Effect of temperature on the growth, reproduction, and germination pattern of two populations of Chloris virgata

Het Desai

het.desai@student.montana.edu

Montana State University

Bhagirath Singh Chauhan

The University of Queensland

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Abstract

A holistic knowledge about the growth of weed species (i.e., from germination to seed production) in response to environmental factors (e.g., temperature, sunlight, moisture, etc.) is of utmost importance to understand the intensity of infestation, especially for *Chloris virgata* which demonstrates year-round germinability. An experiment in naturally lit greenhouse was conducted to assess the vegetative and reproductive growth of two *C. virgata* populations [FTR3 (glyphosate-susceptible, GS) and FTR11 (glyphosate-resistant, GR)] at two alternating temperature regimes: 25/15°C, low temperature and 35/25°C, high temperature. The average seed production of both populations was about 78% higher (12635 seeds/plants) at 25/15°C than at 35/25°C (7117 seeds/plants), indicating that late-winter/early-summer maturing cohorts will produce more seeds compared to the cohorts that mature in mid/late summer. The germination pattern of FTR3 and FTR11 maturing at two alternating temperature regimes (25/15°C and 35/25°C) was evaluated in an incubator calibrated to deliver 30/20°C with a 12 h/ 12 h photoperiod. The seeds collected from FTR3 and FTR11, which completed the lifecycle at 35/25°C, released dormancy faster than those matured at 25/15°C, suggesting the late-winter maturing flushes will have an extended germination period. In the light of climate change, these results could aid in designing sustainable integrated management programs to effectively manage this weed species in Australian farming systems.

Introduction

Chloris virgata Sw. is a non-native summer annual weed in Australian farming systems that follows the C_4 photosynthetic pathway [1]. It is referred to by various common names across the globe, such as feathertop Rhodes grass (used extensively in Australia), feathered *Chloris*, feathered windmill grass, oldland grass, and sweetgrass [2,3]. *Chloris virgata* is a highly competitive weed species in sorghum, mungbean, cotton, and other summer crops as it can attain a height of > 1-m, produce 600 g $m^{-2}$of dry biomass, and > 140000 seeds in favorable conditions [4,5]. It is one of the most prevalent grass weed species, especially in no-till or minimal tillage systems in the Australian agroecosystem, infesting an area of 118,000 ha and causing a considerable revenue and yield loss to grain growers, corresponding to AUD 7.7 million annually and 39300 tons of grain, respectively [6]. The density of 22–25 plants m^{-2} of *C. virgata* could reduce 50% of mungbean yield compared to a weed-free plot [7]. Due to its high competitiveness and invasive attributes, a heavy infestation of *C. virgata* could result in complete crop destruction in sorghum [8]. Owing to the economic impact of this species on the Australian grain industry, it ranked in the top 20 weeds of a major threat.

Chloris virgata is a highly invasive species due to its unique biological feature of seeds, such as being lightweight (0.5 mg), small in size [9], and aerodynamic in shape [10]. The aerodynamically efficient seeds aid in rapid and long-distance anemochory (wind dispersal) due to increased settling velocity. Osten (2012) mentioned that *C. virgata* seeds could disperse up to 13 m in normal wind velocity (16 km h^{-1}). In addition, the seeds possess two protruded hairlike appendages, which help them to adhere to

agricultural machineries and workers' clothes, therefore, minimizing the requirement of dispersal energy. The seeds are dark black and pale white, with the previous hypothesis speculating about the non-viability of white-colored seeds. However, x-ray images of *C. virgata* seeds confirmed that white-colored seeds could also be viable [10].

Evidence suggests that *C. virgata* originated from either tropical and/or subtropical regions of the world based on its summer-annual lifecycle; however, the exact origin of this species is still a matter of debate internationally [11]. The opposition counterpart argues that this could be originated from a temperate region considering its ability to germinate at broad thermal conditions (5 to 35°C) [12]; however, this could be the form of eco-evolutionary adaptation according to the modern weed ecologists. Due to the ability to germinate at a wide range of temperatures, this weed species could occur throughout the year, falling under the hard-to-control weed category.

Despite the numerous benefits of adopting conservation tillage systems (i.e., no-till and/or minimal tillage), many environmental weed species have established in Australian agroecosystems, such as *Avena fatua* L., *Echinochloa colona* (L.) Link, *Sonchus oleraceus* L., and *Lolium rigidum* Gaud. [13], while *C. virgata* is the most recent example [14,15]. In addition, the long-term utilization of conservation tillage systems has led to the over-dependence on herbicides (i.e., glyphosate) for weed control. Glyphosate resistance in *C. virgata* has been recorded in several populations and the first case was recorded in 2015 in New South Wales, Australia [16–18]. Interestingly, glyphosate resistance evolved in a *C. virgata* population collected from the roadside in South Australia, without a history of herbicide application in 2015 [16], indicating either pollen-mediated or seed-mediated gene flow [19,20].

Weed species have acquired various demographic properties for perennation and vegetative-reproductive growth due to eco-evolutionary adaptation. The demographic behavior of any plant species is defined as the kinetic properties of an individual population progressively in response to biotic and/or abiotic stresses [21]. Weed demographic processes, such as germination, emergence, growth, and reproduction, are controlled by environmental conditions (i.e., soil-air temperature, soil moisture, pH, relative humidity, photoperiod, and light intensity) [22]. A detailed understanding of weed demographic processes is important to identify weed species' propensity to establish in agroecology and develop species-site-specific integrated management programs to manage invasive species, for instance, *C. virgata* [23].

