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Temperature Thresholds and Growing-Degree-Day Models for Red Sorrel (*Rumex acetosella*) Ramet Sprouting, Emergence, and Flowering in Wild Blueberry

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Red sorrel is a common herbaceous creeping perennial weed in wild blueberry fields in Nova Scotia that spreads by seeds and an extensive creeping root system. Experiments were established to determine temperature thresholds for ramet sprouting from creeping root fragments and to develop growing-degree-day (GDD) models for predicting ramet emergence and flowering under field conditions in wild blueberry fields in Nova Scotia. Ramets sprouted from root fragments at temperatures as low as 1 C, with an optimum temperature for ramet sprouting around 22 C. Ramet sprouting was completely inhibited at temperatures above 35 C. Cumulative ramet emergence and flowering under field conditions were adequately explained as functions of GDD by a three-parameter power equation ($R^2 = 0.98$) and a four-parameter logistic equation ($R^2 = 0.87$), respectively. Ramet emergence began between 110 and 265 GDD and continued throughout the season at each site. Model prediction for the initiation of emergence was 92 GDD, and 50 and 95% emergence were predicted to occur at 1,322 and 2,696 GDD, respectively. Red sorrel ramets began to flower in the field between 308 and 515 GDD. Model prediction for the initiation of flowering was 289 GDD, and 50 and 95% flowering were predicted to occur at 545 and 1,336 GDD, respectively. Model validation was conducted with the use of two additional independent data sets for emergence and flowering and indicated good performance of the proposed models (R^2 and root-mean-square error values ranging from 0.96 to 0.99 and 4.0 to 13.8, respectively). The models allow for direct comparison of red sorrel phenology to that of the wild blueberry and will aid in the development of new management strategies.

Nomenclature: Red sorrel, *Rumex acetosella* L. RUMAA; wild blueberry, *Vaccinium angustifolium* Ait.

Key words: Creeping herbaceous perennial, creeping root, phenology.

The wild blueberry is a rhizomatous perennial berry species (Glass and Percival 2000). Commercial fields are developed from native stands and managed primarily on a 2-yr cycle in which fields are pruned in the first year (nonbearing year) and harvested in the second year (bearing year) (Agriculture and Agri-Food Canada [AAFC] 2005). Fields are managed to encourage the vegetative spread of blueberry plants, but this also encourages the growth and spread of perennial weeds (McCully et al. 1991; Yarborough and Bhowmik 1989).

Red sorrel is a common herbaceous perennial weed species in commercially managed wild blueberry fields (McCully et al. 1991). The low pH soils and lack of tillage associated with commercial wild blueberry production contributes to the persistence of red sorrel. Seed of red sorrel is also a common contaminant on harvesting equipment (Boyd and White 2009) and control from commonly used herbicides, such as hexazinone, is variable (Kennedy et al. 2010, 2011; Li 2013).

Red sorrel is dioecous and spreads by seeds and a shallow creeping root system (Kennedy 2009). Seedlings contribute to established red sorrel populations in wild blueberry fields (White et al. 2014), but vegetative reproduction of ramets from the creeping root system is the primary means of population maintenance (Kennedy 2009; White et al. 2014). The majority of the creeping root system in wild blueberry fields occurs in the upper 7 cm of soil (White 2014), and roots are not fragmented or buried by tillage in this production system. Root sprouting is therefore unaffected by factors such as fragment size, burial depth, and desiccation. Temperature alone regulates bud sprouting in creeping roots of some species under these types of conditions (McAllister and Haderlie 1985), and, when expressed as growing degree days (GDD), can be used to develop predictive

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models for ramet emergence that can be useful for guiding weed management (Donald 2000; Webster and Cardina 1999). Basic physiological data regarding the sprouting response of red sorrel creeping roots to temperature is lacking (Stopps et al. 2011), and no attempts have been made to model ramet emergence as a function of GDD.

The majority of red sorrel ramets remain vegetative in the year of emergence, as flowering occurs primarily in overwintering ramets (White et al. 2014). GDD have been used to help predict phenological development of some winter annual and monocarpic perennial species following exposure to winter (Ball et al. 2004; Medd and Smith 1978; Roché et al. 1997), but this approach has not been applied to overwintering ramets of a creeping herbaceous perennial. Predictive models for the emergence and development of wild blueberry ramets have recently been developed (White et al. 2012) and allow for direct comparison to the phenological development of weed species if similar models can be developed.

The objectives of this research were (1) to determine the sprouting response of red sorrel creeping roots maintained at constant temperatures, (2) to develop degree-day models to predict red sorrel ramet emergence and flowering in wild blueberry fields, and (3) to validate the proposed degree-day models with independent data sets.

