to examine for any interaction effects between irrigation programs and top up fertilizer applications (Table 5.2). Carrots were harvested and assessed for crown rot in 1 m bed on 17 April 2018 in each treatment block.

Table 5.1. Details of irrigation programs

Code	Irrigation program	Schedule	6 to 9 leaf	9 leaf to harvest
A	Low fb high	Weekly interval	12 mm	30 mm
B	Regular	Weekly interval	25 mm	25 mm
C	High	Twice per week	25 mm	25 mm

fb = followed by

Table 5.2. Details of fertiliser applications

Code	Fertiliser	Rate
1	Seasol	10 L/ha
2	Trace elements	13 L/ha
3	Calcium nitrate	150 kg/ha
4	Potassium nitrate	200 kg/ha

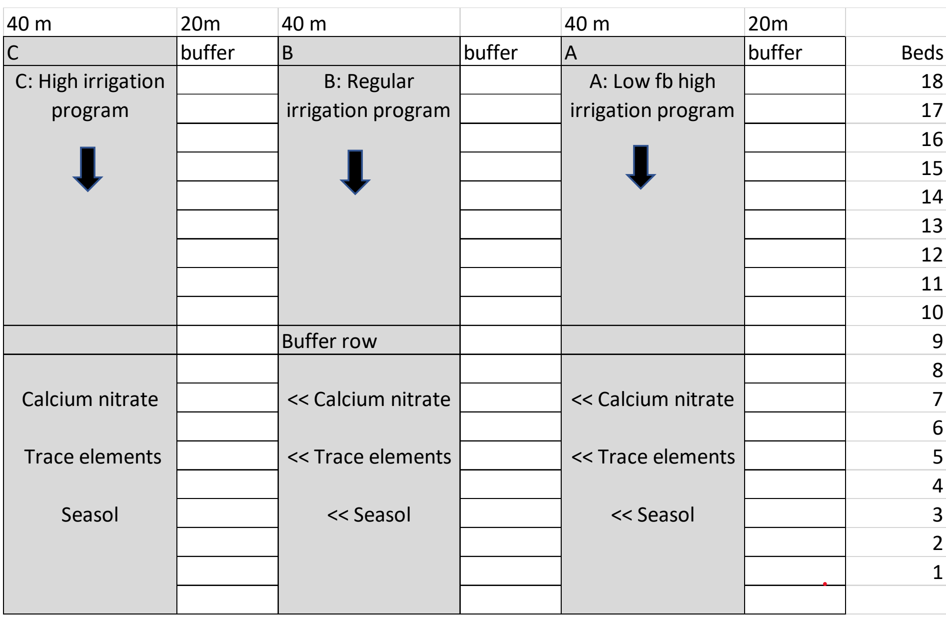

Figure 5.1: Irrigation and fertiliser trial set up

At harvest, the levels of crown rot were relatively low, ranging from 1% to 6% of carrots affected. The crown rots were corky crown rot or ring crown rot. There was a higher incidence of carrot crown rots in the trial block that had a low followed by high irrigation program (Figure 5.2). Top up fertilisers applied at the root bulking stage, especially Seasol fertiliser, also appeared to increase crown rot incidence (Figure 5.3). All the crown rots observed were either corky crown rots or corky ring crown rots. Some carrots also had constrictions just below the crowns due to soil crusting (Figure 5.5). Note that these observations were based on non-replicated demonstration blocks and will requires further studies in a replicated trial to confirm the link between irrigation scheduling, fertilizers and crown rot incidence.

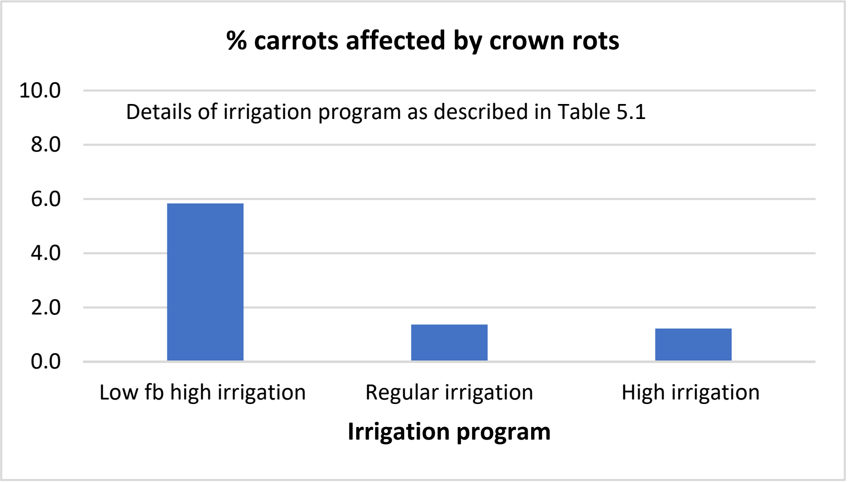

Figure 5.2: Effects of irrigation programs (fb = followed by)

