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Developing a Localized Emergence Model of *Echinochloa crus-galli* to Predict Early Post-Herbicide Effectiveness in Maize

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Abstract: In order to achieve integrated weed management, precision timing is just as important an aspect to consider as spatial precision: the stage of the plant at the time of action will impact its successful control or survivability and thus the selection pressure for herbicide resistance. Weed emergence models are one aspect of this precision timing, but they are yet underutilized. One critique has been that models based on bare ground emergence are not always validated with emergence in the crop, and yet also residual herbicides and their timing may also affect the model. In this work, we compare emergence of Echinochloa crus-galli on bare ground and in maize and the impact of early post-residual herbicides at several timings. Experiments on bare ground and in maize were set in Prague, Czech Republic, in 2021, 2022, and 2023. Bare-ground quadrats of 0.25 m^2 were randomly assigned in a space of 100 m^2. Maize plot treatments of four herbicides at each of five timings were assigned in a randomized complete block design (dimethenamid-P at 1008 g ai ha^{-1}, pethoxamid at 1200 g ai ha^{-1}, isoxaflutole at 96 g ai ha^{-1}, and mesotrione at 480 g ai ha^{-1}). Three 0.25 m^2 quadrats were enumerated in each plot from first emergence to full canopy closure (May to July). Model fit to emergence from the bare-ground plots using thermal time with a base temperature of 10 °C resulted in an AIC of −494. The bare-ground model was validated with emergence from the nontreated control plots in maize in 2022 and 2023, which accounted for over 85% of the variability in observed emergence. At canopy closure, total emergence since herbicide application was affected by herbicide and application timing. All herbicides at all timings reduced the emergence after application except for mesotrione. When beginning thermal time from the day of application, the emergence pattern after mesotrione application at all timings could be modeled with a single equation. *E. crus-galli* had a reliable emergence pattern within a local population; the predictive model created using bare-ground plots adequately predicted emergence in maize. This information can be used to time herbicides to coincide with the most effective moment in the flush in areas where *E. crus-galli* is the driver weed species.

Keywords: predictive model applications; residual herbicides; precision timing; integrated weed management

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1. Introduction

Echinochloa crus-galli (L.) P. Beauv. is a weed of economic concern not just regionally but in many arable landscapes across the world [1,2]. It can be particularly difficult to control in cereal crops due to the necessary specificity in herbicide selection, quick root entanglement to evade mechanical weeding, and even visual similarity in hand-weeding [3]. In all forms of control, whether chemical or mechanical, the timing of the action will ultimately determine its success [4,5].

One characteristic that may contribute to this species' success may be its genetic plasticity, which allows it to locally adapt to climatic regions despite being considered a thermophilic weed [6]. The species exhibits the typical dormancy cycle of summer annual seeds, where dormancy termination requires moist, warm conditions following a period of cold stratification; however, the rate of dormancy termination may be different between primary and secondary dormant seeds [7] Even so, individual populations of *E. crus-galli* have shown a regular pattern of emergence that can be predicted using thermal or hydrothermal models [8–10].

While precisely timing herbicide application is one important practical use of these models [11,12], they could also be used to determine the potential for further emergence later in the growing season and the effectiveness of herbicides to reduce that potential [13,14]. For many herbicides, their expected efficacy is documented according to species, growth stages, and environmental factors and their expected residual activity according to soil characteristics [15,16], but the effect of those herbicides on the pattern of emergence afterwards is less documented [17]. It is true that for a crop like maize, which has a short critical period of weed control, the late emergence of weeds may not pose yield-threatening competition [18], yet late-emerging weeds are more likely to be selected for herbicide resistance because they are exposed to sublethal rates of herbicides and could flower to increase the soil seedbank [19]. Therefore, the influence of an herbicide and application timing on subsequent weed emergence flushes is of interest. If these late individuals do need to be managed in some way, it will be imperative to know how quickly and how densely they begin to emerge again. Meanwhile, it is even more difficult to detect and scout for weeds emerging beneath the crop canopy, especially via aerial imagery, until there is significant effect on the surrounding crop; in these difficult-to-see areas, predictive models for the re-emergence of weeds are even more practical.

In this work, we used bare-ground emergence of a local population of *E. crus-galli* to fit a thermal time model and compare that to emergence in a maize crop. Additionally, emergence after different early post-emergence herbicides with a residual effect at different timings were compared regarding the emergence pattern and final density. This can inform the selection and timing of herbicide application for long-term weed-seedbank management.