Materials and Methods

Temperature Experiments. *Root Material and General Methodology.* Red sorrel creeping roots were collected as needed from a wild blueberry field in Collingwood, Nova Scotia, Canada (45°35′10.900″N, 63°51′37.525″W), in September, October, and November 2010. Roots were collected from the top 5 to 10 cm of soil with the use of a garden rake, placed in paper bags, and stored in a cooler until arrival at the lab, where roots were placed in a 4 C cold room until needed. Roots were gently washed of excess soil under running water at the time of use, and no roots used in experiments were stored for more than 3 wk.

Three experiments were conducted to evaluate the effect of temperature on ramet sprouting from creeping roots. In all experiments, five 2-cm root fragments were placed in petri dishes lined with two pieces of Whatman No. 1 9-cm-diam filter paper (Whatman Ltd., GE Healthcare Companies). Filter paper was moistened with 5 ml of distilled water just prior to placing roots in each dish. Petri dishes were then sealed with Parafilm$^{\mathrm{TM}}$ and covered with aluminum foil to exclude light. Light was excluded in all experiments because light levels could not be kept constant in all incubators. A sprouted, upward-pointing shoot on a root fragment was counted as a ramet when the shoot was at or exceeded 5 mm in length. In each experiment the total number of ramets per root fragment were counted in each petri dish 5 wk after initiation of the experiment and expressed as the mean number of ramets per 2-cm root fragment. Each experiment was repeated once.

Experiment 1: Identification of the Low-Temperature Threshold for Root Sprouting. The objective of experiment 1 was to determine the sprouting response of red sorrel root fragments grown under constant temperatures of 1, 2, 3, 4, and 5 C. Root fragments were placed in low-temperature incubators (Precision Low Temperature Incubator, GCA Corporation, Chicago, IL) for temperatures of 1, 2, and 3 C, in a controlled environment chamber (Model CMP5090, Conviron Controlled Environments Limited, Winnipeg, Manitoba, Canada) for the 4-C temperature, and a cold storage room for the 5-C temperature. Each treatment was replicated 12 times and results from both experimental runs were combined for analysis.

Experiment 2: Identification of the Optimum Temperature for Root Sprouting. The objective of experiment 2 was to determine the sprouting response of red sorrel root fragments grown under constant temperatures of 5, 10, 15, 20, 25, and 35 C. The 5-C treatment was conducted in a cold storage room and the 10-, 15-, 20-, and 25-C treatments were conducted in the same low-temperature incubators used for the low-temperature experiment described above. The 35-C treatment was conducted in a general-purpose incubator (Model 403 L-C Incubator, Thermo Scientific, Dubuque, IA). Each treatment was replicated eight times and results from both experimental runs were combined for analysis.

Experiment 3: Identification of the High-Temperature Threshold for Root Sprouting. The objective of experiment 3 was to determine the sprouting response of red sorrel root fragments grown under constant temperatures of 25, 30, 35, and 40 C. The 25-C treatment was conducted in the same incubator as experiment 2. The 30- and 35-C treatments were conducted in the same incubator used for the 35-C treatment in experiment 2. The 40-C treatment was conducted in a high-temperature general purpose

Table 1. Description of study sites used to collect data for calibration and validation of growing-degree-day models developed for red sorrel ramet emergence and flowering in wild blueberry fields in Nova Scotia, Canada. Nonbearing year sites established in 2009 and 2010 were retained for bearing-year data collection in 2010 and 2011, respectively.

		Elevation			Soil OM[b]
Site-year	Production year	m	Soil type[a]	Soil pH[b]	%
Purdy-2009	Nonbearing	114	Sandy loam	4.8	5.5
Purdy-2010	Bearing				
Wyvern-2009	Nonbearing	238	Sandy loam	4.6	6.0
Wyvern-2010	Bearing				
Pigeon Hill-2010	Nonbearing	190	Sandy loam	4.8	10.0
Pigeon Hill-2011	Bearing				

[a] Soil type for Purdy-2009, Purdy-2010, Wyvern-2009, Wyvern-2010, Pigeon Hill-2010, and Pigeon Hill-2011 obtained from Nowland and MacDougall (1973).

[b] pH and % OM (% organic matter) determined from four soil cores taken to a depth of 10 cm at each site. Cores were combined to form a composite sample for each site. Composite samples submitted to the Nova Scotia Department of Agriculture Provincial Analytical Laboratory, Truro, Nova Scotia, for analysis.

incubator (Chicago Surgical and Electrical Co., Melrose Park, IL). Petri dishes in this experiment were monitored every 3 to 5 d for moisture, and 3 to 5 ml of distilled water was added to each dish as needed. Each treatment was replicated eight times and results from both experimental runs were combined for analysis.

