Using weed emergence and phenology models to determine critical control windows for winter-grown carinata (*Brassica carinata*)

Research Article

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Abstract

Adoption of the new biofuel crop carinata (*Brassica carinata* A. Braun) in the southeastern United States will largely hinge on sound agronomic recommendations that can be economically incorporated into and are compatible with existing rotations. Timing of weed control is crucial for yield protection and long-term weed seedbank management, but predictive weed emergence models have not been as widely studied in winter crops for this purpose. In this work, we use observed and predicted emergence of a winter annual weed community to create recommendations for timing weed control according to weed and crop phenology progression. Observed emergence timings for four winter annual weed species in North Carolina were used to validate previously published models developed for winter annual weeds in Florida by accounting for temperature and daylength differences, and this approach explained more than 70% of the variability in observed emergence. Emergence of stinking chamomile (*Anthemis cotula* L.) and cutleaf evening primrose (*Oenothera laciniata* Hill.) followed biphasic patterns comparable to wild radish (*Raphanus raphanistrum* L.), which were predicted with previously published models accounting for 82% and 84% of the variation, respectively. Using the predictive models for weed emergence and carinata growth, critical control windows (CCW) were estimated for Clayton, NC, and Jay, FL, according to different planting dates. The results demonstrated how early planting coincided with the emergence of three competitive winter weeds, but early control could also remove a large proportion of the predicted emergence of these species. The framework for how planting timing will affect winter weed emergence and crop growth will be an instructive decision-making tool to help prepare farmers to manage weeds in carinata, but it could also be useful for weed management planning for other winter crops.

Introduction

Carinata (*Brassica carinata* A. Braun; also known as Ethiopian mustard) is an oilseed crop with potential for winter production in subtropical regions such as the southeastern United States (George et al. 2021; Seepaul et al. 2020). Incorporating this crop into existing crop rotations presents ecological and agronomic advantages and provides new market opportunities. Including ground cover over the winter, with cover crops or cash crops, can help to improve soil health and provide habitat for vertebrates and invertebrates by increasing landscape heterogeneity (Dille et al. 2021; Stiles et al. 2021; Tiwari et al. 2021a). Selection of a Brassicaceae crop has been especially attractive to favor pollinator habitat (Eberle et al. 2015; Holzschuh et al. 2013). In the southeastern United States, the underutilized winter season and the market opportunity for oilseeds have stimulated interest in this crop (Adegbeye et al. 2020; Hagos et al. 2020). However, due to the limited number of registered herbicides in carinata, weed management will need to be well timed to meet the expected yields (Ethridge et al. 2021; Leon et al. 2017).

Adoption of carinata by farmers and incorporation into existing crop rotations must be preceded by a well-developed plan for cost-effective management. This type of plan might include the use of models defining the critical period of weed control (CPWC), especially considering their proven benefit in other crops (Knezevic et al. 2002). The chief aim of such an approach is to target control efforts to maximize resultant economic returns. However, one limitation of relying on CPWC in summer annual crops is that summer annual weeds may outpace the crop, resulting in early escapes, which might threaten herbicide resistance and weed seedbank management (Geddes and Davis 2021). Furthermore, CPWC models implicitly (and incorrectly) assume that weeds will be present at similar densities throughout the CPWC. This issue can be mitigated by integrating CPWC with weed emergence and phenology models (e.g., thermal, hydrothermal). This combined strategy, referred to as critical control windows (CCW), can increase weed control efficacy and efficiency by optimizing weed control, especially when focusing on the growth of weed species driving yield loss (Reinhardt Piskackova et al. 2020b, 2021).

Challenges to using the CPWC in winter crops arise from the extreme variability in planting dates and the extended cold period, which may affect crops (Boote et al. 2021) and weeds differently (Schramski et al. 2021). Especially during winter, the difference in base temperature for growth among species becomes crucial for the CPWC. Thus, if weeds have a lower base temperature than the crop, they may gain competitive height and canopy potential while the crop does not. The duration of this period of differential growth could dramatically change the onset and length of the CPWC (Sans and Masalles 1995).

We propose that evaluating weed emergence of several common weed species throughout winter combined with weed phenology models can help identify key weed species that should drive boundaries of CCW for carinata yield protection. We expect that this approach could be used to create many different management scenarios and strategies based on site-specific planting conditions and variable weed emergence timing. The objective of this work was to use existing emergence and phenology models for weed and crop growth to create a framework for making weed control timing decisions in winter-grown carinata.