2. Materials and Methods

2.1. Site Description

Field plots were established from 2021 to 2023 in Prague, Czech Republic, Central Europe (300 m a.s.l.; GPS: 50°7′ N, 14°22′ E). This region is characterized by a temperate climate (annual average air temperature of around 9 °C and total average annual precipitation of nearly 500 mm). The soil of the experimental fields was classified as a Haplic Chernozem consisting of 19% clay, 26% sand, and 55% silt (silt loam soil) with a sorption capacity of 210 $mmol^{(+)}$/kg and a soil pH_{KCl} of 7.3. Nutrient content in the top layer (0–25 cm) was as follows: 2.7 μg/g N, 136 μg/g P, 289 μg g^{-1} K, 142 μg/g Mg, and 6858 μg/g Ca; C_{OX} (oxidizable carbon): 2.0%. A block of bare-ground observational quadrats and a small plot maize trial were set within 100 m of each other each year. Their experimental designs follow.

2.2. Bare Ground Observational Plots

Within an area of 100 m^2, nine 0.25 m^2 observational plots (six for model fitting and three for validation) were established each spring. The area was prepared as usual for spring planting in April using a rotary harrow to a depth of 15 cm. New seedling emergence was counted every week, ending when the emergence of new seedlings accounted for less than 5% of the total for 3 weeks (usually before the end of July). Emerged seedlings were counted and removed without soil surface disturbance. The area was not pre-sown but maintained a natural seedbank. Even so, the total emergence density was well over 100 plants of *E. crus-galli* m^{-2}, which provided an adequate density in the small plots for modeling the pattern (*E. crus-galli* m^{-2}: 2021, 960 ± 433 sd; 2022, 802 ± 526 sd; 2023, 616 ± 469 sd).

2.3. Herbicide Treatments in Maize

In a field within 100 m of the bare-ground observational plots, a small-plot experimental field was planted using the maize variety RGT Feroxxy (FAO 270; SET 1700 °C) 2021–2023. This area was prepared at the same time as the bare-ground area, and maize was planted at the end of April each year (April 22, 28, and 26, respectively). Before soil preparation, urea was applied at 250 kg ha^{-1}. Treatments were assigned in a randomized complete block design (RCBD) with 3 replications to small plots 2.25 m wide by 6.5 m long. Four herbicides were applied at each of five timings, and two plots were left as nontreated controls (NTC) in each replication for a total of 66 experimental units.

The herbicides selected were labeled to control *E. crus-galli*: dimathinamid-P at 1008 g ai ha^{-1} in the emulsifiable concentrate (EC) formulated product sold as Outlook® (BASF AG, Agricultural Products, Carl-Bosch str. 38, Postfach 120 D-67056 Ludwigshafen, DE), pethoxamid at 1200 g ai ha^{-1} in the EC formulated product Somero (Stähler International GmbH&Co.KG, Stade, DE), isoxaflutole at 96 g ai ha^{-1} in the suspension concentrate (SC) formulated product Merlin® Flexx (Bayer Crop Science AG, Monheim, DE), and mesotrione at 480 g ai ha^{-1} in the SC product Callisto® (Syngenta Limited, Fernhurst, GB). This selection included two chloracetamides that inhibit very-long-chain fatty acid synthesis (VLCFA; HRAC 15), dimethenamid and pethoxamid; and two triketones that inhibit 4-hydroxyphenylpyruvate dioxygenase (HPPD; HRAC 27), isoxaflutole and mesotrione. To focus on *E. crus-galli*, broadleaf (dicot) weeds were controlled with dicamba (HRAC 4) at 75 g ai ha^{-1} + tritosulfuron (HRAC 2) at 37.5 g ai ha^{-1}, formulated as Arrat® (BASF AG, Agricultural Products, Ludwigshafen, DE) and recommended adjuvant Mero® (Bayer Crop Science AG, Monheim, DE) at 1 L ha^{-1}.

Five different application timings were tested for each of the four selected herbicides, starting when the maize was at stage BBCH 09 and then each subsequent 5 days. New *Echinochloa crus-galli* plants were counted weekly in three 0.25 m^2 quadrats in every plot from the first emergence after planting to full canopy closure (May through July). At each data recording, the counts from the three quadrats were pooled for total counts per experimental unit. Counted plants in the maize plots were not removed.