GDD Models to Predict Ramet Emergence and Flowering. *Site Selection and Data Collection.* Data on red sorrel ramet emergence and flowering were collected during both the nonbearing and bearing years at three wild blueberry fields in Nova Scotia, Canada, between 2009 and 2011 (Table 1). Study sites at the Purdy (45°35′34.904″N, 63°50′49.932″W) and Wyvern (45°32′57.042″N, 63°55′56.311″W) fields were selected in the spring of the nonbearing year in 2009, with the Pigeon Hill site (45°35′10.900″N, 63°51′37.525″W) selected in autumn 2009 following the autumn pruning operation prior to the nonbearing year in 2010. A total of eight quadrats were established for monitoring ramet emergence and flowering at each site. Quadrat size was 0.09 m^{-2}, and all quadrat locations established in the nonbearing year were retained for bearing-year data collection at each site.

Emergence and flowering counts were initiated as early as possible in the spring of both the nonbearing and bearing years, generally by late April or early May. Flowering counts were conducted once or twice weekly at each site throughout spring and summer until no new flowering ramets were observed. All flowering ramets at each count were examined with a hand lens to identify male and female flower organs (stamens and pistils), and the total number of identifiable male and female flowering ramets were counted and marked with colored paper clips to keep flowering ramets separate over counting dates. Emergence counts were initiated at the same time as flowering counts but were conducted once or twice weekly throughout spring, summer, and fall until no new ramets emerged. Newly emerged ramets at each count were marked with colored elastics to keep emergence cohorts separate. Flowering and emergence counts were expressed on a percent cumulative scale for modeling purposes.

Weather Data and GDD Calculations. Hourly air temperature at each site was monitored with the use of temperature loggers (HOBO Pro V2, Onset Computer Corporation, Bourne, MA). Data loggers were attached to wooden stakes and were located about 0.5 m above the soil surface. Regional air temperature data from the nearest Environment Canada weather station were used to supplement field-based temperature data so that GDD could be calculated starting on April 1 (Julian date 91). Cumulative GDDs were calculated with the use of the formula:

$$\mathrm{GDD} = \sum_{i=1}^{n} (T_{\mathrm{mean}} - T_{\mathrm{base}}), \qquad [1]$$

where T_{mean} is the mean daily air temperature, T_{base} is the lowest air temperature at which it is assumed ramet flowering or emergence will not occur, and n is the number of days over which GDDs are calculated. In this equation, GDD = 0 if $T_{\mathrm{mean}} \leq T_{\mathrm{base}}$, similar to the approach used by Gordon and Bootsma (1993). Rainfall data for each site were obtained from the nearest Environment Canada weather station. Mean daily air temperature and rainfall data for each site is provided in Figure 1.

