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Paclobutrazol increases canola seed yield by enhancing lodging and pod shatter resistance in *Brassica napus* L.

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ABSTRACT

This 2-year field study investigated the effects of time and paclobutrazol concentration on the seed yield and the lodging and pod shatter resistance of oilseed rape (*Brassica napus* L.). Paclobutrazol was sprayed on the foliar tissue of two rapeseed cultivars, Yangguang 2009 and Fengyou 520, at the closed canopy stage and the early bud stage at concentrations of 0, 150 and 300 mg L^{-1}. Our results demonstrated the following: (1) Paclobutrazol significantly increased lodging resistance, pod shatter resistance. Paclobutrazol reduced the number of seeds per pod but increased the number of pods per plant, the 1000-seed weight and the yield. With increasing paclobutrazol concentrations, the resistance to lodging and pod shattering increased, whereas the increment in yield decreased. Compared with treatment at the early bud stage, the application of 150 mg L^{-1} paclobutrazol at the closed canopy stage significantly enhanced the lodging and pod shatter resistance and increased the yield increment in both cultivars. (2) After treatment with paclobutrazol, the increment of lodging resistance and pod shatter resistance were higher for Fengyou 520 than for Yangguang 2009, and the yield increment was less. (3) The increased root-top ratio, increased snapping resistance and reduced plant height resulting from paclobutrazol treatment reduced the angle of plant lodging, which improved the ability of the culm to resist lodging. Pod shatter resistance increased as pod water content and pod dry weight increased. In summary, 150 mg L^{-1} of paclobutrazol sprayed on foliar tissue at the closed canopy stage significantly enhanced lodging resistance, pod shatter resistance and yield. These improvements could help augment the mechanical production of rapeseed in China.

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1. Introduction

Rapeseed (*Brassica napus* L.) is an important source of edible vegetable oil worldwide (Karp and Richter, 2011), and it is one of the major oilseed crops in China. For decades, conventional rapeseed production in China has depended on manual labor: nearly 50% of the total cost of rapeseed production in China was for manual labor. In fact, rape production is much more expensive in China than in Canada, the USA or Germany because of the low level of mechanization (Zhang et al., 2010); the lower mechanization rates and the high labor force usage during the harvesting are the major factors restricting rapeseed production in China (Yin and Wang, 2012). Consequently, the future success of canola production in China depends on the advancement of mechanical harvesting. This issue is of great concern to farmers, as the domestic labor force engaged in crop farming is in sharp decline.

Mechanization is an important and efficient tool to enhance crop yield; it also helps to reduce labor demands and ultimately increases farmers' prosperity (Shahid et al., 2010). The mechanical harvesting of rapeseed requires several agronomic traits, such as the appropriate plant height, sufficient lodging resistance and sufficient pod shatter resistance (Hua et al., 2014). Among these, lodging and pod shattering are the two main factors that limit mechanical harvesting (Pari et al., 2012). Lodging and shattered pods not only are unsuitable for mechanical harvesting but also cause substantial yield loss (Li et al., 2010). Typically, rapeseed produces plants that easily lodge when yields are high. Under lodging conditions, inefficiency in nutrient assimilation, remobilization, and utilization, combined with poor light penetration, can result in fewer

Abbreviations: CV (%), coefficient of variation; MDT (°C), mean daily temperature; MDTmin (°C), mean daily minimum temperature; MDTmax (°C), mean daily maximum temperature; *Pn*, net photosynthetic rate; PGRs, plant growth regulators.

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seeds per pod and a greater proportion of immature pods. In some cases, there is a yield penalty to lodging, leading to smaller crops with far fewer pods. Lodging incidence can be curtailed to a certain extent with cultivar selection and the use of plant growth regulators (PGRs) (Tripathi et al., 2004). PGRs, such as chlorocholine chloride, paclobutrazol, and mepiquat chloride, act as stem shorteners and effectively control plant height, which can assist with mechanical seed harvest (Kumar et al., 2012). PGRs have also been shown to increase the stem snapping resistance and the lodging resistance (Pinthus, 1974; Crook and Ennos, 1995; Zhang et al., 2001; Rajala et al., 2002; Tripathi et al., 2003) and have been used to manage seed shattering of Bird's-foot-trefoil (*Lotus corniculatus*), resulting in reduced shattering and seed yield increases (Wiggans et al., 1956).

Among PGRs, paclobutrazol, a triazole compound, is widely used as a growth retardant for controlling vegetative growth in a large range of plant species; it impedes plant growth by inhibiting sterol and gibberellin biosynthesis (Khalil and Rahman, 1995; Khan, 2009). Paclobutrazol can also significantly affect plant growth and development by altering the photosynthetic rate and modifying phytohormone levels (Vu and Yelenosky, 1992; Wang and Lin, 1992; Huang et al., 1995; Kim et al., 2012). Previous research in wheat has revealed that the appropriate application of paclobutrazol can increase the photosynthetic area as well as the number of tillers and spikes on a plant, which ultimately increases yield (Rajala and Peltonen-Sainio, 2001). However, several studies have shown that yield was reduced when plants were shortened too much with excessive amounts of plant growth regulators (Zhang et al., 2001; Acreche and Slafer, 2011; Peng et al., 2014). The effects of paclobutrazol on rapeseed growth have been previously reported by others (Addo-Quaye et al., 1985; Zhou and Xi, 1993); plant height and lodging were reduced by paclobutrazol in rapeseed (Armstrong and Nicol, 1991) and rapeseed oil yield was significantly improved by paclobutrazol application (Baylis and Hutley-Bull, 1991; Zhou and Xi, 1993). Conversely, Zhou and Xi (1993) concluded that early spraying of paclobutrazol at the three-leaf stage did not significantly affect the plant height of mature rapeseed (Zhou and Xi, 1993). The effects of paclobutrazol on plant growth and seed yield may be erratic because, under field conditions, they are dependent not only on the plants' biochemical potential but also on several other factors, such as plant responsiveness, weather conditions and management practices (Scarisbrick et al., 1985; Oswalt et al., 2014). Because of the complexity of these interactions, to date, there has not been a precise recommendation for paclobutrazol application time and concentration in rapeseed in China.