2.4. Bare-Ground Validation Plots with Herbicide

Additionally in 2023, six 0.25 m^2 observational plots were established on bare ground for each of the aforementioned four tested herbicides in maize at the first, third, and fifth corresponding timings (12 treatments, 72 observational quadrats). New emergence of *E. crus-galli* plants were counted and removed every week from the time of herbicide application.

2.5. Statistical Analysis and Modeling

In the bare-ground experiments, weekly counts in each quadrat were converted to percentage of cumulative emergence at the conclusion of each season and then plotted over thermal time accumulating from January 1 with a base temperature of 10 °C [4,5]. Average daily temperatures were usually not over 10 °C until April, so accumulation from the time of soil preparation or from January 1 was nearly the same. The growing degree days(GDD) were calculated daily using the following equation:

$$GDD = \sum_{i-1}^{n} (T_{mean} - T_{base}), \quad (1)$$

Data from six of the nine observational quadrats were fit to log-logistic, Gompertz, and Weibull curves using the R studio package drmSeedGerm [20], which also provides fitness parameters. The final equation was chosen by selecting the most parsimonious model considering the lowest root-mean-squared error (RMSE) and the most negative Akaike information criterion (AIC). The best-fit model was tested against the pattern of emergence in the remaining three bare-ground validation plots and the NTCs in maize. If more than 40 plants cumulatively emerged in at least four of the six bare ground quadrats for each of the herbicide treatments, those data were also fit to curves, with GDD accumulating from the day of application. The best-fit curves were validated using corresponding treatments in maize.

An analysis of variance was performed in SAS 9.4 (SAS Institute Inc.; Cary, NC, USA) using proc glm on the final cumulative emergence from the time of herbicide application while considering the year, herbicide, and timing as main effects.

3. Results

3.1. Describing Echinochloa Crus-Galli Emergence without a Crop

Soil disturbance and field preparation always occurred before the end of April; however, *E. crus-galli* emergence usually began toward the end of May. When accumulating GDD from the beginning of the year with a base temperature of 10 °C, emergence in all years followed a consistent pattern. A Gompertz curve with three parameters was the most parsimonious with an AIC of −494 compared to the log-logistic and Weibull curves with AICs of −485 and −460, respectively (Table 1).

Table 1. Fit statistics for bare-ground emergence for different equations.

Curve [a]	AIC	RMSE
Log-logistic	−485	0.089
Gompertz	−494	0.087
Weibull	−460	0.094

[a] Curves fit using package drmSeedGerm in R studio [18].

Therefore, the resulting model for further validation with the NTC used the following Gompertz equation:

$$f(x) = ae^{-e^{-\left(\frac{x-xo}{b}\right)}}, \tag{2}$$

where $f(x)$ represents the predicted relative emergence in values from 0–1 as a function of x or GDD with a base temperature of 10. Other model parameters are constants, where a is the maximum relative cumulative emergence, x_0 is the inflection point, and b adjusts the slope of the curve or rate of emergence at the inflection point.

3.2. Validation of Bare-Ground Model with Nontreated Emergence in Maize

The best-fit curve using three years of bare ground was plotted with each year seperately and with the emergence of the nontreated control quadrats from each year within the maize crop (Figure 1). More variability in emergence was seen within the growing maize crop, but the pattern of emergence was still very close between all years both with and without maize when accounting for GDD. The bare-ground model accounted for over 75% and over 85% of the variation within 2022 and 2023 (Table 2).

Table 2. Fit statistics for emergence from validation quadrats on bare ground and in nontreated maize.

Emergence Validation Dataset	AIC [a]	RMSE [b]	R^2
Other bare-ground quadrats	−469.7	0.112	0.91
NTC [c] 2021	−14.6	0.211	0.62
NTC 2022	−89.3	0.117	0.89
NTC 2023	−120.7	0.084	0.95

[a] AIC is the Akaike information criterion; [b] RMSE is the root-mean-squared error; [c] NTCs refer to the emergence observed in nontreated control plots in maize.

3.3. Effect of Herbicide and Application timing on Echinochloa Crus-Galli Final Emergence

Figure 1 may suggest that the three years of the study were very uniform, but in fact, they were not. In 2021, the weather was particularly cold and wet throughout spring and early summer. The year 2023 had a cold beginning, but between April and July, it had just over half of the recorded precipitation of 2021 (Table 3).