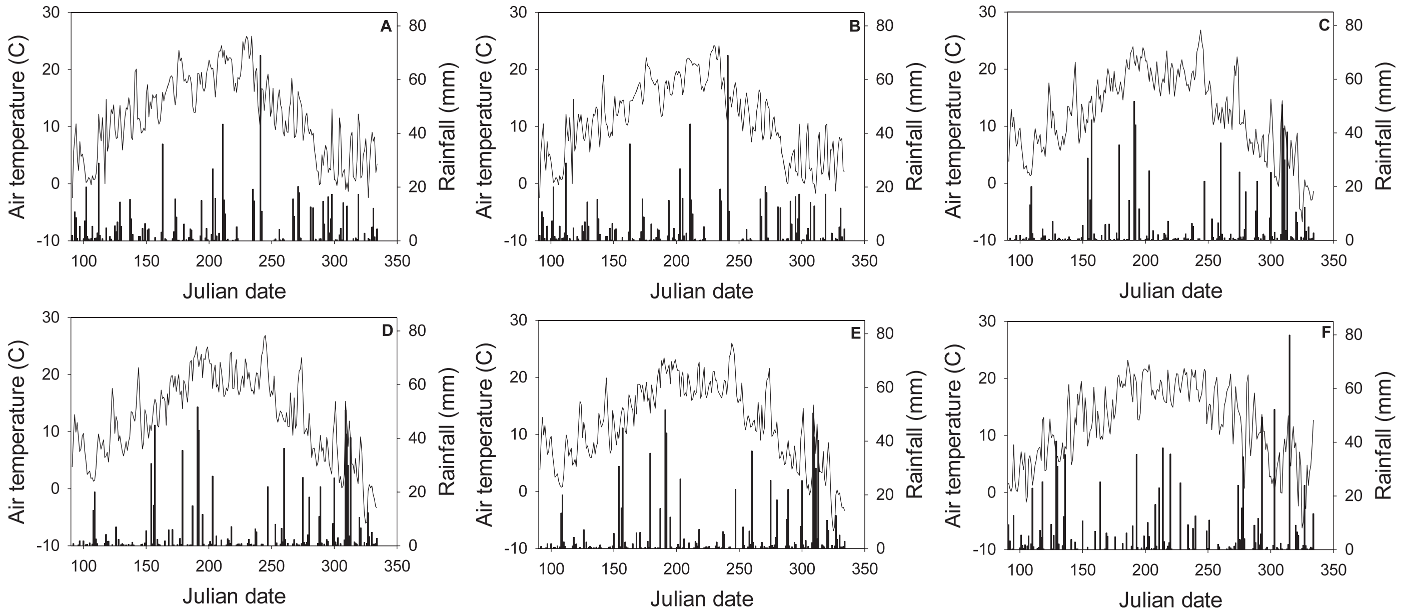

Figure 1. Daily mean air temperature (line) and rainfall (bars) during red sorrel ramet emergence and flowering at (A) Purdy-2009, (B) Wyvern-2009, (C) Pigeon Hill-2010, (D) Purdy-2010, (E) Wyvern-2010, and (F) Pigeon Hill-2011. Mean daily air temperature was obtained from HOBO temperature loggers placed 0.5 m above the soil surface at each site. Rainfall data for all sites were obtained from the Environment Canada weather station located at Nappan, Nova Scotia. Flowering data were collected between Julian date 91 and 240. Emergence data were collected between Julian date 91 and 334.

Statistical Analysis. *Temperature Experiments*. The mean number of ramets per 2-cm root fragment in experiment 1 were analyzed with the use of linear regression (PROC REG, SAS Version 9.2, SAS Institute, Cary, NC). In experiment 2 a nonlinear, four-parameter Gaussian model was fitted to the mean number of ramets per 2-cm root fragment. The model was of the form:

$$y = y_0 + a * \exp\left[-0.5(x - x_0/b)^2\right], \qquad [2]$$

where y is the mean number of ramets per 2-cm root fragment, y_0 is the value of x when $y = 0$, x is temperature, x_0 is the temperature that produces the peak mean number of ramets per 2-cm root fragment, a is the theoretical maximum mean number of ramets per 2-cm root fragment, and b is a shape parameter. The model was fit with the use of the Gauss-Newton algorithm in PROC NLIN in SAS (SAS Version 9.2, SAS Institute, Cary, NC). Assessment of model fit was determined by calculating the coefficient of determination (R^2) and adjusted coefficient of determination $\left(R^2_{\mathrm{Adj}}\right)$, described below. Data for experiment 3 were subject to ANOVA (PROC GLM, SAS Version 9.2, SAS Institute, Cary, NC) with temperature modeled as a fixed effect.

GDD Models. Cumulative ramet flowering and emergence were plotted as functions of GDD. Fitting of nonlinear equations, as well as parameter estimates for these equations, was conducted with the use of the Gauss-Newton algorithm in PROC NLIN in SAS (SAS Version 9.2, SAS Institute, Cary, NC). Percent cumulative flowering ramets (Y) was related to cumulative GDD with a four-parameter logistic equation of the form

$$y = a + b/\left[1 + (x/x_0)^c\right], \qquad [3]$$

where y is percent cumulative flowering at any given GDD, a and c are shape parameters, b is the theoretical maximum percent cumulative ramet flowering, x is time in GDD, and x_0 is the time, in GDD, until 50% flowering. The base air temperature for ramet flowering was determined by iterating a series of base temperatures (0 to 10 C in 1-C intervals) in Equation 2 until the best fit was obtained between percent cumulative ramet emergence and cumulative GDD (Izquierdo et al. 2009). The best fit was obtained for T_{base} equal to 0 C. Given no current biological justification for using an alternative T_{base}, 0 C was chosen based on best fit and simplicity in data calculation in both the current study and for potential end users of the proposed model.

