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Research Paper

Assessment of canola crop lodging under elevated temperatures for adaptation to climate change

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ABSTRACT

With temperatures rising due to global climate change, many endeavors have been looking into how this will affect crop production and food security. Lodging, which is the permanent displacement of crop plants from upright position, is one of the main causes of yield loss and quality reduction in canola/oilseed rape. However, there has been little research to date on how the mechanisms of crop lodging might be affected by high temperature. The objectives of this study were to examine the effect of high temperature on the structural features of lodging resistance in four canola genotypes, to determine what kind of lodging (stem or root) was more prevalent, and to identify corresponding mechanistic traits associated with lodging under high temperature conditions. The experiment was carried out in controlled growth facilities with the genotypes tested under normal (23/17 °C; CK) and high temperature (27.01/24.3 °C) regimes. The results showed that high temperature reduced root lodging resistance significantly, as indicated by a dramatic reduction in both root anchorage and safety factor (against anchorage failure). These were attributable to the large suppression on lateral root growth (32%), and thereby reduction in root bending resistance (33%), root–soil cone dimension (13%), and its shear strength (33%). High temperature showed an inconsistent effect on stem lodging resistance, which was in alignment with the engineering mechanics theory and supported by the anatomical observations. These results indicated that canola genotypes were more prone to anchorage failure than stem buckling. Consequently, root lodging resulted from anchorage failure would become a critical aspect under rising temperatures with the global warming. The present study indicates that root lodging should be targeted as a priority to improve crop lodging resistance through breeding selection for a root system with high anchorage strength, especially when the crop plants are expected to encounter inevitable high temperature stress.

1. Introduction

World food security and agricultural production are directly affected by global warming (Peng et al., 2004; IPCC, 2007; Battisti and Rosamond, 2009; Lobell et al., 2011; Singh et al., 2013). Therefore, extensive research has been conducted to project the potential impacts of global warming on agricultural productivity through *in situ* experimentation, and using crop and global climate models (Tao and Zhang, 2011; Ma et al., 2010). Canola (*Brassica napus* L.) is one of the world's most important oilseed crops and the most profitable commodity for Canadian farmers (Canola Council of Canada, http://www.canolacouncil.org/oil-and-meal/what-is-canola/). As a C_3 cool season crop, canola is more susceptible to heat stress than other C_3 and C_4 field crops. High temperatures significantly change the rate of plant metabolic processes that ultimately reduces biomass accumulation, and grain formation (Tripathi et al., 2016). For example, in a field study conducted in eastern Canada, both harvest index and seed yield were reduced by as much as 40% in 2012, a year with severe heat and drought stress, compared to a year with more or less normal temperatures (Ma and Herath, 2016).

Lodging, the permanent displacement of aboveground portions of the crop from the upright position is caused by the interactions between the biophysical properties of the plant and environmental forces such as wind, storm, rain, or hail. Lodging is a common phenomenon in canola production and the main constraint for increasing canola yields under excessive nitrogen application and favorable weather conditions (Pinthus, 1973; Goodman et al., 2001; Foulkes et al., 2011). Multiple studies on grain cereal crops, such as rice, wheat, barley and oat have shown that lodging can decrease both yields and grain quality (Pinthus, 1973; Ma et al., 2012). Lodging can also cause problems for harvest operations and consequently, production costs (Berry et al., 2004). Hence, scientific understanding of high temperature impact on crop

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lodging is of critical importance in crop adaptation to future global climate change.

Crop lodging can be classified as stem lodging and root lodging (Berry et al., 2003a; Wu and Ma, 2016). Stem lodging is mainly due to previous tissue damage by insects and diseases or physically by storm and hail that break the basal internodes of the stem (Pinthus, 1973). Stem lodging resistance is related to the morphological and mechanical characteristics of basal internodes, such as stem diameter, bending strength, flexural rigidity and Young's modulus, etc. (Berry et al., 2004). Root lodging is induced by the failure of the root–soil anchorage system (Ennos, 2004). Root lodging risk depends on the external force exerted on the self–weight moment (bending moment) of the intact plant and anchorage strength of the root system. Crook and Ennos (1993, 1994) suggested that root lodging should be regarded as predominant over stem lodging in modern wheat cultivars. Baker et al. (1998) and Berry et al. (2003a) further reasoned that both types of lodging were possible depending on the circumstances of a particular crop. For example, moist and sandy soils increased the risk of root lodging over that of stem lodging due to weakened soil shear strength (Sposaro et al., 2008). Application of high nitrogen rate, and high plant population densities, both can increase the risk of stem lodging over root lodging due to weakened stem bending strength and extended plant height (Pinthus, 1973; Wu et al., 2012). The underlying properties that cause the stem and root lodging should be differentiated (van Delden et al., 2010; Wu and Ma, 2016). Classifying the root and stem lodging susceptibility of genotypes under specific environment is of importance to decision–making on choosing the appropriate strategies for minimizing the most likely form of lodging.