The present study was conducted to understand the effect of alternating temperature regimes on the vegetative growth, seed production, and germination pattern of two agroecologically distinct populations of *C. virgata*. In our previous experiment, *C. virgata* populations exhibited differential germination patterns in response to different alternating temperature regimes [3,10]. However, currently, no holistic knowledge of the germination, growth, and reproduction of *C. virgata* in different thermal conditions is available. The major aim of this study is to extend the current knowledge of weed demographics of this species and to provide comprehensive information from germination to reproduction in response to

temperature. The data generated from this study will have direct implications based on intellectual merits, as weed scientists and agronomists could use these data to develop efficient weed management protocols for this problematic weed species.

Results and Discussion

Vegetative and reproductive growth experiment

All the response variables appeared to differ between high and low alternating temperature regimes [25/15°C (LT) and 35/25°C (HT)]. The interaction of two populations (FTR3 and FTR11) in the same thermal condition was observably different. The vegetative growth parameters (plant height and leaf numbers plant^{-1}) and the reproductive growth parameter (panicles plant^{-1}) of FTR3 and FTR11 gradually increased in both temperature regimes (25/15°C and 35/25°C) (Figs. 1 and 2). For FTR3, plant height was 33 cm and 16 cm at 35/25°C and 25/15°C 14 days after planting (DAP), respectively, and it reached 165 cm at 35/25°C and 140 cm at 25/15°C 91 DAP (Fig. 1; Table 1). Similarly, for FTR11, plants were taller at 35/25°C than at 25/15°C. FTR11 attained 28 cm and 9 cm of plant height at 35/25°C and 25/15°C at 14 DAP, respectively, with the final recorded plant height of 129 cm at 35/25°C and 113 cm and 25/15°C 91 DAP (Fig. 1; Table 1).

The lower slope (*b*) values of FTR11 for plant height (8.6 at 35/25°C and 25/15°C) indicate that FTR11 acquired the final height in a short time (63 DAP) compared to FTR3 (91 DAP), which is also reflected in T_{50} values (time taken to reach 50% of each growth parameters) (Table 1). FTR11 required 29 days (an average across temperature regimes) to reach T_{50}, which is shorter than FTR3 (38 days) (Table 1). The increased plant height of FTR3 and FTR11 in response to HT (35/25°C) could be a sign of the phytochrome-interacting factor 4 (PIF4) regulated thermomorphogenetic response observed in *Arabidopsis thaliana* (L.) Heynh. [24]. The increased plant height in response to a higher temperature could weaken the overall plant architecture [25], causing instability of *C. virgata*; therefore, promoting seed-shattering rate, which might affect weed management operations, such as harvest weed seed control.

Table 1
Vegetative growth parameters (plant height and leaf number) and reproductive growth parameter (panicles plant^{-1}) estimated by three-parameter sigmoidal model: $f = a/[1 + (\quad)^{b}]$, of two *Chloris virgata* populations (FTR3 and FTR11) which completed their lifecycle at two alternating temperature regimes: 25/15°C, low temperature, and 35/25°C, high temperature. Seed lot 1 and Seed lot 2 were collected at a 14 days interval.

Parameter and Populations	Temperature regimes (C) [b]	Parameter estimates (± standard error) [c]			
		a [a]	*b* [a]	T_{50} [a]	R^2 [a]
Plant height (cm)					
FTR3	LT	142 (5.2)	14.3 (1.6)	37.2 (1.8)	0.98
FTR3	HT	176 (4.6)	19.6 (3.6)	39.1 (4.6)	0.96
FTR11	LT	114 (1.8)	8.6 (0.7)	33.1 (0.7)	0.99
FTR11	HT	128 (1.6)	8.6 (0.6)	25.1 (0.7)	0.99
Leaf (number plant^{-1})					
FTR3	LT	207 (10.8)	12.9 (1.9)	44.4 (2.4)	0.98
FTR3	HT	130 (3.0)	6.8 (0.9)	29.6 (1.0)	0.98
FTR11	LT	227 (13.3)	13.7 (1.7)	53.4 (2.5)	0.99
FTR11	HT	125 (4.0)	7.0 (1.3)	31.7 (1.4)	0.97
Panicle (number plant^{-1})					
FTR3	LT	20.9 (1.1)	5.9 (1.0)	66.3 (1.3)	0.98
FTR3	HT	10.7 (0.6)	3.7 (1.0)	70.3 (1.1)	0.98
FTR11	LT	20.8 (0.2)	3.5 (0.2)	62.6 (0.3)	0.99
FTR11	HT	9.3 (0.1)	4.0 (0.3)	47.4 (0.3)	0.99

[a] *'a'*, upper limit of a curve; *'b'*, the slope of a curve; 'T_{50}', growing days required to attain 50% plant height, leaf and panicle numbers/plant; 'R^2', coefficient of determination of goodness of fit.