Materials and Methods

Aggregation of Models

Winter Weed Emergence
The life-history traits and phenology of winter weeds are less well explored, especially for species present in the U.S. Southeast, which is dominated by summer annual cash crops. While several published studies can be used as references for winter weed emergence patterns (Hill et al. 2014; Werle et al. 2014), the models published in Tiwari et al. (2021b) for common chickweed [*Stellaria media* (L.) Vill.], henbit (*Lamium amplexicaule* L.), and cutleaf evening primrose (*Oenothera laciniata* Hill), with data from Florida, are most appropriate for application in U.S. Southeast winter annual cropping cycles. These models were already developed and validated (Tiwari et al. 2021b); here, we assess their validity for use in North Carolina and apply them to the coordinated framework for defining CCW (Table 1). In creating a management plan for a winter crop, *R. raphanistrum* was considered the "driver" weed species, the species on which economic decisions are usually based, as it is usually considered one of the most competitive weeds in winter cropping systems and a close relative of carinata (Blackshaw et al. 1999; Cheam and Code 1995). Therefore, previously published models for emergence and phenology (Reinhardt Piskackova et al. 2020a) were also included in the framework for finding CCW, as detailed in Reinhardt Piskackova et al. (2021; Table 1).

Critical Period of Weed Control
Currently, there is no CPWC specific to carinata. However, its life cycle, phenology, and growth habit are similar to those of canola/rapeseed (*Brassica napus* L.) (Gesch et al. 2015). Most importantly, both species can be planted in fall or spring and still flower to produce seed; they do not require a vernalization period for seed production. In spring-planted canola in Canada, the CPWC was defined from emergence to 4 to 6 leaves (Martin et al. 2001). In winter rapeseed, the CPWC has also been defined as early vegetative stages (Aghaalikhani and Yaghoobi 2008) or from 6 leaves to bolting (Hamzei et al. 2007). We used these data to define two possible CPWCs for carinata growth scenarios. Early CPWC was mainly based on the models of Aghaalikhani and Yaghoobi

(2008), and late CPWC was based on the models of Hamzei et al. (2007; Table 1; Figure 1).

Crop Growth
Carinata phenology progression was modeled with CROPGRO (Boote et al. 2021). Expected carinata phenology stages in relation to growing degree days (GDD) were also recorded by Tiwari et al. (2021b). These were used to predict CPWC in connection with the weed emergence and phenology models (Table 1).

Validation of Previously Published Models
Throughout the winter season, weed species emergence, arising from the natural seedbank, was used to validate four previously published models. Seedbank emergence timing of stinking chamomile (*Anthemis cotula* L.), *S. media*, *L. amplexicaule*, and *O. laciniata* was quantified throughout the winter in randomly placed quadrats in a bare-ground study from 2018 to 2019 at the Central Crops Research Station in Clayton, NC, USA (35.66°N, 78.49°W) on a site previously under annual cropping systems. These four species typify winter annual cropping systems in North Carolina. While *O. laciniata* can behave as an annual or biennial species, in annual crop systems and especially following a summer crop, the plant is more likely to behave as an annual. The soil was a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kanpludult) with pH 4.5 and 1.5% organic matter. The site was disked in late August as though it were being prepared for a winter crop sowing but was left unplanted. It was important to begin with a uniform seedbed before the time when winter crop planting would occur. A 400-m² area was prepared, and 20 quadrats of 1 m by 2 m were randomly assigned for monitoring emergence.

A HOBO U30 data logger (Onset Computer, Bourne, MA, USA), fitted with 12-bit temperature sensors and ECH20 EC-5 soil moisture sensors, was used to monitor soil temperature and moisture on-site at 5-cm depth every 30 min for the duration of the data collection. The research station also collected rainfall, air temperature, and solar radiation within 300 m of the experiment (Figure 2).

Emerged seedlings were counted and removed at 2-wk intervals without disturbing the soil surface. In the case of large seedlings or highly dense emergence events, glyphosate at 11.9 g ae L^{-1} was applied with a handheld spray bottle after seedling enumeration. When winter weeds had not emerged for at least 3 wk at the end of the spring, data collection on emergence ceased.