To effectively adapt to future climate changes, several strategies, such as breeding selection, agronomic practice and crop rotation have been undertaken to mitigate its negative impact on canola yield performance. High or warmer temperatures have been shown to induce the floral sterility or pollen abortion, and shorten seed filling duration and subsequently reduce inflorescence size in canola plants (Morrison and Stewart, 2000; Shah et al., 2011). It may result in less self–weight moment, potentially compromising stem lodging resistance. Furthermore, high and warmer temperatures could alter the partitioning of photoassimilate to roots, and suppress root growth/extension or change root system architecture (Tripathi et al., 2016), or even decrease the elliptical root–soil cone volume. Therefore, root anchorage strength is reduced. High or warmer temperatures would also accelerate cell growth and cell proliferation, which may lead to larger cells with thinner cell walls and weakened vascular bundles that would negatively influence the Young's modulus of plant tissues (Trueba et al., 1982; Ristic and Cass, 1991). In a field study, late-seeded canola plants often produced a smaller root system, due to higher temperature and/or drought stress encountered during the crop development, and was therefore more prone to root lodging than the optimum-seeded canola plants (Wu and Ma, 2016).

Although it is known that high temperatures could affect the morphological and agronomic characteristics of shoot and root, few published studies have considered the direct impact of high temperatures on root and stem lodging resistance, and on the variations in related structural features. To date, only one study (Zhu et al., 2013) suggested that elevated soil temperature alone or together with CO_2 enrichment increased the risk of stem lodging in rice plants. Unfortunately root lodging risk was not examined in their study. Furthermore, there were no studies examining the prevalence or susceptibility between stem lodging and root lodging of canola plants subjected to high temperature environments. High temperature stress has recently been reported to alter biomass production (Ma and Herath, 2016), nutrient uptake, distribution and balance (Ma and Zheng, 2016). Thus, we hypothesized that (1) high temperature stress would significantly influence lodging resistance, and (2) high temperature may exert a different force on stem and root lodging susceptibility. A better understanding of those mechanisms will be helpful to mitigate the most likely form of lodging. The objectives of this study were to (1) assess the impact of high temperature stress on stem and root lodging resistance in four different genotypes under controlled growth facility conditions, (2) determine which kind of lodging (stem or root) is more susceptible under high temperature stress, and (3) identify lodging-related morphological, biophysical, mechanical properties. This knowledge will be useful to plant breeders, and/or agronomists for canola improvement, and/or selection of genotypes of canola that is more resistant to lodging under increased temperature with global warming.

2. Materials and methods

2.1. Plant and treatments establishment

A pot culture experiment was conducted in a controlled environment at the Ottawa Research and Development Centre Laboratory of Agriculture and Agri–Food Canada, Ottawa, ON, Canada. Treatments were arranged in a split–plot design with temperature treatment as the main–plot and genotype as the subplot, to form a randomized complete block design. Four canola genotypes were tested in this study. Two genotypes (13C220 and 13C204) were kindly provided by Dr. Rob Duncan from the University of Manitoba, Winnipeg, Canada, and the other two were commercial hybrids (Pioneer45A65 and Invigor5440). Invigor5440 shows strong lodging resistance and is commonly used as a check cultivar in provincial canola cooperative performance trials conducted in Ontario and Quebec. These four genotypes were chosen to represent a wide range of sensitivity to lodging. Three seeds were sown in each of the 32 plastic pots (10.5 cm diameter and 9 cm height), filled with soil mix (sieved top sandy loam soil + vermiculite + peat moss + perlite). The soil mix contained 17.3 g kg^{-1} organic C, 45 mg kg^{-1} Olsen P, 400 mg kg^{-1} soil test K, 4000 mg kg^{-1} available Ca, 36 mg kg^{-1} available Mg, 3 mg kg^{-1} available Na, with 250 meq kg^{-1} total cation exchange capacity, and a pH 6.6. The experiment was conducted twice in duplicate runs.

In each run of the experiment, sixteen pots were moved to each of the two growth chambers (Model GR 96, CONVIRON, Control Environment Ltd., Winnipeg, MB) for seed germination. The usable area for each growth chamber is 1.8 m^2 (0.9 × 2.0 m) and the distance between each pot was set at 25 cm apart. The position of the pots within each chamber was rotated at random on a weekly basis to avoid any potential light/temperature/water gradient within the chamber on plant growth. There were four replications for each genotype. The seedlings were thinned to one per pot on the 6th day after planting. The plants were grown in two growth chambers for two weeks at 23/17 °C (day/night) prior to the application of temperature treatments. Based on the long-term mean temperature and diurnal high temperature fluctuations in the summer that occur commonly in this region (Wu et al., 2017), the high temperature treatment of one growth chamber was set in a 24–h cycle as follows: 6:00–10:00 = 23 °C, 10:01–11:00 = 26 °C, 11:01–12:00 = 29 °C, 12:01–16:00 = 32 °C, 16:01–17:00 = 29 °C, 17:01–18:00 = 26 °C, 18:01–22:00 = 23 °C, 22:01–2:00 = 26 °C, 2:01–5:59 = 23 °C; and the normal temperature chamber (control) was maintained at 23/17 °C (light/dark) until maturity stage. The average temperatures in the hot and control chambers were 27.01/24.33 °C and 23.0/17.0 °C (light/dark), respectively. The growth chambers were set at 16/8–h light/dark cycle, with approximately 500 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) at the canopy level and 75% relative humidity. Each pot was well–-irrigated to avoid any drought stress, and received 0.1 g of compound fertilizer (N: P_2O_5: K_2O = 15:15:15) once a week until 10 days after flowering stage.

2.2. Sampling and data collection

2.2.1. Simulated root lodging test

The lodging–related traits were determined for each plant at the