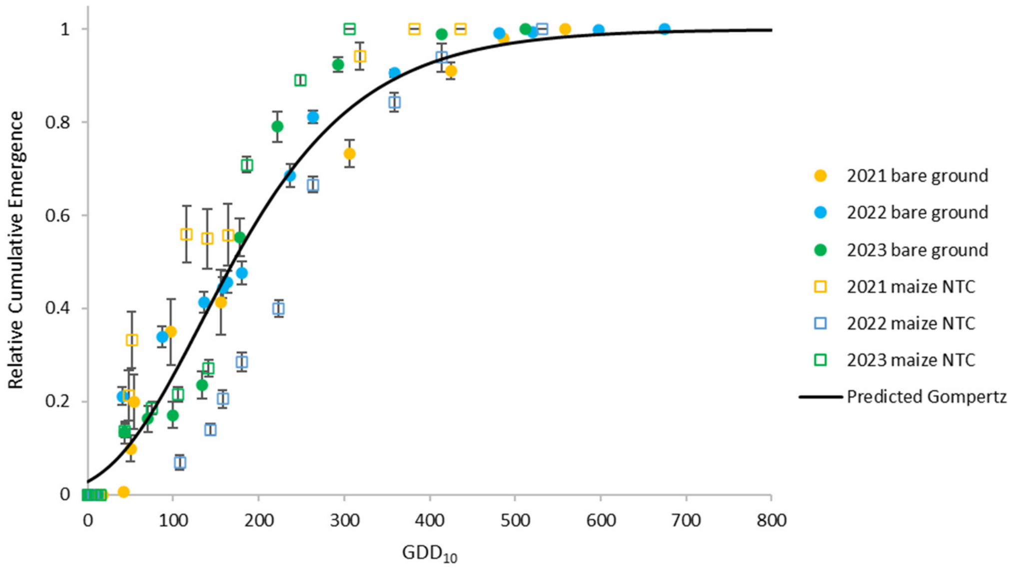

Figure 1. Observed emergence with and without maize in 2021, 2022, and 2023 and the predicted emergence from the fitted Gompertz curve (*predicted relative emergence* $= 1e^{-e^{\left(\frac{-GDD_{10}-132.13}{103.89}\right)}}$). Corresponding years are in the same color: 2021 (yellow), 2022 (blue), and 2023 (green). Bare-ground observations are represented by solid circles, and nontreated maize plots (NTC) are represented by unfilled squares. Error bars represent the standard error of replicates at each observation point.

Table 3. Monthly and cumulative precipitation and growing degree days (GDDs) during the emergence period of *E. crus-galli* (April 15 to July 31).

Month	Monthly Precipitation (mm)			Monthly GDDs [a]		
	2021	2022	2023	2021	2022	2023
April	37.2	40.9	17.6	8	9.5	10
May	88.2	25.4	8.6	42.5	158.5	86.5
June	90.5	129.6	73.1	272.5	274	219.5
July	80.1	74.3	58.1	268	266	296
TOTAL	**296**	**270.2**	**157.4**	**600.5**	**708.5**	**621**

[a] GDD T_{base} = 10 °C.

Despite the differences in soil moisture, the pattern of emergence of *E. crus-galli* in NTC maize and on bare-ground quadrats was very consistent when the thermal time was accounted for. It could be expected that the emergence after the herbicide treatments could be more variably affected by the year, since the herbicide activity was more reliant on available soil moisture and the depth in the soil profile relative to the germinable seed bank. However, the portion of the expected emergence that was growing at the time of each application should first be considered (Figure 2). While the first treatment in all years coincided at about 5% expected emergence, the final application in 2022 coincided with about 50% of expected emergence, while in 2021 and 2023, the applications occurred before 20% of the expected emergence was predicted to have occurred. The point of the curve at the time of herbicide application should proportionally affect the expected total emergence after the application; however, when herbicides have some degree of residual activity, that proportion could be even less.

Given the variability in weather (Table 1) and the subsequent effect on GDD accumulation at the time of herbicide applications (Figure 2), it could be expected that average total emergence would be different by year. In fact, 'year' did have a significant effect on the average total emergence each year when pooled over all treatments (Table 4). While herbicide treatment and application timing were also significant, there was no interaction between year and the main effects of 'herbicide' and 'timing'. For this reason, means were separated only within year by the main effects of 'timing' and 'herbicide' (Table 4). The total emergence in each year was very different, but the magnitude of proportions between application timings is apparent. The averages by timing are pooled over all herbicides, but it can still be seen that some timings reduced total emergence. In 2021, only the last timing had a total reduction significantly different from the NTC, while in 2022, the last three timings had a significant reduction (Table 4). As there was no interaction between the timing and herbicide, we do not have enough information to indicate what combination of herbicide and timing might most reduce emergence.