Relative cumulative seedling emergence was calculated as a percent of total emergence over the season per quadrat. These probabilities over time were plotted as a function of thermal time as prescribed by previously published equations (Reinhardt Piskackova et al. 2020a; Tiwari et al. 2021b). Thermal time accumulation, measured in GDD, began with the day of soil disturbance according to Equation 1:

$$GDD = \sum_{i=1}^{n} \left(T_{mean} - T_{base} \right) \quad [1]$$

where T_{mean} represented the daily mean soil temperature in C, and T_{base} was the minimum germination temperature for each species. Thermal time was considered zero when the daily average temperature dropped below the base temperature. Base temperatures followed those in Reinhardt Piskackova et al. (2020a) and Tiwari et al. (2021b), where the equations were originally presented. Similarly, daily thermal time was zero when conditions were not within the

Table 1. Coordinated framework for creating critical windows of weed control in carinata.

Model	Species	Data type	Source
CROPGRO phenology model	Carinata	Weather station data	Boote et al. 2021
Weed emergence model	*Oenothera laciniata* *Stellaria media* *Lamium amplexicaule*	Weather station data	Tiwari et al. 2021b
	Raphanus raphanistrum		Reinhardt Piskackova et al. 2020a
Weed phenology models	*Raphanus raphanistrum*	Weed emergence timing and weather station data	Reinhardt Piskackova et al. 2020a
Critical period of weed control	Canola 1–6 leaves	Crop phenology timing	Aghaalikhani and Yaghoobi 2008
	Canola 6 leaves to bolting		Hamzei et al. 2007
Critical control windows		Weed emergence and phenology timing within CPWC	
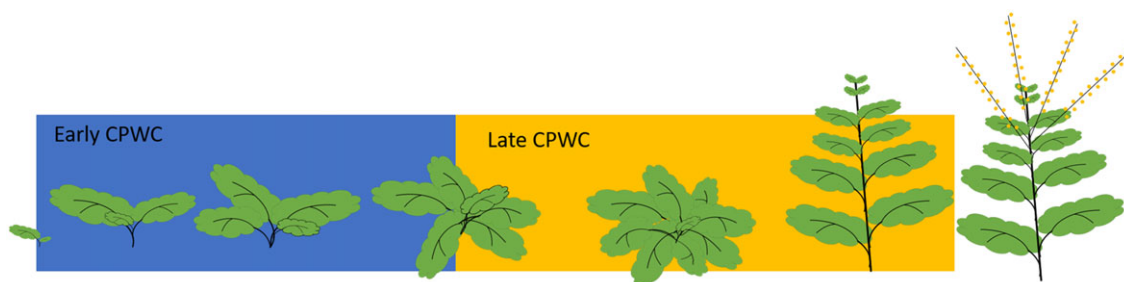
Figure 1. Visual representation of the critical period of weed control (CPWC) adapted from canola to carinata growth stages for prediction of critical control windows (Aghaalikhani and Yaghoobi 2008; Hamzei et al. 2007).

thresholds for other environmental variables, such as when the daylength was shorter than the daylength restriction or the average daily temperature was above the temperature ceiling. The same approach was used for the *R. raphanistrum* phenology models (Reinhardt Piskackova et al. 2020a).

Collected weed emergence data for the four aforementioned species were used to test the three species-specific models from Tiwari et al. (2021b) and the locally created model for *R. raphanistrum*. Models were tested using PROC NLMIX and PROC REG in SAS (SAS Institute, Cary, NC, USA) by running regressions of the predicted model values with the observed values of each species with its respective model. The selection of additional restrictions such as daylength and temperature ceilings and the decision on which models to use for the predictive framework were determined by the lowest root mean-square error (RMSE).

## Results and Discussion

Describing Weed Emergence

Weather from the sites of the validation data (2017 to 2019 in Clayton, NC, USA) and the model data (2018 to 2020, Jay, FL, USA) was close to the 30-yr average from each site (Figure 2). Precipitation was near the 30-year average and coincided with expected weather patterns (Figure 2). There can be high levels of rainfall in September and early October during the hurricane season, which usually ensures adequate soil moisture in fall for seed germination and seedling emergence in the southeastern United States. The environment in which the data were collected to parameterize and validate the models was considered representative of average local conditions and thus could be used to begin to understand the behavior of the studied weed species. Most

importantly, the thermal time models are most appropriate where water is not a limiting factor, and the site data from the years evaluated support that it was not.