[b] LT, low temperature: 25/15°C; HT, high temperature: 35/25°C

[c] Values in parentheses denote the standard error of the mean

In contrast to plant height, FTR3 and FTR11 produced higher leaf and panicle number per plant at 25/15°C (LT) compared to 35/25°C (HT) (Figs. 1 and 2). On average, FTR3 and FTR11 produced approximately 197 leaves and 21 panicles plant^{-1} at 25/15°C and 132 leaves and 11 panicles at 35/25°C (Figs. 1 and 2). However, higher '*b*' values of FTR3 and FTR11 for leaf and panicle numbers at 25/15°C suggest that a longer time is required to reach the optimum leaf and panicle number compared to that at 35/25°C (Table 1). The '*b*' of FTR11 for panicle numbers was lower at 25/15°C (3.5) than at 35/25°C (4.0); however, the difference was non-significant. The trend of acquiring optimum leaf and panicle numbers in a short time at HT (35/25°C) is also revealed by smaller T_{50} values of FTR3 and FTR11 associated with leaf and panicle numbers per plant at 35/25°C (Table 1). The reduction in the leaf number of FTR3 and FTR11 at HT (35/25°C) suggests the mechanism involved in water conservation, which is regulated by a process called transpiration [26]. In the light of climate change, the leaf number reduction of *C. virgata* at 35/25°C could have a negative impact on chemical weed management in the future since the rate of herbicide absorption/translocation is positively correlated with the leaf numbers per plant [27,28]. In recent study, glyphosate efficacy on *C. virgata* was found to be reduced at LT (25/15°C) compared with HT (35/25°C) [17].

FTR3 and FTR11 produced more seeds plant^{-1} at LT (25/15°C) than at HT (35/25°C) (Fig. 2). FTR3 produced 16785 seeds plant^{-1} at LT (25/15°C), which was 97% higher than the seed production (≥ 8513 seeds plant^{-1}) at HT (35/25°C) (Fig. 2). FTR11 produced 39% more seeds at LT (25/15°C, 8327 seeds plant^{-1}) compared to at HT (35/25°C, 5997 seeds plant^{-1}) (Fig. 2). *Chloris virgata* tends to germinate at wide alternating temperature regimes (15/5 C to 35/25°C) [3], occurring throughout the year in Australian farming systems. Based on these results, *C. virgata* populations that reach physiological maturity in October-November (late-spring) produce more seeds than those attaining physiological maturity in December to February (mid-late summer).

Both populations produced greater biomass at HT (35/25°C) than at LT (25/15°C) (Fig. 3). However, for FTR11, the difference in biomass was non-significant between temperature regimes. FTR3 produced about 93 g plant^{-1} biomass at HT (35/25°C), which was 22% higher than the biomass produced at LT (25/15°C). It is important to note that FTR3 produced considerably more seeds plant^{-1} and biomass when compared with FTR11 at both temperature regimes. For FTR3, the average seed production at LT (25/15°C) and HT (35/25°C) was estimated at about 12556 seeds plant^{-1}, which was 72% higher than the average seed production of FTR11 (7285 seeds plant^{-1}) (Fig. 2). Similarly, the average biomass of FTR3 at LT (25/15°C) and HT (35/25°C) was 89% greater than the average biomass of FTR11 (Fig. 3).

As mentioned previously, FTR11 was previously categorized as GR due to the missense mutation (Pro > Leu) [12]. The reduced ability of FTR11 for seed and biomass production compared with FTR3 grown in a similar environmental condition indicates the fitness penalty associated with the missense mutation (Pro > Leu) that occurred in the conserved region of the 5-enolpyruvylshikimate-3-phosphate (EPSP) gene. Only two Pro > Leu mutation cases have been recorded with no affiliated fitness cost [29,30]; therefore, this could be the first case of fitness cost associated this the Pro > Leu mutation in *C. virgata*. The presence of a rare mutation (Pro > Leu) [12] and the indication of fitness penalty in FTR11 suggests that further research effort is needed to estimate the fitness costs and the eco-evolutionary consequences of this particular population in Australian agroecosystems [31].

Germination experiment

Seed lot 1 (SL1) and seed lot 2 (SL2) were collected at a 14 days interval followed by immediate incubation at 30/20°C to estimate the germination pattern of FTR3 and FTR11 matured at LT (25/15°C) and HT (35/25°C). No evident difference was observed in the germination pattern of FTR3 and FTR11 between SL1 and SL2 matured at both temperature regimes (Fig. 4). A gradual increment in germination was observed over time for FTR3 and FTR11 matured at LT (25/15°C) and HT (35/25°C) (Fig. 4).

FTR3 and FTR11 acquired FCG in a shorter time for plants matured at HT (35/25°C) than LT (25/15°C), and this was more evident in SL2, thus plants matured at HT (35/25°C) completed the germination cycle more quickly (Fig. 4; Table 2). FTR3 and FTR11 reached FCG within 28 days of incubation for plants matured at HT (35/25°C), while 49 days of incubation was required for plants matured at the LT (25/15°C) by FTR3 and FTR11 (Fig. 4). The difference in the number of days required for 50% germination (T_{50}) is noticeable between FTR3 and FTR11 for both SL1 and SL2, in plants matured under HT (35/25°C) and LT (25/15°C) (Table 2.) The SL1 of FTR3 and FTR11 acquired 'T_{50}' in 24 days of incubation for plants matured at LT (25/15°C), which is 13 days later when compared with 'T_{50}' attained for plants matured at HT (35/25°C) (Table 2). Similarly, the SL2 of FTR3 and FTR11 reached 'T_{50}' after 20 and 29 days of incubation for the plants matured at LT (25/15°C), respectively, whereas, for plants matured at HT (35/25°C), FTR3 took 7 days of incubation and FTR11 required 9 days of incubation for 'T_{50}' (Table 2).