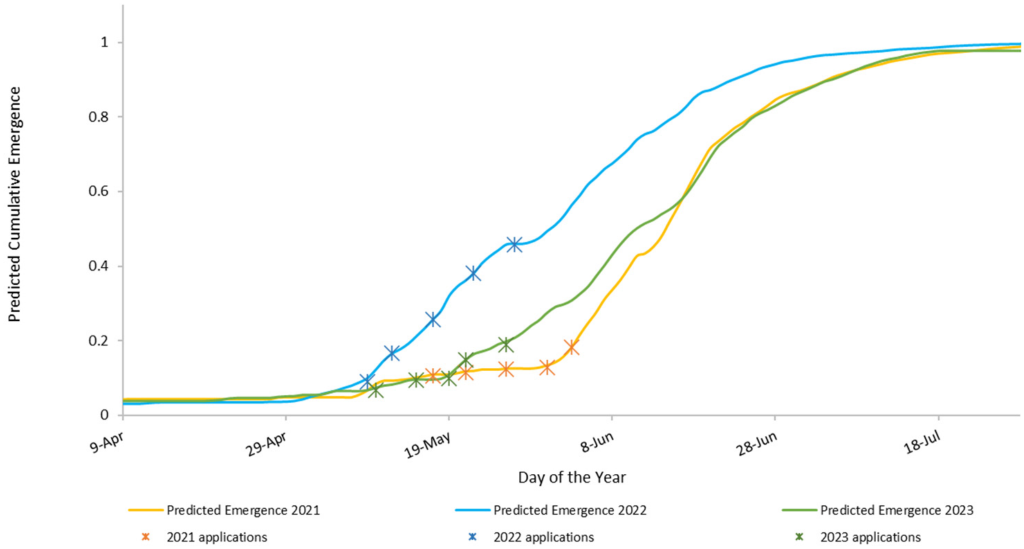

Figure 2. Predicted emergence for each year using the fitted Gompertz curve to GDD_{10} accumulation and the corresponding times of herbicide applications all represented. The fitted Gompertz model ($predicted\ relative\ emergence = 1e^{-e^{\left(\frac{-GDD_{10}-132.13}{103.89}\right)}}$) is shown predicting the percent relative emergence according to the accumulated GDD each day in 2021, 2022, and 2023 using yellow, blue, and green lines, respectively. Each of the five herbicide application timings are represented with starbursts colored corresponding to the year.

3.4. Modeling Emergence Following Application of Mesotrione

In order to attempt a descriptive model of emergence, there must be enough total emergence and time points to effectively create a curve. Three of the four herbicides tested did not accumulate enough emergence per plot to be deemed adequate for transforming to the relative cumulative emergence; when the density was too low, each single plant would be given too much weight in the model. Only emergence following applications of mesotrione resulted in densities adequate for modeling. While unfortunate for modeling distinct patterns, this was not unexpected, as each of the other herbicides have longer residual activity. As most of these herbicides are applied in a tank-mix with other effective herbicides (usually with a different mode of action) that can create some synergism, the emergence of weeds in the field following these herbicides is not often documented.

In 2023, separate bare-ground plots were applied with the four herbicides at the first, third, and fifth treatment times. As was observed in maize, the quadrats treated with dimethenamid-P, pethoxamid, and isoxaflutole did not accumulate enough emergence to model. A model fit to the emergence from the bare-ground quadrats treated with mesotrione and the sets of emergence following each application of mesotrione in maize can be seen in Figure 3.

Table 4. Cumulative *Echinochloa crus-galli* emergence from the time of application according to timing, herbicide, and year. Values represent the average total emergence after application in plants m^{-2} (emergence within all three quadrats combined) pooled over the nonincluded parameters: *by timing* are averages according to timing pooled over all herbicides, *by herbicides* are averages of each herbicide treatment pooled over all timings, and *by year* is the average total emergence pooled over all treatments.