Of the four weeds for which emergence was tracked through winter in North Carolina, *A. cotula* and *O. laciniata* began emergence in September immediately after field preparation, while *S. media* and *L. amplexicaule* did not begin emerging until 6 wk later in the fall (Figure 3). While the models for winter weeds from Tiwari et al. (2021b) were all continuous emergence models, the observed pattern of emergence in the present study could be described as having emergence lags at different intervals for separate species, reminiscent of the biphasic pattern previously reported for *R. raphanistrum* in North Carolina (Reinhardt Piskackova et al. 2020a), despite temperatures and water conditions being adequate for emergence (Figure 2). Also, like *R. raphanistrum*, the early-emerging species *A. cotula* and *O. laciniata* initially form basal rosettes.

Considering Daylength and Temperature Ceilings for Winter Weeds

Cumulative weed emergence for the three species-specific models was continuous when the thermal time was used, but other environmental factors possibly influencing emergence were not included in the original models. In North Carolina, *L. amplexicaule* and *S. media* did not emerge until later in the fall, coinciding with the time that Florida emergence observations began after carinata planting (Tiwari et al. 2021b). Before validations with equations from Tiwari et al. (2021b) were run, variations in soil moisture, temperature, and daylength between the two locations were all considered. As the moisture levels were comparable between sites and generally ample (Figure 2), annual patterns of temperature and
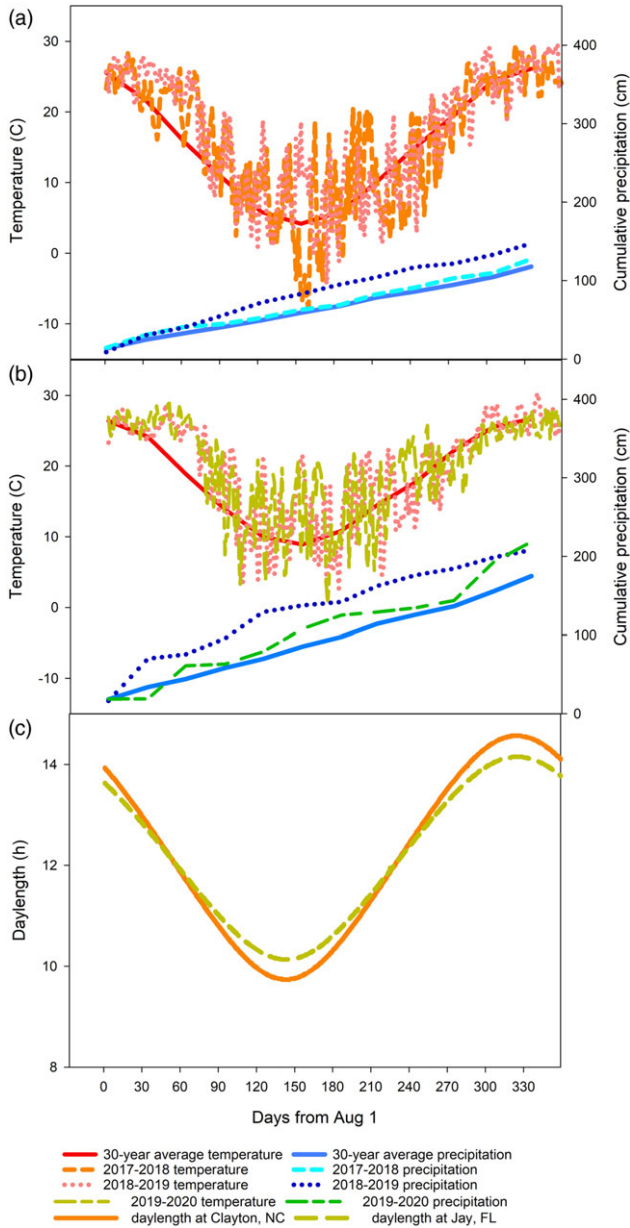
Figure 2. Environmental conditions in Clayton, NC, USA, for 2017–2019 (A) and Jay, FL, USA, for 2018–2020 (B) and daylength patterns in each location (C).

Table 2. Root mean-square error from iterations of temperature ceilings and daylength restrictions using the model from Tiwari et al. (2021b) for *Oenothera laciniata* and observations from Clayton, NC, USA.