Table 2

Germination parameters estimated using three-parameter sigmoidal model: $f = a/[1 + \left(\right)^{b}$, of two *Chloris virgata* populations (FTR3 and FTR11) at 30/20°C with 12 h/12 h photoperiod. Populations completed their lifecycle at two alternating temperature regimes: 25/15°C, low temperature, and 35/25°C, high temperature. Seed lot 1 and Seed lot 2 were collected at 14 days intervals.

Seed lot and Populations	Temperature regimes [b]	Parameter estimates (± standard error of mean)			
		a [a]	*b* [a]	T_{50} [a]	R^2 [a]
Seed lot 1					
FTR3	LT	97 (2.1)	3.0 (0.5)	23.8 (0.6)	0.99
FTR3	HT	92 (2.7)	6.9 (1.2)	12.8 (1.3)	0.97
FTR11	LT	93 (1.6)	5.0 (0.5)	24.2 (0.6)	0.99
FTR11	HT	92 (2.5)	6.7 (1.1)	13.2 (1.1)	0.97
Seed lot 2					
FTR3	LT	99 (3.7)	6.4 (1.3)	20.4 (1.5)	0.97
FTR3	HT	93 (2.4)	3.8 (0.9)	7.3 (0.9)	0.96
FTR11	LT	95 (1.1)	5.1 (0.3)	28.9 (0.4)	0.99
FTR11	HT	92 (2.0)	4.6 (0.7)	9.4 (0.8)	0.98

[a] *'a'*, upper limit of a curve; *'b'*, slope of a curve; 'T_{50}', incubation days required to attain 50% germination; 'R^2', coefficient of determination of a goodness of fit.

[b] LT, low temperature: 25/15°C; HT, high temperature: 35/25°C.

Seed maturing at HT (35/25°C) released dormancy faster when compared with seeds maturing at LT (25/15°C), indicating that populations that attain physiological maturity in January-February in Queensland would germinate quickly compared to populations maturing in September-October. Consequently, late winter germinating cohorts will be more problematic as they will have an extended germination period and could escape pre-emergence herbicide applications in spring-planted crops. As mentioned previously, the germination test was conducted immediately after seed collection for SL1 and SL2. Although germination initiated within 7 days of incubation for plants matured at LT (25/15°C) and HT (35/25°C), seeds of FTR3 and FTR11 required at least 28 days to complete the germination cycle. Hence, the signs of primary dormancy were evident. This finding is consistent with the previous study in which, Boutsalis et al. (2017) discovered two months of innate dormancy after the maturity of *C. virgata*. Despite the geographical and genetic dissimilarity of FTR3 and FTR11, the trend of germination patterns

remained similar across seed lots and temperature regimes. Therefore, the results of the current study could be used and interpreted similarly across Australia.

The SL1 and SL2 of FTR3 required less time to reach 50% germination (T_{50}) for plants matured at LT (25/15°C) and HT (35/25°C) than FTR11. The average 'T_{50}' of FTR3 across alternating temperature regimes and seed lots was 16 days of incubation as opposed to the average 'T_{50}' of 19 days of incubation for FTR11 (Table 2). Our previous research on the germination response of *C. virgata* to temperature and water stress reported a similar trend [3,10]. The extended germination of FTR11 may indicate a disturbance-induced escape mechanism [an ecological adaptation to avoid weed management operations or any abiotic/biotic stress [32]. FTR11 is a GR population, and extended germination due to glyphosate resistance evolution was previously recorded in *Bassia scoparia* (L.) A. J. Scott [33,34], and *Avena fatua* L. [35].

Data from this study could be used to develop ecologically sustainable multi-tactic weed management protocols and select on-farm agronomic operations to manage this weed species proactively. Results from this study could also aid in generating computer simulation-based population dynamics models, especially for GR populations of *C. virgata*.

Summary

The ability of both populations (FTR3 and FTR11) to produce more seeds at LT (25/15°C) than at HT (35/25°C) indicates that the *C. virgata* populations attaining physiological maturity in late winter or early summer will produce more seeds than those maturing in mid-late summer. Considering the previously recorded occurrence of glyphosate resistance in the FTR11 population and its lower biomass and seed production at both temperature regimes (LT and HT) compared to known GS population FTR3, fitness penalty could be associated with the GR endowing mutation (Pro > Leu at codon 106). However, a thorough investigation is needed to confirm that the glyphosate resistance event endows FTR11 with reduced vegetative and reproductive potential. The estimation of fitness costs associated with mutations conferring herbicide resistance can be used in parametrizing population dynamics models. The tendency of both populations to acquire 50% germination (T50) later when completing their lifecycle in LT (25/15°C) than in HT (35/25°C) suggests the extended germination pattern in late winter or early summer. Results of this study suggest the need for species-site-specific weed management programs for *C. virgata* due to its evolutionary ability.

Materials and Methods

Populations information

Seed collection and production were performed as described by Desai et al. (2020). The seeds of FTR3 (-26.8264, 150.5802) and FTR11 (-27.2935, 151.1283) were collected in 2017 from a wheat-fallow field in Chinchilla, Queensland, and a sorghum field in Cecil Plains, Queensland, respectively. A verbal

permission was obtained from local agronomists for population collection. The secondary author of this study undertook the formal identification and collection of the populations. FTR3 was previously characterized as glyphosate-susceptible (GS), while FTR11 was characterized as target-site glyphosate-resistant (GR) [12].