We hypothesized that lodging and pod shattering were two important determinants of yield differences between paclobutrazol treatments. It is clear that to disentangle these relationships, a greater understanding is needed of the traits influencing lodging and pod shattering after foliar spraying of paclobutrazol at different times and different concentrations. However, relatively few studies have investigated the effects of paclobutrazol on lodging and pod shattering traits in rapeseed. To understand the underlying mechanisms of lodging and pod shattering and to identify the optimum time and concentration of paclobutrazol application, we conducted field experiments during 2012–2013 and 2013–2014 growing seasons. The main objectives of this study were (i) to investigate the effects of different paclobutrazol concentrations and application times on rapeseed lodging and pod shattering and their related agronomic responses and (ii) to examine the interaction between paclobutrazol concentration and application time and provide recommendations on the optimal combination to produce sufficient lodging resistance without adverse effects on either crop development or seed yield.

2. Material and methods

2.1. Experimental site

A replicated field experiment was conducted during two seasons (2012–2013 and 2013–2014) at the Huazhong Agricultural University Experimental Farm (30°28′12″ N, 114°21′05″ E) in Wuhan, China. The previous crop, rice, was harvested in September. The initial soil status (0–20 cm) of the field in available nitrogen (N), phosphorus (P) and potassium (K) concentrations was as follows: 118.72 mg kg^{-1}, 13.79 mg kg^{-1} and 138.33 mg kg^{-1}, respectively, in 2012–2013 and 125.72 mg kg^{-1}, 14.79 mg kg^{-1} and 147.33 mg kg^{-1}, respectively, in 2013–2014. Fig. 1 showed the rainfall and temperature during the two seasons; these data were provided by the National Meteorological Information Center of the China Meteorological Administration.

2.2. Experimental design

The experiment was carried out in a split-split-plot design with two paclobutrazol application times (T1, the closed canopy stage; T2, the early bud stage) as the main plots (the agronomic traits of the two application times are shown in Table 1), three paclobutrazol concentrations (P0, 0 mg L^{-1}; P1, 150 mg L^{-1}; P2, 300 mg L^{-1}) as the split plots and two cultivars as the split-split-plots (the agronomic traits of the two cultivars are shown in Table 2). The closed canopy stage and the early bud stage were selected for application times in an effort to most effectively improve leaf quality and control stem development, respectively. Each treatment was performed in three replicate plots, each of which had an area of 20.0 m^2 (10.0 m long

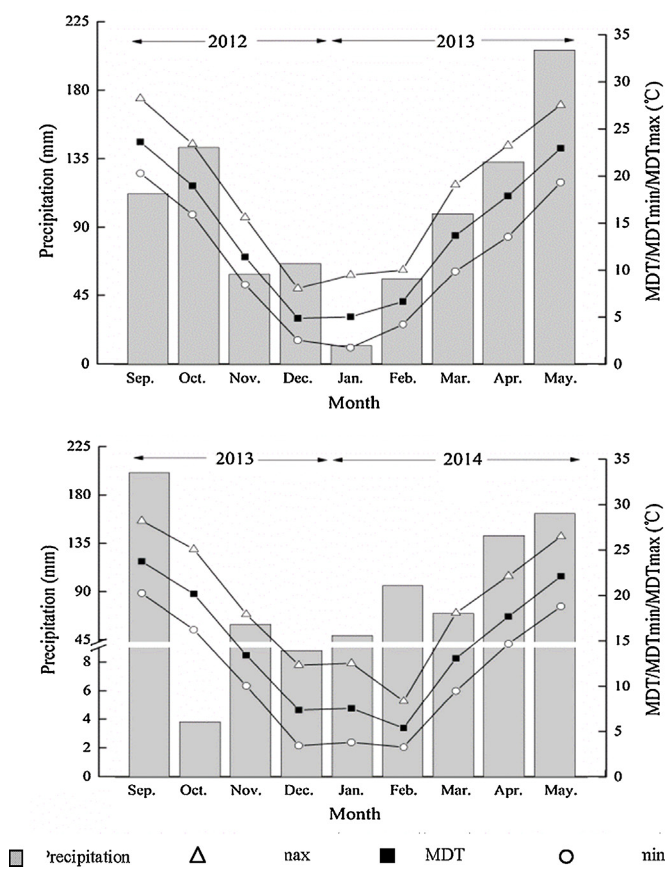

Fig. 1. Monthly temperatures and total monthly rainfall during the rapeseed season in 2012–2014. MDTmax, MDT and MDTmin stand for mean daily maximum temperature, mean daily temperature and mean daily minimum temperature.

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