		Temperature ceiling C			
		None	15	20	25
Daylength restriction h	None	0.1595	0.2930	0.2756	0.2457
	9.75	0.1595	0.2934	0.2752	0.2452
	10	0.1594	0.3065	0.2797	0.2411
	10.25	0.1592	0.3163	0.2927	0.2434
	10.5	0.1591	0.3210	0.3092	0.2577
	10.75	0.1591	0.3229	0.3204	0.2870
	11	0.1591	0.3242	0.3236	0.3083
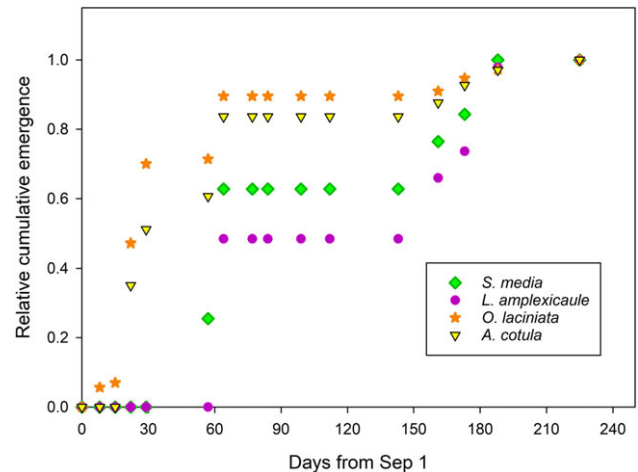
Figure 3. Emergence pattern in Clayton, NC, for four winter annual weed species (*Stellaria media*, *Lamium amplexicaule*, *Oenothera laciniata*, *Anthemis cotula*) in 2019–2020.

daylength seemed to be more plausible determinants of emergence. If the plants did not emerge in both locations until later in the fall, could this be the result of a similar drop in temperature? Alternatively, if plants stopped emerging in one location through the winter while still emerging in the other, could it be due to a difference in daylength? Testing several temperature ceilings and daylengths iteratively (Tables 2–4), we considered new restrictions for calculating GDD for each species while still using the previously published equations.

Oenothera laciniata fit best without any temperature ceiling for GDD, and daylength restrictions did not improve the model greatly, all accounting for 84% of the variation in the data (Table 2). The late emergence of *S. media* seemed to indicate a temperature ceiling (i.e., no emergence at higher temperatures), and setting a temperature restriction at 20 C produced the lowest RMSE values. Model fits varied with daylength restriction values.

Including a daylength restriction value of 10.5 h (i.e., no emergence under shorter days) with the 20 C temperature ceiling to calculate GDD allowed the model to account for 90% of the variation in the data (Table 3). Finally, a temperature ceiling of 20 C combined with the daylength restriction value of 10.25 h provided the lowest RMSE for *L. amplexicaule*, accounting for 87% of the variation in the data (Table 4).

As a negative control, the *R. raphanistrum* biphasic model from Reinhardt Piskackova et al. (2020a) was tested for fit with all observed species emergence. The *R. raphanistrum* model accounted for more than 80% of the variation in *A. cotula* and *O. laciniata* emergence data (Table 5). All species emerged no earlier than *R. raphanistrum*, as predicted by the biphasic model. Considering all five species as a potential weed community in carinata, the first emerging species will influence management decisions the most. The emergence of *A. cotula*, *O. laciniata*, and *R. raphanistrum* will be the species of concern until late October, when *S. media* and *L. amplexicaule* emergence begins (Figure 4A and B).

Using Weed Emergence and Phenology for Decision Making

Planting date can affect the rate of growth in the crop, especially for a crop growing through winter (Begna and Angadi 2016). As carinata is expected to be planted from Florida to North Carolina, we

Table 3. Root mean-square error from iterations of temperature ceilings and daylength restrictions using model from Tiwari et al. (2021b) for *S. media* and observations from Clayton, NC, USA.

		Temperature ceiling C			
		None	15	20	25
Daylength restriction h	None	0.3191	0.2013	0.1547	0.1655
	9.75	0.3191	0.2006	0.1546	0.1655
	10	0.3191	0.1783	0.1492	0.1651
	10.25	0.3191	0.1856	0.1357	0.1644
	10.5	0.3191	0.2502	0.1022	0.1621
	10.75	0.3191	0.2818	0.1645	0.1576
	11	0.3191	0.3311	0.2930	0.1552

Table 4. Root mean-square error from iterations of temperature ceilings and daylength restrictions using model from Tiwari et al. (2021b) for *Lamium amplexicaule* and observations from Clayton, NC, USA.