Vegetative and reproductive growth experiment

The experiment was established in a randomized complete block design (RCBD) with six replications, two populations (FTR3 and FTR11) and two alternating temperature regimes (25/15°C and 35/25°C) at the University of Queensland greenhouse facility, Gatton, Queensland, Australia. Two alternating temperature regimes, 25/15°C (low temperature, LT) and 35/25°C (high temperature, HT), were maintained in naturally-lit greenhouses throughout the experiment. Five seeds were placed on the surface of plastic pots (in the centre) filled with the potting mix (Centenary Landscaping, Mt Ommaney, Queensland) using forceps, and a thin layer of the potting mix was spread over the seeds to attain a consistent depth (0.2 cm). After emergence, plants were thinned to 1 plant/pot.

Plant height, leaf numbers plant^{-1}, and panicle numbers plant^{-1} were measured at a weekly interval after planting up to 13 weeks (91 days); however, the first observations were taken 14 days after planting (DAP). Plant height was measured from the surface of the potting mix to the topmost leaf or panicle of the plant using a measuring scale. Leaf and panicle numbers were counted manually at each data point. At physiological maturity, five panicles plant^{-1} were randomly selected, and each panicle's total number of seeds were counted. The average seed production based on the five panicles was calculated and multiplied by the total number of panicles plant^{-1} to determine seed production plant^{-1}. Shoot biomass of individual plant was obtained by detaching from the base using a sickle, followed by immediate placement in paper bags for oven-drying. All samples were oven-dried at 70°C for 72 hours before recording the final shoot dry biomass.

Germination experiment

A laboratory experiment was carried out at the Queensland Alliance for Agriculture and Food Innovation (QAAFI) weed science laboratory, Gatton, Queensland, Australia (latitude − 27.5551 and longitude 152.3343) in 2021. Both populations, FTR3 and FTR11, were employed in the germination assay, and an RCBD was used. The seeds were collected from the plants grown at the two temperature regimes in the greenhouse at the first shattering event and 14 days after the first shattering event to procure seed lot 1 (SL1) and seed lot 2 (SL2), respectively. These plants were the same as those grown in the *vegetative and reproductive growth experiment*. Seeds were subjected to incubation at 30/20°C with a 12/12 hours light/dark photoperiod immediately after collection to study the germination pattern. The thermal cycle (30/20°C) and photoperiod (12 h/ 12 h light/dark) were chosen as these conditions were identified as ideal for optimum germination of *C. virgata* [14]. Petri dishes (diameter: 92-mm and height: 16-mm) were prepared with two layers of filter paper (Whatman®, Number 1) and moistened with 5 ml of ionized water using a micropipette. Twenty-five seeds of each population per Petri dish were placed, maintaining a uniform distance using forceps. Given the higher viability percentage of black-colored seeds [10], only

such seeds were selected using a desk-mounted LED laboratory magnifier lamp (model no. QM3546, White Label). In addition, the 'seed-pressing technique' was utilized in order to choose only viable seeds [36]. All Petri dishes were placed in resealable plastic bags to ensure minimal evaporation loss throughout the experiment.

The resealable bags were then arranged in the incubator set at 30/20°C temperatures with a 12/12 hours light/dark photoperiod. The incubator was equipped with a data logger (Invensys Eurotherm, 3216 PID temperature controller), fluorescent lamps (Ultralamp ECO-T5, 28W, 1170 mm), and the flush-mounted time clock (Grasslin Uni 45 series timers). Seed germination was monitored weekly throughout the experiment for up to 70 days. Seeds were considered to have germinated upon the emergence of at least 1 mm of the radicle. Germinated seeds were removed using forceps at every data point, and germination counts were recorded. Germination counts were converted into the final cumulative percentage (FCG)

Statistical analyses

Both experiments were conducted in an RCBD with six replications for the *vegetative and reproductive growth experiment* and three replications for the *germination experiment*. The original data set was used as no indication of any severe violation of normality of residuals, and homogeneity of variance was observed in diagnostic plots. FCG, leaf numbers plant^{-1}, panicle numbers plant^{-1}, and plant height data were fitted using a three-parameter sigmoidal model (Eq. 1) (SigmaPlot 14.5 Systas Software Inc., San Jose, California, USA)

$$f = a/\left[1 + \left(\frac{x}{T50}\right)^{b}\right] \textbf{ [1]}$$

Codifications: 'f' is the estimated plant height, leaf, and panicle numbers per plant and final cumulative germination percentage, 'a' is the maximum number of each response variable, 'T_{50}' is the time required to reach 50% of each aforementioned response variables, 'b' is the slope of plant height, leaf and panicle number per plant, and FCG. The coefficient of determination 'R^2' was considered to determine the goodness of fit.

Guidelines required

Chloris virgata populations used in this study were collected following the standard procedures and comply with the University of Queensland institutional guidelines.

Declarations

Contributions

Writing – original draft: H.S.D Writing – review & editing: H.S.D & B.S.C Conceptualization: B.S.C. Data curation and analysis: B.S.C. Funding acquisition: B.S.C. Investigation: B.S.C. Methodology: B.S.C. Supervision: B.S.C. Project administration: B.S.C.