Treatment Main Effects		2021 [a]	2022 [a]	2023 [a]
By timing				
	NTC	84.4 bc	78.0 a	404.6 a
	1	110.3 b	48.8 ab	309.7 ab
	2	172.4 a	72.9 a	250.8 ab
	3	87.3 b	35.3 b	223.1 ab
	4	37.2 cd	29.7 b	175.6 bc
	5	28.8 d	35.5 b	128.0 c
By herbicide				
	NTC	84.4 bc	78.0 ab	404.6 a
	Mesotrione	104.4 ab	54.0 bc	381.9 a
	Isoxaflutole	94.3 bc	32.3 c	260.8 a
	Dimethenamid-P	63.6 c	39.6 c	65.1 b
	Pethoxamid	86.8 bc	52.1 bc	162.1 b
By year [b]				
		86.9 B	47.5 C	234.5 A

[a] Lowercase letters indicate separation according to Tukey's LSD within the column and only within the category 'timing' or 'herbicide'. [b] Uppercase letters indicate separation according to Tukey's LSD only within the category 'year'.

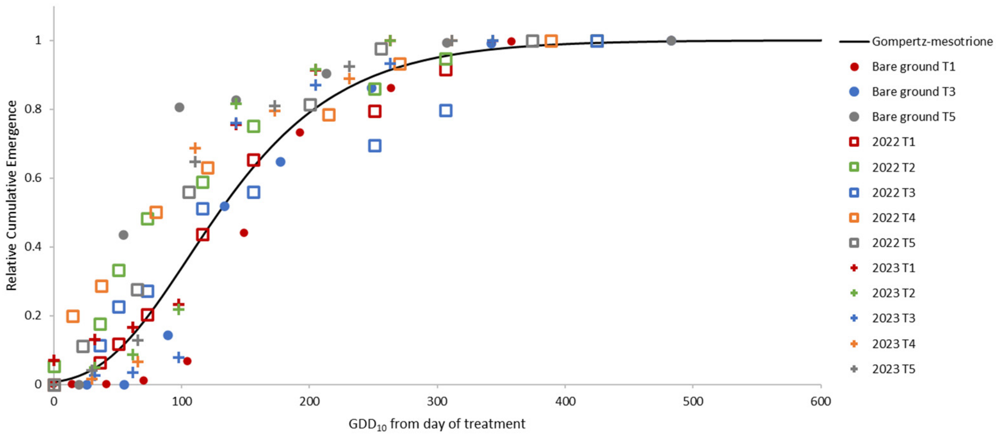

Figure 3. Relative cumulative emergence following mesotrione application in crop and bare-ground treatments from the time of application. The fitted Gompertz model for emergence following application of mesotrione was ($predicted\ relative\ emergence = 1e^{-e^{\left(\frac{-GDD_{10}-105.2}{65.6}\right)}}$). Timings for bare ground were applied on bare ground at the corresponding timings in maize in 2023. Timing 1 was at maize stage BBCH 09 and each subsequent timing 5 days after. Emergence from bare ground is represented by solid circles, from maize in 2022 by squares, and from 2023 by crosses.

4. Discussion

4.1. Does the Bare-Ground Emergence Model Predict Emergence in Corn?

While there are still many more validations and crops in which this could be tested, the model fit to emergence from bare ground does seem to coincide with the same emergence pattern within the crop for this population of *E. crus-galli*. Many weed descriptive models are fit with data from bare-ground plots and/or with artificial seedbanks [6,10,21,22], but not all of these models are validated with weed emergence in the crop. It is therefore valuable to have support that an emergence model fit to data from a natural seedbank in bare ground can successfully predict emergence within the crop canopy, as seen in Figure 1 and supported in Table 2 Further applications of these locally validated models could be used in integrated models for timing weed control based on weed emergence and the critical period of weed control [23]. As demonstrated in Figure 2, herbicide applications that are timed according to crop stage may coincide at different proportions of the yearly expected weed emergence.