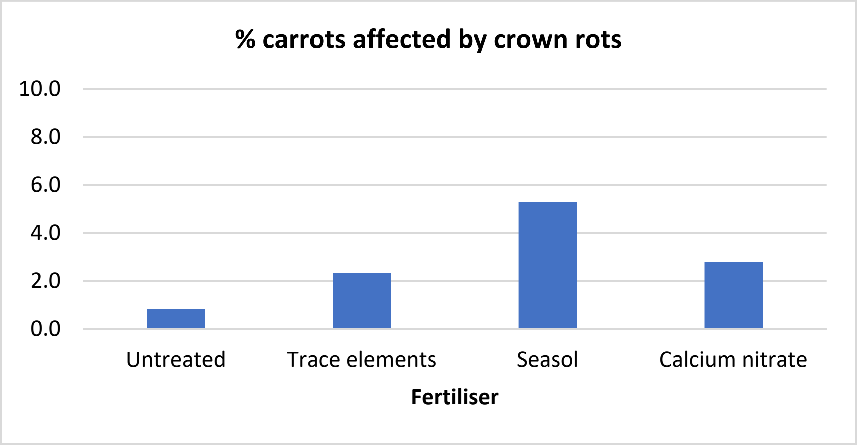

Figure 5.3: Effects of fertiliser applications

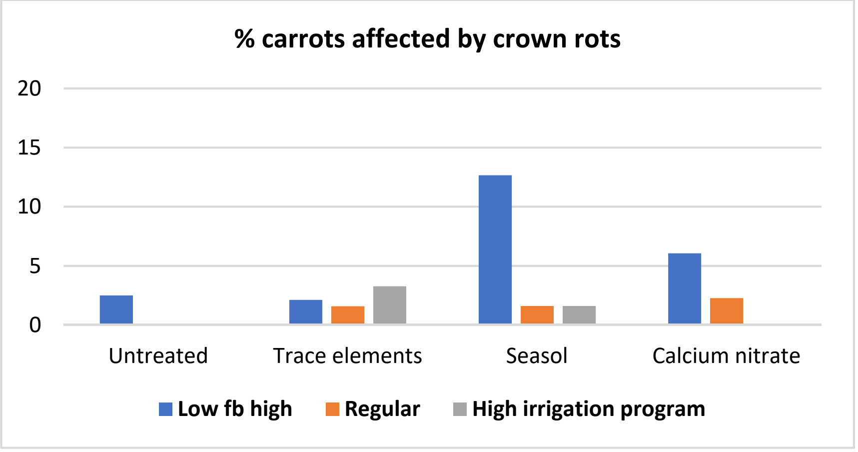

Figure 5.4: Interaction between irrigation programs and fertiliser applications

Figure 5.5: Constrictions due to top soil crusting (top) and ring crown rot (bottom)

Recommendations

It is vital to maintain a friable soil surface around the carrot crown, particularly at the early crop stages. Key factors influencing this are good soil preparation prior to seeding the crop and then maintaining soil moisture to reduce crusting of the top soil.

The cultivation of soils when moisture content is higher than optimal can lead to crusting in the top 10 to 20 mm, particularly when using a bed-forming implement. When this dries it will lead to the formation of a layer that has high bulk density and high penetration resistance. If moisture levels in this layer at the surface are not maintained near field capacity (which is difficult to achieve under conditions of high evaporation), it creates a restrictive zone around the crown of the carrot. This has the potential to cause distortion of the epidermis of the carrot crown which is formed in this zone as the carrot increases in diameter resulting in crown rot development.

Techniques that optimize ground preparation should be used and if this is not possible at the time, due to unfavorable weather and ground conditions, focus on maintaining the surface of the soil as close to field capacity as practically possible during early stages of crown development. Ensure over irrigation does not lead to other crop issues.

Explore methods to remediate the soil surface post cultivation to shatter the crusting formed in the surface layer. Ideally, this needs to occur before seed drilling. This would increase the friability of the surface, reducing the friction between the crown and the soil.

Ensure that carrot crowns are covered with soil to protect them from extreme fluctuations in soil moisture and temperature on soil surfaces.

Implement growing techniques that don't promote excessive foliar growth that then lead to a microclimate forming around the carrot crown and/or causing die back of the lower leaves in the canopy.

Excessive top or canopy development also reduces the ability to achieve good fungicide penetration to the lower leaves at later stages of the crop. This, combined with the microclimate created, significantly increases the likelihood of foliar disease near the crown of the crop. Apply an effective fungicide program for foliar disease management to reduce black ring on crowns

Trimming of tops (horizontally or vertically) could assist in reducing soft watery and black ring crown rot by improving air flow around the carrot crown and light interception to the lower canopy.

Acknowledgements

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