Competing interests

The authors declare no competing interests.

Data availability

Raw data shall be provided upon reasonable request. Please contact corresponding author for raw data.

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Figures

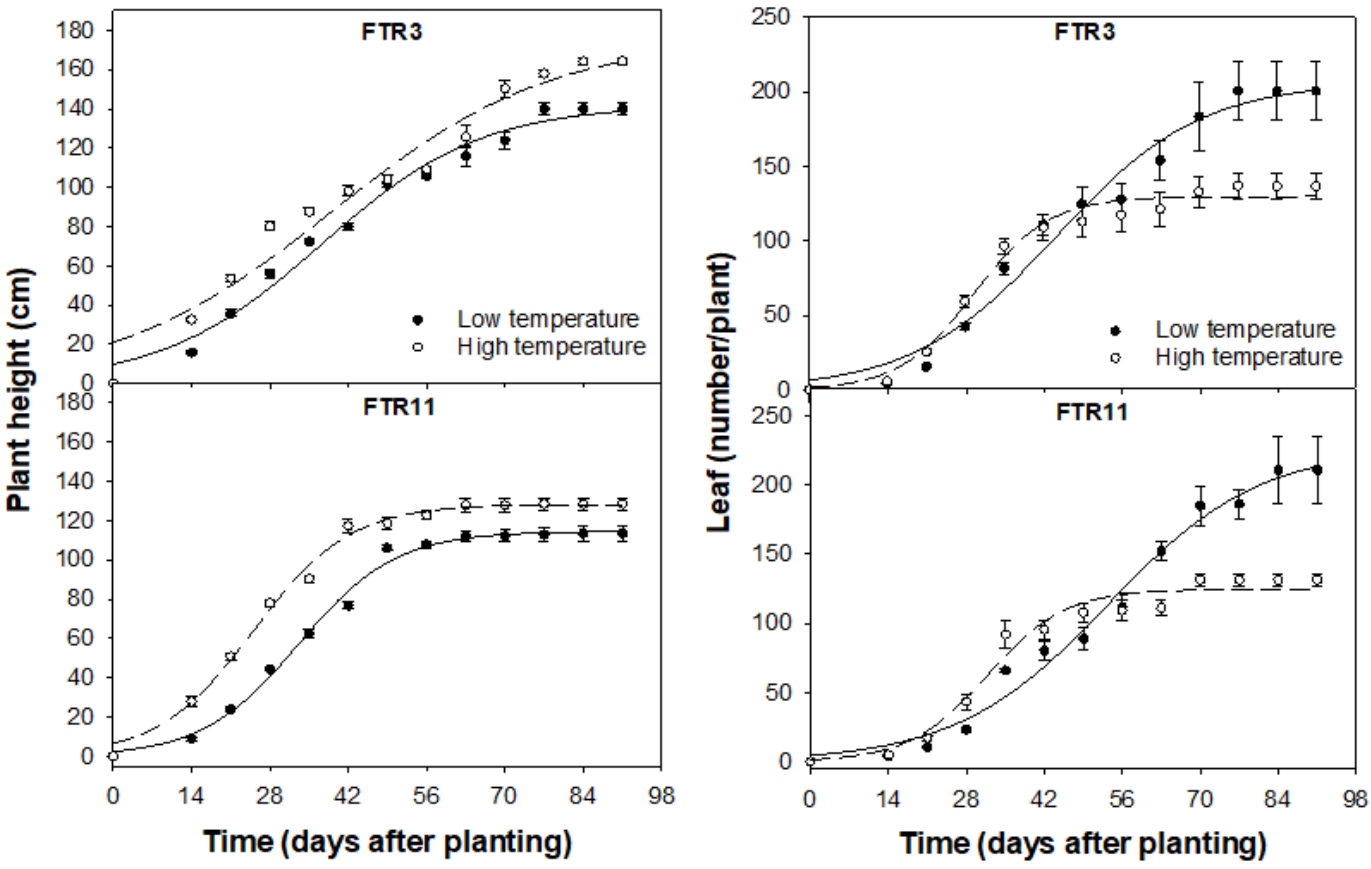

Figure 1

The response of vegetative growth parameters (plant height and leaf number) of two populations of *Chloris virgata* (FTR3 and FTR11) to alternating temperature regimes; 25/15 °C, low temperature, and 35/25 °C, high temperature. Error bars represent the standard error of means.