Percent cumulative ramet emergence (Y) was related to cumulative GDD with a three-parameter power equation of the form

$$y = a + bx^c, \qquad [4]$$

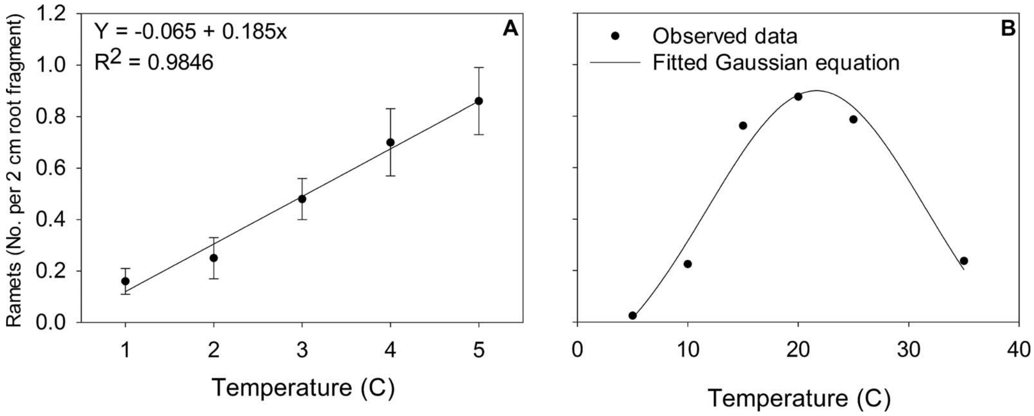

Figure 2. (A) The relationship between the mean number of ramets per 2-cm red sorrel root fragment and constant temperatures of 1, 2, 3, 4, and 5 C. Symbols are the mean number of ramets per 2-cm root fragment. Error bars represent one SE of the mean. The line is a fitted linear regression equation. (B) The relationship between the mean number of ramets per 2-cm red sorrel root fragment and constant temperatures of 5, 10, 15, 20, 25, and 35 C. Symbols are the mean number of ramets per 2-cm root fragment. The line is a fitted nonlinear Gaussian equation of the form $y = y_0 + a * \exp[-0.5(x - x_0/b)^2]$. Parameter estimates and goodness-of-fit statistics for the Gaussian model are provided in Table 2.

where y is percent cumulative ramet emergence at any given GDD, a is the approximate value of y when $x = 0$, x is time, in GDD, and b and c are shape parameters. The base air temperature for ramet emergence was determined through iteration, as described above. The best fit was obtained for T_{base} equal to 0 C.

Goodness of fit for the proposed models was determined by calculating the coefficient of determination (R^2) and adjusted coefficient of determination $\left(R^2_{\text{Adj}}\right)$:

$$R^2 = 1 - \left[\sum \left(y_{\text{obs}} - y_{\text{pred}}\right)^2\right] \Big/ \left[\sum \left(y_{\text{obs}}\right)^2\right] \qquad [5]$$

and

$$R^2_{\text{Adj}} = 1 - \left[n\left(1 - R^2\right)/n - p\right], \qquad [6]$$

where y_{obs} and y_{pred} are the observed and predicted values, respectively, n is the number of observations, and p is the number of parameters in the regression equation (Bowley 2008), and the root-mean-square error (RMSE):

$$\text{RMSE} = \sqrt{(1/n) \sum_{i=1}^{n} \left(y_{\text{obs}} - y_{\text{pred}}\right)^2}. \qquad [7]$$

Goodness of model fit was based on low RMSE and R^2_{Adj} values close to 1. The proposed flowering and emergence models were validated with two additional site-years of flowering and emergence data that were not included in the model calibration. Flowering and emergence data from each site were expressed on a percent cumulative scale and plotted against cumulative GDD. Flowering and emergence predictions were calculated with the model and plotted against observed flowering and emergence at each site, and the R^2_{Adj} and RMSE described above were used to assess agreement between observed data and model predictions.

Results and Discussion

Temperature Experiments. *Experiment 1: Identification of the Low-Temperature Threshold for Root Sprouting*. The mean number of ramets per 2-cm root fragment increased linearly between 1 and 5 C (Figure 2A). Results of the linear regression indicate an increase of 0.185 ramets per 2-cm root fragment per degree Celsius increase between 1 and 5 C and a base temperature for ramet sprouting of −0.065 C (Figure 2A). This base temperature is very similar to the 0-C base temperature identified through the

Table 2. Parameter estimates and goodness-of-fit statistics for the Gaussian equation fit to red sorrel ramet sprouting at constant temperatures of 5, 10, 15, 20, 25, and 35 C.

	Parameters[a]				
Equation	a	b	y_0	x_0	R^2_{Adj}
$y = y_0 + a * \exp[-0.5(x - x_0/b)^2]$	1.1657 (0.4823)	9.9013 (3.9920)	−0.2672 (0.5107)	21.6647 (0.8484)	0.9177

[a] Standard errors of each parameter estimate appear in parentheses.

Table 3. Effect of constant temperatures of 25, 30, 35, and 40 C on the mean number of red sorrel ramets per 2-cm root fragment.

