Final Report

Project # CARP ADF 2017-105 Catellier:

An on-farm approach to monitor and evaluate the interaction of management and environment on canola stand establishment and disease development

Part I: Canola stand establishment

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ABSTRACT

Improvements in plant establishment and integrated pest management have been identified as two of the key factors that will help achieve the canola production goal specified in the Canola Council of Canada's strategic plan. As many of the key drivers impacting canola production are well understood, the increase in production that we are striving to achieve can potentially be attained with a better understanding of the interactive effects of management and environment on stand establishment and disease development in canola. An observational study was conducted on commercial farms, in collaboration with local producers in the Indian Head area, from 2018-2020. Environmental and agronomic data were collected from several sample sites in several fields throughout the growing season, and management data was provided by producers. Data were analyzed using a multiple regression, forward-selection and competing models approach. The additive and interactive effects of management and environment on the speed, temporal uniformity, and spatial uniformity of canola emergence were examined. Several management variables were found to be significantly influencing the emergence response at the location and in the years studied. Nearly all the environmental variables measured consistently influenced the emergence response and had additive and sometimes interactive effects with the management variables. Temperature and heat units were consistently more influential on emergence than precipitation and moisture. The analysis and findings of the study were limited by the level of replication. In particular, conducting the study in a single location limited the range of certain environmental conditions represented in the study. An extension of the study to provide additional replication at several locations would be insightful and would allow for the interpolation of the results to different agricultural production regions. Yet, the study was useful in demonstrating the potential of on-farm observational studies in agronomic research. Results of the disease development component of the study will be presented in a separate report.

INTRODUCTION

Improvements in plant establishment and integrated pest management have been identified as two of the key factors that will help achieve the canola production goal specified in the Canola Council of Canada's strategic plan. The strategic plan indicates that maximizing production will come from a more customized approach to agronomy, where targeted and relevant agronomic information and advice will be provided more specifically based on region, soil zone, and farm operation.

Canola research to date has contributed significantly to our understanding of the behaviour of important agronomic and management variables in the canola production system. However, the same results are not consistently observed across regions, soil zones, or farms, where environmental conditions are highly variable. In fact, environmental factors have been shown to be significantly limiting to canola production under western Canadian field conditions (Kutcher et al. 2010). Agronomic experiments are fundamentally designed to isolate the effect of specific factors of interest, while factoring out the variability resulting from environmental conditions. Differential responses among site-years are analyzed separately and discussed, yet the effect of environmental variables is rarely explicitly measured or quantified.

Thus, the increase in production that we are striving to achieve through better emergence and disease management can potentially be attained with a better understanding of how environmental conditions impact the effectiveness of management decisions, and how management decisions can in turn affect the microclimate that canola seeds and plants are responding to during different developmental stages.

The objective of this study is to examine the additive and interactive effects of management and environment on stand establishment and disease development in canola. This study will fill the gap between agronomic research results and on-farm observations by simultaneously examining the many interacting factors affecting canola establishment and disease development, and additionally, by explicitly measuring and incorporating environmental data in a multivariate analysis.

Fortunately, factors that are influential on canola establishment and disease development have been identified through previous agronomic research as well as growers' and agronomists' knowledge and experience, thus, effort can be focused on these particular variables in this study. Canola establishment and disease development are two separate management issues that would usually be studied independently; however, there is overlap in data collection for the two management issues when utilizing the approach chosen for this study. The present report will focus on the stand establishment component of the study, and the disease development component will be presented in a follow-up report.

Rapid and uniform emergence of canola is important for obtaining the yield potential of the crop (Yang et al. 2014) because it limits the amount of time that seeds and seedlings can be infected by soil-borne diseases (Kharbanda & Tewari 1996, Cutforth et al 2006), and it ensures a uniformly developing crop that can be managed more effectively in terms of crop protection product applications and harvest management (Clayton et al 2004, Kirk et al 2014). Canola emergence and seedling establishment has been shown to be influenced by management factors such as seeding speed and depth (Harker et al 2012), seeding date (Clayton et al 2004), seed size (Hwang et al 2014), row spacing (Kutcher et al 2013a), crop rotation (Hwang et al 2009), and stubble management (Bruce et al 2005), among other factors. In many cases, the influence of management depends on the presence or intensity of other management factors, or on environmental conditions such as seedbed moisture and temperature (Harker et al 2012). The response to management can be quite variable among sites or years, indicating an environmental effect (Clayton et al 2004, Hwang et al 2015). Furthermore, agronomic practices and management can, in turn, impact the microclimate to which canola seeds and seedlings are exposed (Cutforth et al 2006, Cardillo et al 2015). It is clear that canola emergence and seedling establishment is influenced by a network of inter-correlated variables, and that in order to progress in our understanding of this topic, more will be gained by examining these factors simultaneously rather than independently.

METHODOLOGY

Study design

The study design consisted of an observational, or survey-style approach, with a multivariate and nested/hierarchical data structure. The study was conducted on commercial farms, in collaboration with local producers in the Indian Head area for three growing seasons, from 2018-2020.

Producers were contacted ahead of seeding in the spring to identify fields which would be planted to canola. There were no treatments or experimental manipulation; producers managed their fields as usual. The fields chosen for the study were approximately 160 acres in area but could be part of larger management units. The geographical coordinates of 3 or 4 representative sample sites in each field was marked for repeated sampling. The sample sites were located along roads for quick access but at sufficient distance to avoid headlands, and were isolated from each other as much as possible within a field. The replicates were arranged hierarchically, in that sample sites were nested within fields, fields were nested within operations, and the same operations were included over the 3 years of the study. As each operation had multiple fields of canola that were seeded successively in the spring, this provided a range of environmental conditions for each replicate at time of seeding and throughout the growth stages of the crop. The number of replicates at each level over the 3 years of the study is summarized in Table 1. Over the 3-year duration of the study, data was collected at 184 sample sites, in 57 fields from 6 different operations.