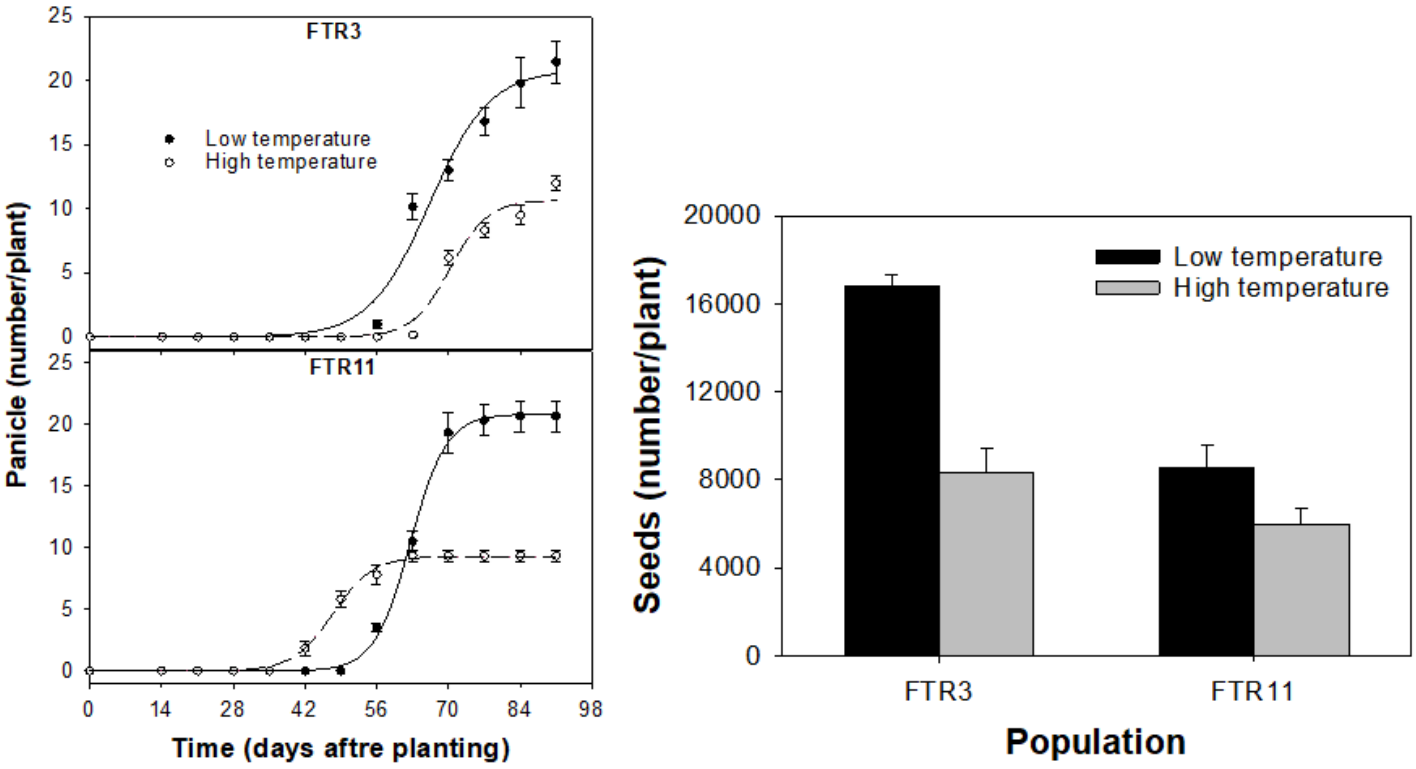

Figure 2

The response of reproductive growth parameters (panicle number and seed production) of two populations of *Chloris virgata* (FTR3 and FTR11) at alternating temperature regimes; 25/15 °C, low temperature, and 35/25 °C, high temperature. Error bars represent the standard error of means