Temperature	Mean ramets
C	Ramets per 2-cm root fragment
25	0.94 ± 0.126[a]
30	0.94 ± 0.134
35	0.04 ± 0.027
40	0.0

[a] Values (mean ± standard error).

iterative process used to develop the GDD models for this species. Temperatures below freezing were not directly tested in our experiments, however, so 0 C was used as an initial estimate as T_{base} for sprouting. Base temperatures for seed germination or sprouting of vegetative propagules are often species specific (Holt and Orcutt 1996; Steinmaus et al. 2000), though our estimate of 0 C for red sorrel is in general agreement with that used for modeling emergence of Canada thistle [*Cirsium arvense* L. (Scop.)] from creeping roots in North Dakota (Donald 2000) and common dandelion (*Taraxacum officinale* Weber in Wiggers) from rootstock in Western Canada (Hacault and Van Acker 2006). A higher base temperature has been reported for modeling the emergence of hemp dogbane (*Apocynum cannabinum* L.) and spreading dogbane (*A. androsaemifolium* L.) from creeping roots (Webster and Cardina 1999; Wu et al. 2013). Base temperatures for emergence of ramets from creeping roots of other perennial species, however, are lacking.

Experiment 2: Identification of the Optimum Temperature for Root Sprouting. The mean number of ramets per 2-cm root fragment increased in a sigmoidal fashion up to temperatures near 20 C but then declined as temperatures approached 35 C (Figure 2B). The Gaussian model fit the data well and predicted a maximum mean number of ramets per 2-cm root fragment at a temperature near 22 C (Table 2). The optimum temperature for root sprouting of Canada thistle is reported to be 15 C (Hamdoun 1972), slightly lower than the optimum of approximately 22 C found for root sprouting in red sorrel. It is unclear why the mean number of ramets per root fragment was higher at 5 C in the low-temperature experiment than in the optimum-temperature experiment (Figure 2), but roots for the low-temperature experiment were collected in late September as opposed to the mid-November collection date for roots used in the optimum temperature experiment. The sprouting capacity of creeping root fragments of some perennial species is reported to decline in late autumn and winter (Liew et al. 2012; Swan and Chancellor 1976), potentially due to endodormancy induced by abiotic factors such as photoperiod (Horvath et al. 2003; Liew et al. 2012). It is unknown if red sorrel creeping roots exhibit such behavior, but the potential impacts on results of root sprouting experiments should be considered in the future.

Experiment 3: Identification of the High-Temperature Threshold for Root Sprouting. Mean ramet data for experiment 3 could not be made to conform to the assumptions for the variance analysis, but no ramets sprouted at temperatures greater than 35 C (Table 3) and the results are reflective of those reported in Figure 2B. This temperature is well above the mean maximum temperatures observed at the study sites (Figure 1) and indicates that models incorporating impacts of high temperature thresholds on emergence may be unnecessary. These thresholds are also highly reflective of the predominant air temperatures

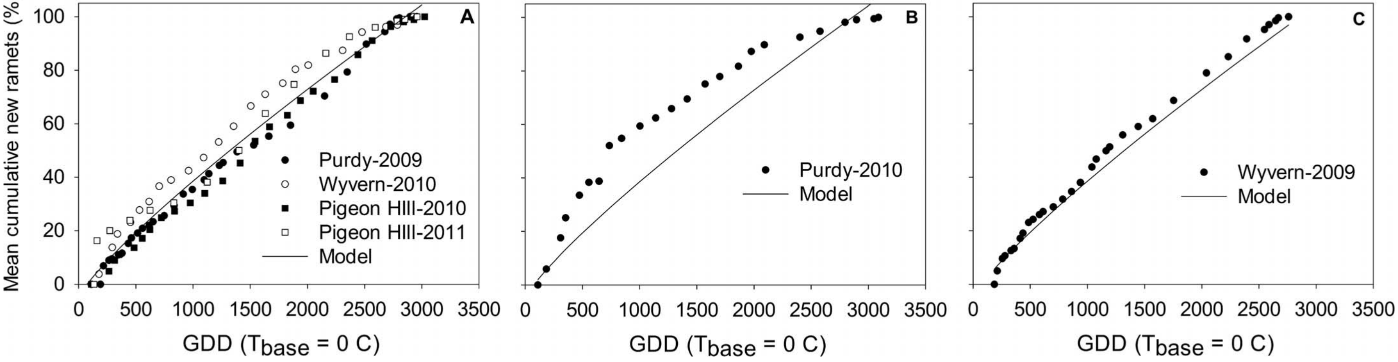

Figure 3. (A) Calibration of a growing-degree-day (GDD; T_{base} = 0 C) model for predicting red sorrel ramet emergence in wild blueberry fields in Nova Scotia and validation of the proposed model at (B) Purdy-2010 and (C) Wyvern-2009. Symbols are the mean of eight observations at each site. Lines are calibrated model predictions.