4.2. How Does Herbicide Application Affect Subsequent Emergence?

Each of the tested herbicides had different foliar activity (maximal growth stage sufficient for good control of *E. crus-galli*) and soil residual activity for control of new emerging plants. Dimethenamid typically has limited aboveground control of *E. crus-galli*, however, its residual activity is relatively long [24]. In our observations of emergence after all timings of dimethenamid, the average total emergence was less than that of the NTC (Table 4). Pethoxamid usually has lower foliar and residual activity, especially in dry conditions; we found that in the wetter years of 2021 and 2022, the average emergence over all timings was similar to that of the NTC and significantly less than that of the NTC in 2023 (Table 4). The foliar activity of mesotrione and isoxaflutole is usually higher compared to both previously mentioned herbicides. However, the residual activity of mesotrione is relatively short. Meanwhile, isoxaflutole has a lower foliar activity on *E. crus-galli* in dry conditions, but its residual activity is relatively long [25]. In this study, isoxaflutole applications in 2022 were the only year in which the average emergence after application from all timings was less than that of the NTC, and mesotrione emergence after application was similar to that of the NTC in each year studied (Table 4). It should be further clarified that the object of this work was the emergence of *E. crus-galli* that occurred *after* the herbicide application. The efficacy on the plants already present at the time of application is not further elaborated here, as it is a common object of herbicide efficacy studies. Furthermore, it would not be beneficial as a recommendation because these herbicides are usually combined with other potentially synergistic herbicides.

4.3. Can Emergence Models Be Used Following Herbicide Application?

Empirical models that describe the expected emergence pattern of a weed species are interesting for their potential to implement precision timing in weed control [13,23]. Applications of such models are already in effect [9]. The underlying biological understanding is that the unseen pattern of germination is proportional to the aboveground emergence of seedlings. Application of an herbicide with only foliar activity should not affect the usefulness of standard emergence models (such as those shown in Figures 1 and 2) to predict the emergence following the application. Yet, the predictive power of these models after an in-season disturbance event is sometimes stilted depending on the length of time that aboveground emergence is halted and any change it could have induced in the seed population (e.g., dormancy breaking) [17]. After a residual herbicide, it is probable that the germination rate of the population does not change. Once germinating seedlings can survive the dose of herbicide that has broken down or diluted in the soil, they will emerge above the ground and still cease emergence at the same expected time (e.g., 500 GDD_{10}; Figure 1); however, from a predictive point of view, this does not inform practitioners regarding when emergence might resume.

Certainly, there are many factors that impact the emergence pattern after herbicide application even if there is no residual activity. Depending on the size and density of the weeds at the time of application, there could be plant residue remaining on the soil surface that could reduce the light reaching the soil even if the crop canopy is not yet shading the row [26]. Even if these light dynamics are not particularly important for *E. crus-galli,* it could impact the soil surface temperature or unevenly distribute the moisture [27]. Further investigations should be conducted on weed community dynamics in combination with selective herbicide applications. For instance, when an herbicide is used with an expected lower efficacy for one species (not necessarily resistant but with natural tolerance), those individuals that survive have an unusual opportunity to grow even if they would not be particularly competitive in a weed mixture. Their mere existence in the field with the crop may affect the environment for recruitment of new seedlings. The high density of *E. crus-galli* in some treatments seemed to lower the temperature in those plots, which may have slowed the GDD accumulation and prolonged emergence [28], although our meteorological data could not account for such small variations in the microclimate.

The major challenge affecting the possibility to model emergence after residual herbicides is mainly the extreme reduction in target species below the point where it is statistically viable to model the relative emergence. In this study, we attempted to model the pattern of emergence following applications of these residual herbicides at different times; however, three of the four herbicides tested effectively controlled *E. crus-galli* to near the end of the emergence window. As a result, there was not enough emergence in those treatments to model. This is of course good news from the point of view of weed control and yield protection, but if we are concerned about the seed production of the small percentage of surviving individuals that inevitably add up at the landscape scale and over time, then it is important to understand when and relatively how many could be expected. Pursuit of this research will demand larger areas than the usual small-plot field design to answer these questions. In the case of mesotrione, which was the only herbicide that had enough emergence data after application to model, emergence followed a stable predictable pattern regardless of the time of application (Figure 3).

5. Conclusions

Throughout the literature, *E. crus-galli* has been characterized as having many adaptive traits, which implies that predictive models must be locally adapted. Here, we were able to use a natural infestation on bare ground and fit a simple Gompertz model that was validated with emergence that occurred within the crop canopy by using accumulated GDD alone. This allows for easy application of the model and future validation throughout the countryside in non-water-limiting conditions. Also, using the predictive emergence curve, the expected emergence following herbicide application can be gauged when no residual or low residual herbicides are applied. While it is still necessary to further investigate the seedling recruitment pattern after residual herbicides that greatly reduce the density, the pattern of emergence following mesotrione application could be modeled, as mesotrione is an herbicide with a shorter residual activity on *E. crus-galli*. Therefore, weed recruitment after other herbicides may also be modeled and require its own unique equation.

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