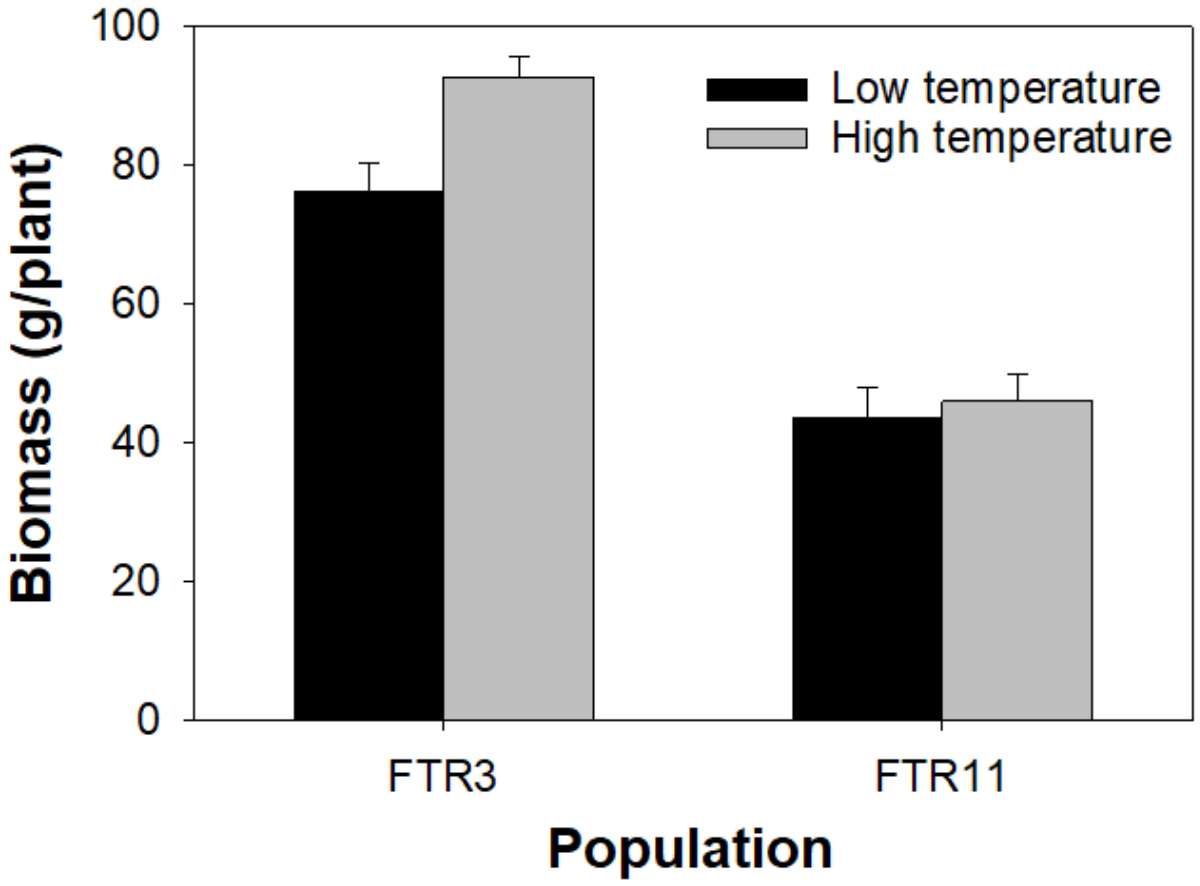

Figure 3

Effect of temperature regimes (25/15 °C, low temperature and 35/25 °C, high temperature) on shoot biomass of two populations of *Chloris virgata* (FTR3 and FTR11). Error bars represent the standard error of means

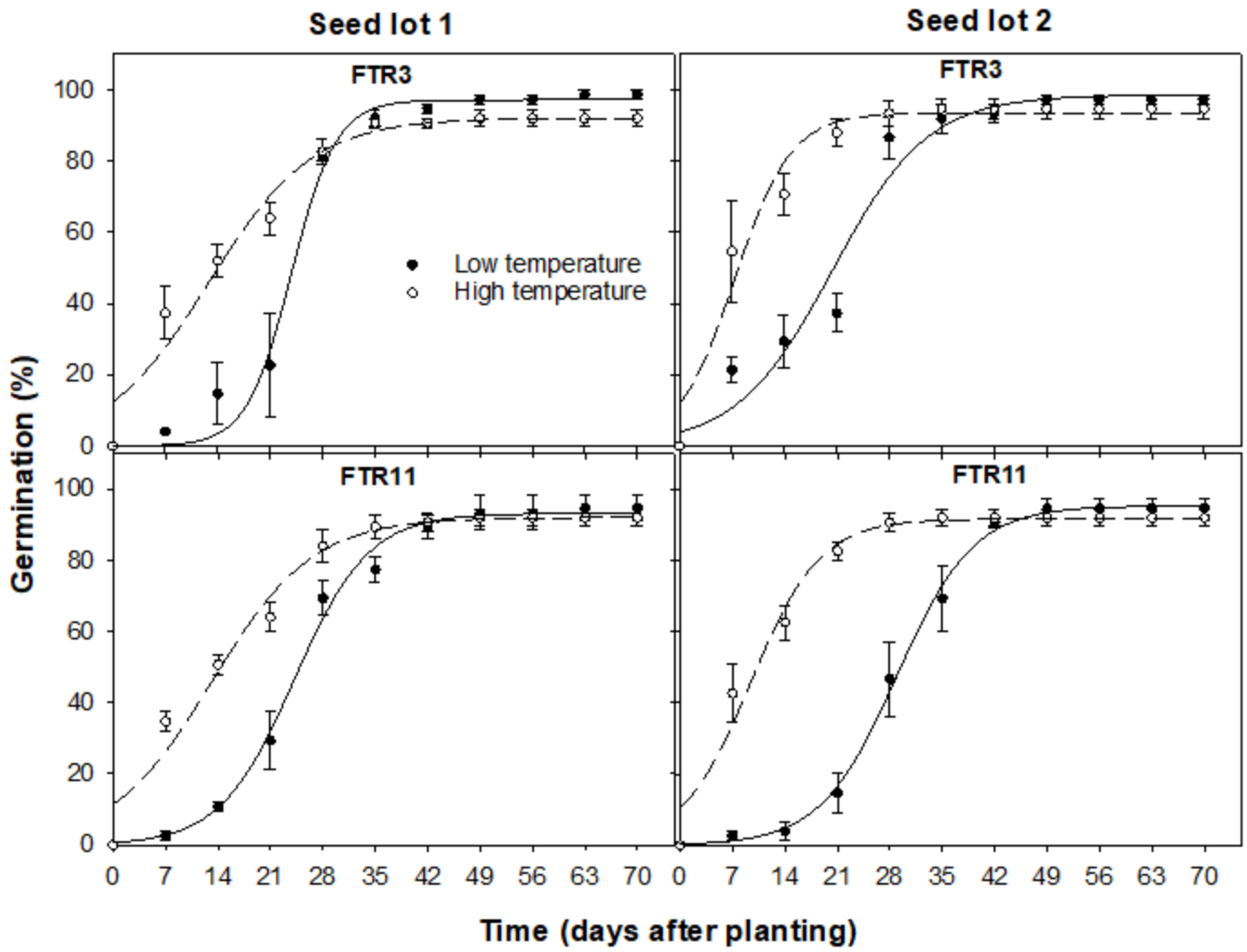

Figure 4

The germination pattern of two populations (FTR3 and FTR11) of *Chloris virgata* incubated for 70 days at 30/20 °C with 12 h/12 h photoperiod, maturing at different alternating temperature regimes (25/15 °C, low temperature, and 35/25 °C, high temperature). Seeds were collected at a 14-d gap between seed lot 1 and seed lot 2. Error bars represent the standard error of means.