Table 4. Parameter estimates and goodness-of-fit statistics for calibration of the power and logistic equations fit to red sorrel ramet emergence and ramet flowering, respectively, as a function of growing degree days (GDD; $T_{\text{base}} = 0$ C).

Model	Site-year	Equation	Model parameters[a]				R^2_{Adj}	RMSE[b]
			a	b	c	x_0		
Emergence	Purdy-2009 Wyvern-2010 Pigeon Hill-2010 Pigeon Hill-2011	$y = a + bx^c$	−4.7767 (2.7556)	0.1296 (0.0546)	0.8413 (0.0506)	–	0.98	5.1
Flowering	Purdy-2009 Purdy-2010 Wyvern-2009 Pigeon Hill-2011	$y = (a + b)/[1 + (x/x_0)^c]$	−1.9855 (4.2197)	97.5330 (5.4659)	−5.6300 (0.9479)	532.3 (17.4672)	0.87	14.6

[a] Standard errors of each parameter estimate appear in parentheses.
[b] RMSE = root-mean-square error.

Table 5. Goodness-of-fit statistics for validation of proposed growing-degree-day (GDD; $T_{\text{base}} = 0$ C) models for predicting red sorrel ramet emergence and flowering in wild blueberry fields in Nova Scotia, Canada.

Model validated	Site-year	R^2_{Adj}	RMSE[a]
Emergence	Purdy-2010	0.96	13.8
	Wyvern-2009	0.99	4.0
Flowering	Wyvern-2010	0.99	5.7
	Pigeon Hill-2010	0.99	6.9

[a] RMSE = root-mean-square error.

recorded at each study site (Figure 1) and indicate that red sorrel is highly adapted to the climatic conditions prevalent in Atlantic Canada.

GDD Models to Predict Ramet Emergence and Flowering. Red sorrel ramet emergence began between 110 and 265 GDD (mid to late April) (Figure 3A). Emergence continued throughout the season at each site and ramet populations reached 90% emergence between 2,091 and 2,565 GDD (mid to late September) (Figure 3A). The proposed power model fit the field data well and accurately predicted emergence in the field as a function of GDD (Figure 3A; Table 4). Model prediction for the initiation of emergence was 92 GDD, and 50 and 95% emergence were predicted to occur at 1,322 and 2,696 GDD, respectively. Red sorrel ramets therefore emerge much earlier, and for a much longer duration, than ramets of the wild blueberry (White et al. 2012). Model predictions for ramet emergence generally agreed with observed values (Figure 3B and 3C; Table 5), with the primary exception being the deviation of the observed emergence from the predicted emergence at Purdy-2010 (Figure 3B; Table 5). Additional emergence data sets should therefore be collected to help improve model fit and provide additional opportunity for model validation.

The general emergence pattern of red sorrel ramets as a function of GDD is much more prolonged than is reported for emergence of other perennial weeds from creeping roots. For example, ramet emergence of spreading dogbane in wild blueberry fields was much more rapid, with ramet populations reaching 50 and 100% emergence at 184 and 420 GDD ($T_{\text{base}} = 6$ C) (Wu et al. 2013). Similar GDD thresholds are also reported for spreading dogbane ramet emergence from creeping roots in Ohio (Webster and Cardina 1999). Ramets of Canada thistle reached 1 and 80% emergence from creeping roots at 197 and 587 GDD ($T_{\text{base}} = 0$ C) in spring wheat in North Dakota (Donald