		Temperature ceiling C			
		None	15	20	25
Daylength restriction h	None	0.2834	0.1920	0.1841	0.1955
	9.75	0.2834	0.1876	0.1821	0.1950
	10	0.2835	0.1551	0.1507	0.1858
	10.25	0.2836	0.1827	0.1298	0.1768
	10.5	0.2837	0.2287	0.1392	0.1644
	10.75	0.2841	0.2564	0.2146	0.1655
	11	0.2847	0.2961	0.2748	0.1953

Table 5. Observations of fitness of four winter annual weed species in Clayton, NC, USA, using biphasic model from Reinhardt Piskackova et al. (2020a).

	R^2	RMSE[a]
Anthemis cotula	0.74	0.1846
Oenothera laciniata	0.81	0.1553
Stellaria media	0.73	0.1991
Lamium amplexicaule	0.63	0.2224

[a]RMSE, root mean-square error.

have used the soil temperature data from both field stations to run simulations of these models to demonstrate their use for decision making (Figure 4). Because the CPWC is based on crop phenology, a delayed planting date will also affect the length of time carinata is in a less-competitive vegetative state (Figure 4E and F). Less thermal time accumulation in the northern latitudes also means that carinata planted in North Carolina will have a longer vulnerable period than in Florida, if planting is delayed. However, the rate of weed growth, and hence controllability, is seldom considered during CPWC or other economic threshold models (Werner et al. 2000). Using *R. raphanistrum* emergence and phenology models, the risk of control can also be elicited.

We will use Figure 4 to illustrate several scenarios. In North Carolina, if carinata is planted promptly on September 1 (4E), the CPWC defined by either Aghaalikhani and Yaghoobi (2008; first CPWC, blue) or Hamzei et al. (2007; second CPWC, yellow) is very short but will coincide with the largest portion of *R. raphanistrum* emergence and rapid growth. Up to 50% of emergence will occur before October 15 (the second CPWC, yellow), and 10% of emerged individuals will be at the 10-cm rosette stage (Figure 4A and C). Additionally, 10% of the earliest-emerged weeds (30th

percentile of emergence) could be flowering before the end of the year, with a greater risk of replenishing the weed seedbank and competing with the crop. Waiting to plant carinata until October 1 may avoid 50% of *R. raphanistrum* emergence; however, the growth of *R. raphanistrum* that emerged in October may still outpace control measures if one waits for the CPWC to begin, as seen in Figure 4C: 10% of the weeds that emerge on October 1 will have reached the 10-cm rosette stage before the beginning of the first CPWC (blue). Furthermore, if a farmer used the later CPWC from 8-leaf to bolting (yellow) in any planting date up to October 15, more than 10% of emerged plants will be larger than 10-cm rosettes, and escapes would be more likely. Increased emergence of weed species like *S. media* and *L. amplexicaule* is possible when planting after October 15. Still, the majority of R. raphanistrum plants could be eliminated before planting. The growth rate of any late-emerging individuals would have slowed enough, making effective control more likely within the first CPWC (Figure 4A, C, and E).

Considering the Weed Community for Control Decisions

Successful weed control should consider the difference in phenological development of weeds within a community context. However, weed control design might need a prioritization of species based on their economic importance or difficulty to control (Walker and Oliver 2008). Our results demonstrated that, because common winter weeds emerge at different times, planting timing may result in various weed communities that must be managed. In North Carolina, *R. raphanistrum*, *O. laciniata*, and *A. cotula* emerge considerably earlier than *S. media* and *L. amplexicaule*, but in Florida, emergence in November included basal rosette species and *S. media* and *L. amplexicaule* (Tiwari et al. 2021b). Soil disturbance timing will affect community assemblage but not necessarily the emergence pattern, so delayed planting can eliminate a large portion of the seasonal seedling emergence (Cordeau et al. 2017; Sans and Masalles 1995). In North Carolina, delaying planting to October may avoid nearly 60% of *R. raphanistrum* and the other basal rosette species (Figure 4A), simplifying control and reducing the risk of yield loss. However, in Florida, October planting will result in a lot of weed seedling emergence during the CPWC (Figure 4B and F). Coordinating multiple weed emergence models can help determine which weeds are most likely to emerge at the time of planting, as also demonstrated in summer annual weed emergence patterns in the northeastern United States (Meyers et al. 2004). A further evaluation of which weeds are the most troublesome could permit delaying planting or using extra precautions against a particular weed according to decision timing. Various herbicides may be recommended based on the expected weed community composition.

Considering Weed Growth and Crop Growth Separately

Carinata growth has a base temperature of 5 C (Boote et al. 2021), as do many winter annual weeds (Hill et al. 2014); however, the number of GDD required for carinata to flower compared with *R. raphanistrum* is different (Reinhardt Piskackova et al. 2020a). Carinata planted on September 15 in North Carolina would be in the rosette stage, while populations of *R. raphanistrum* that emerged at the same time as the crop can have a significant proportion of flowering individuals (Figure 4C and E). Emergence models are insufficient to determine when weeds would compete with the crop, although weeds with a lower base temperature than the crop will pose a greater risk of outpacing the crop during
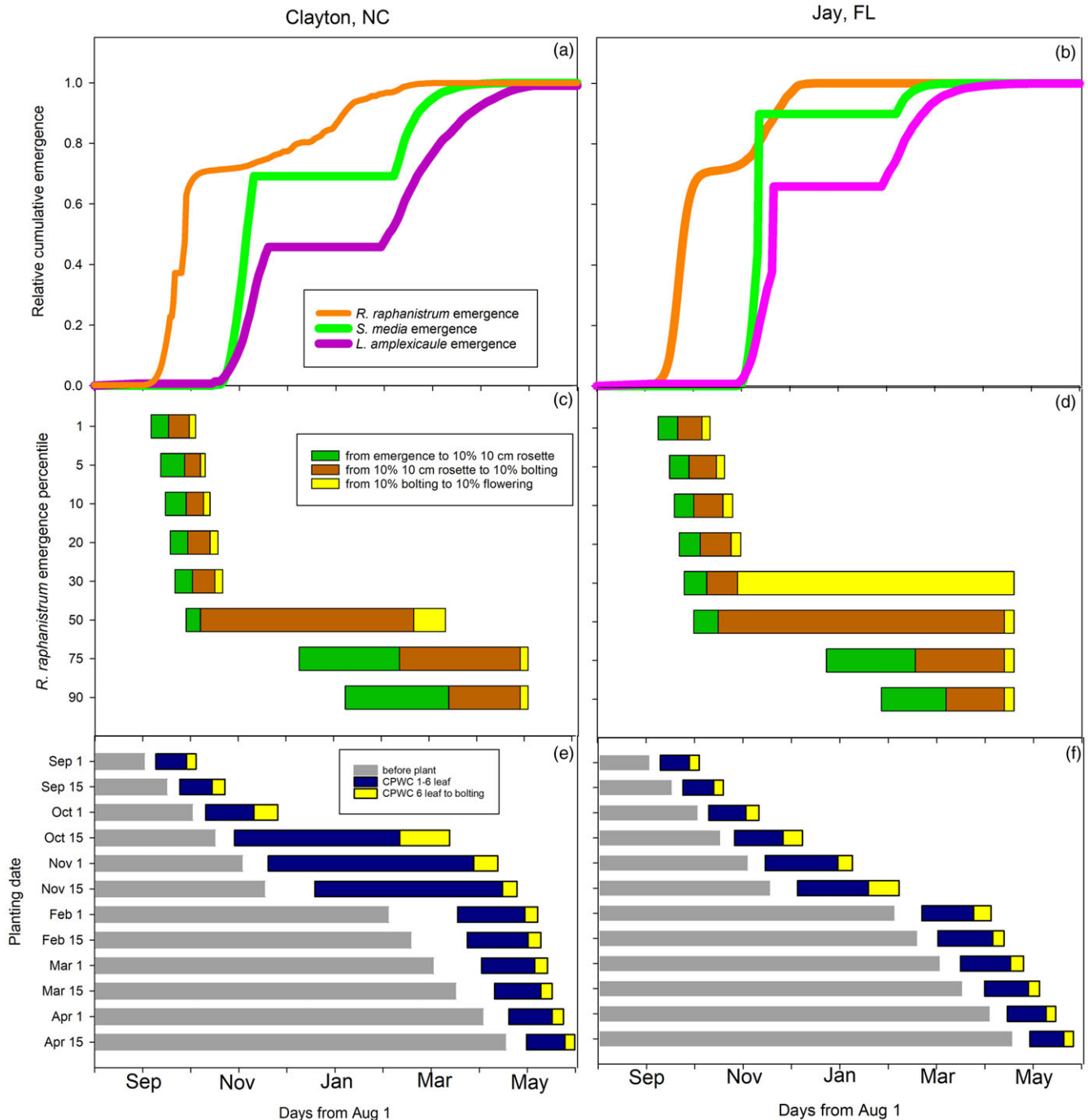
Figure 4. Using weed emergence and phenology models to decide weed control timing simulated using predictive models and soil temperature data from 2018 to 2019 in Clayton, NC, USA (left) and Jay, FL, USA (right). Predicted weed emergence in (A) Clayton and (B) Jay of *Oenothera laciniata*, *Anthemis cotula*, and *Raphanus raphanistrum* (orange, all three species predicted with one model according to validation), *Stellaria media* (green), *Lamium amplexicaule* (purple). Predicted phenology windows for different cohorts of driver species *R. raphanistrum* using phenology models from (Reinhardt Piskackova et al. 2020b) in (C) Clayton and (D) Jay. Cohorts of emergence were determined by using different emergence percentiles from the *R. raphanistrum* emergence model (seen in A and B). Predicted critical period of weed control (CPWC) for carinata at different planting timings at (E) Clayton and (F) Jay.