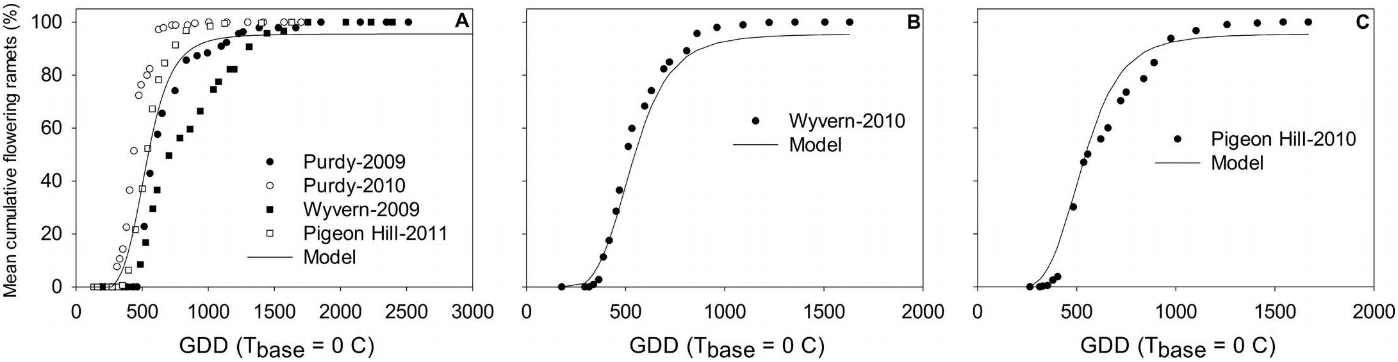

Figure 4. (A) Calibration of a growing-degree-day (GDD; T_{base} = 0 C) model for predicting red sorrel ramet flowering in wild blueberry fields in Nova Scotia and validation of the proposed model at (B) Wyvern-2010 and (C) Pigeon Hill-2010. Symbols are the mean of eight observations at each site. Lines are calibrated model predictions.

2000). Inherent differences in the biology of these species when compared to red sorrel, however, may make comparisons of emergence patterns difficult. Ramets of spreading dogbane and Canada thistle die back to soil level each year and do not generally persist for more than one season (Moore 1975; Robison and Jeffrey 1972). In contrast, surviving red sorrel ramets from a single season persist for at least two growing seasons (White et al. 2014). These species therefore exhibit inherent differences in the demographic aspects of ramet production at the genet level that ultimately affect ramet emergence patterns observed in the field.

Red sorrel ramets began to flower in the field between 308 and 515 GDD (mid to late May) (Figure 4A). Flowering generally occurred quite rapidly at each site and ramet populations reached 90% flowering between 623 and 1,308 GDD (mid-June to mid-July) (Figure 4A). The proposed model fit the field data well and accurately predicted flowering in the field as a function of GDD (Figure 4A; Table 4). Model prediction for the initiation of flowering was 289 GDD, and 50 and 95% flowering were predicted to occur at 545 and 1,336 GDD, respectively. Model validation indicated good performance of the proposed model (Figures 4B and 4C; Table 5).

Predicted GDD thresholds for red sorrel flowering were similar to thresholds previously established for wild blueberry (White et al. 2012), with 50% of blueberry and red sorrel ramets having open flowers at 477 and 545 GDD (T_{base} = 0 C), respectively. Peak blueberry bloom occurs between 562 and 565 GDD (White et al. 2012), and red sorrel flowering therefore occurs during a critical time for pollination of the wild blueberry. Red sorrel flowers are foraged by introduced pollinators (Hughes 2012), though the overall impact of this foraging on pollination of the wild blueberry is unclear. Hughes (2012) also found large amounts of pollen from male red sorrel flowers deposited inside open blueberry flowers. Red sorrel pollen increased the incidence of *Botrytis cinerea* infection on blueberry flowers under controlled conditions (Hughes 2012), though the impact of red sorrel pollen on disease incidence under field conditions has not been confirmed. Wild blueberry growers nonetheless report increased requirement for fungicide applications to control outbreaks of *B. cinerea* in fields with heavy red sorrel infestations, a requirement potentially accentuated by the overlapping flowering of the two species.

In terms of management, the emergence model helps explain the general lack of control from current management practices and provides insight into effective new strategies. Weed control with soil-applied herbicides prior to blueberry emergence in the spring of the nonbearing year is one of the primary components of weed management in wild blueberry. The most common herbicide applied in this manner is hexazinone, which is generally applied in late April or early May prior to blueberry emergence. Hexazinone tends to dissipate rapidly in blueberry soils, however, with less than 10% of applied hexazinone remaining 60 d after application (Jensen and Kimball 1985, 1987). Red sorrel ramets emerging in late summer and early autumn therefore avoid contact with hexazinone and established genets likely recover following dissipation of the herbicide. New management strategies should focus on identifying new herbicide products with longer soil activity, and targeting peak ramet populations with postemergence herbicides. Postharvest pruning provides a window for postemergence herbicide applications, but growers prune harvested fields in late autumn because of improved cutting efficiency of blueberry stems, and/or to prevent yield losses associated with early pruning (Yarborough and Hess

1998). In fields with heavy red sorrel infestations, however, growers should consider the impact of late pruning on the activity of foliar-applied herbicides used for red sorrel control. Coordinating blueberry pruning with the onset of peak ramet populations through the use of the proposed degree-day model should provide a basis for maximizing the delay in autumn pruning without compromising weed control.

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