winter. Also, late-emerging *R. raphanistrum* in Florida that occurs after the CPWC, while not necessarily a threat to the crop through competition, may flower with carinata and risk seed contamination or further additions to the weed seedbank (Figure 4D and F). Therefore, weed phenology models can play an important role in complementing emergence models and CPWC to determine weed control timing and assess crop risk

beyond economic thresholds of competition while considering weed resistance management and harvest purity.

Challenges of CPWC in Winter Crops

The CPWC starts after an early phase when weed growth could happen without interfering with the crop, for example, when the

target yield is still attainable (Knezevic et al. 2002). When the base temperature for weed growth is lower than the one for the crop, the beginning of CPWC is subject to question for fall-planted crops, especially in instances of late planting and slow crop establishment. For summer crops, weeds may be controllable if one waits until the later limit of the CPWC. However, in winter crops, the growth period could be longer than expected (Begna and Angadi 2016) and give much more opportunity for weed growth beyond that which could be managed. Weed emergence and phenology progression can still be rapid through the extended vulnerable period for crops. In North Carolina, while delaying planting to October could reduce the competition from early-emerging species (such as *R. raphanistrum*, *O. laciniata*, and *A. cotula*), delay to October 15 results in a lengthy CPWC during which *S. media* and *L. amplexicaule* are at the height of emergence (Figure 4A and E). Because cold weather and snow cover are limitations for plant growth, the variability in winter weather provides a much more heterogeneous landscape of growth conditions for crop and weed growth across geographic regions. It is important to remember that the slow growth of the crop during winter months, indicated by the lengthened CPWC, has an increased risk of mortality and stand loss (Begna and Angadi 2016; Noia-Junior et al. 2022; Seepaul et al. 2020). Delayed planting for the sake of weed emergence avoidance should not be undertaken at the risk of optimal growing conditions for the crop. Although we encourage using these models using real-time weather data to attempt reduced pesticide use and optimize weed control timing, there are clear trade-offs between weed avoidance and crop vigor (Figure 4E and F).

Building on the idea of CCW approaches that use weed emergence and phenology models to time control actions, two major conclusions can be made from this assessment. First, integrating emergence and phenology models for a weed community provides a more realistic picture than single species emergence models used in isolation, and can visually represent the timing available for control based on the local climate. Second, the framework for using emergence and phenology models in coordination for weeds and crops has been shown to be especially relevant for winter crops and winter weeds due to the drastic effects that delayed planting can have on the weed spectrum (Figure 4A and B) and rate of weed growth (Figure 4C and D) compared with crop growth (Figure 4E and F). We currently have a limited understanding of winter weed biology timing, and great diversity in weed survival strategies exists. Still, exploration in this area could be especially important for winter crop management and the expected future favorability toward winter soil cover and diversified crop rotations (USDA 2021). Based on the projections of weed emergence and growth, farmers might be able to find an optimal time to plant. However, even if planting cannot happen at that time, the model may help anticipate timings that allow effective control and yield protection. This work demonstrates the need for more detailed investigations to understand weed biology and the development of models considering weeds as a community in agroecosystems. If increased cropping system diversity in agriculture landscapes is desired, it will be necessary to explore and characterize weed community dynamics in winter cropping systems to help inform decision making by farmers so they are more knowledgeable and confident about the diversification of their crop rotations.

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