Table 1. Replication at the sample site, field, and operation level in each growing season over the duration of the study.

	2018		2019		2020	
Operation ID	Fields	Sample Sites	Fields	Sample Sites	Fields	Sample Sites
001	5	17	3	10	3	9
002	4	13	3	11	4	12
003	5	18	3	9	5	15
004	4	12	3	10	-	-
005	3	11	3	10	3	9
006	-	-	3	9	3	9
Total	21	71	18	59	18	54

Data collection

The geographical location of each sample site was marked so all repeated samples were taken within an approximately 5-m radius area. The following data were collected at each sample site:

i. Spring soil quality: Soil samples were collected prior to seeding and/or spring fertilizer application, and analyzed for macronutrients (N, P, K, S), organic matter, pH, and cation exchange capacity (CEC). Soil samples from 2020 had not yet been analyzed at the time of data analysis.

ii. Surface residue, before and after seeding: Digital photographs were taken and percent ground cover was assessed digitally using SamplePoint image analysis software (Booth et al. 2006).

iii. Plant density: The length of crop row encompassing 10 plants in four different crop rows was measured at approximately 2, 3, and 4 weeks after seeding. Plant density per area was determined using producer-reported row spacing. Percent emergence was determined using producer-reported seeding rate.

iv. Canola growth stage (BBCH decimal scale): At the same time as plant density measurement (2, 3, and 4 weeks after seeding), the growth stage of 10 adjacent plants in 4 different crop rows (40 plants total) was recorded. Growth stage records begin at BBCH 10 which represents the cotyledon stage.

v. Seeding depth: At 4 weeks after seeding, ten seedlings from 4 separate crop rows were uprooted and the length of the hypocotyl remaining white was measured. Seeding depth was only measured in 2018, as it was decided that producer-reported seeding depth would be sufficient because the added level of precision attained with direct measurement did not justify the associated logistical and time requirement.

vi. Visual assessment of disease symptoms: At 20-30% seed colour change, crops were scouted thoroughly for symptoms of sclerotinia stem rot. As there was very low or no sclerotinia infection in any of the three years, only presence/absence was noted at each sample site. At 40-60% seed colour change, or immediately following swathing, a total of 50 plants (10 plants in 5 locations following a W-pattern at each sample site) were clipped at the base and assessed for symptoms of blackleg as per the Blackleg Field Rating Scale (https://www.canolacouncil.org/canola-encyclopedia/diseases/blackleg/identifying-blackleg/).

vii. Fall stubble density: The length of crop row encompassing 10 stems in four different crop rows was measured in undisturbed crop stubble after harvest. Stubble density per area was determined using producer-reported row spacing. Percent mortality was determined using spring plant density measurements. This measurement was added in 2019 as an additional variable of interest.

viii. Weekly monitoring data: The following measurements were taken at each sample site approximately weekly from the seeding date until crop maturity.
   a. Soil moisture and temperature: several point measurements of soil temperature and of soil volumetric water content were taken using a WaterScout SM 100 sensor attached to a hand-held reader. Measurements were taken before 10:00 am for the large majority of samples, and the time was recorded to be able to control for the effect of sample time on soil temperature.
   b. Precipitation: rain gauges were placed within a 1-mile radius of each sample site. Precipitation was recorded and the gauges were emptied at the time of weekly sampling.
   c. Canola growth stage (BBCH decimal scale): After the emergence period (4 weeks after seeding), the minimum, maximum, and average growth stage was recorded weekly for the sample site overall.

ix. Producer-reported management data: The following information was requested from producers for each field.

a. Seeding date, seeding rate, variety, thousand kernel weight (TKW) and seed treatment;
b. Applied fertilizer rate, form, placement and timing;
c. Row spacing/width, seeding speed, seeding implement type;
d. Fungicide application date, product, rate, and nozzle type and sprayer speed for fungicide application;
e. Other crop protection product application dates, rates, and products;
f. Swathing, desiccation, or crop termination date, harvest date and yield;
g. Crop type and variety (if canola) in the previous 3 years;
h. Fungicide products used in previous 3 years.

Regional weather data was also compiled from Environment Canada's online database (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html). Daily mean temperature and daily precipitation from the Indian Head station was compiled for the three growing seasons. Hourly air temperature was also compiled to account for the effect of air temperature at sample time on the soil temperature measurement. Daily growing degree days (GDD) was calculated from the daily mean air temperature, using 5°C as the base temperature.

Data was collected simultaneously for both the stand establishment and disease development components of the study. However, separate data sets were developed, and analyses were conducted independently for the two components, as the variables of interest are fundamentally different. The remainder of this report is concerned with the stand establishment component. Specific methodology and results pertaining to the disease development component will be presented in a separate report.

Data management and calculations

Data from all sources were associated by year, julian date and location (sample site or field) using database management software. Weekly measurements (soil temperature, soil moisture, precipitation from rain gauges) were interpolated to obtain daily estimates that could be averaged or totalled over specific pre- and post-seeding date intervals, as sampling did not always occur precisely at these intervals. Daily weather data (mean temperature, GDD, and precipitation) was also averaged or totalled over specific pre- and post-seeding date intervals.

Management data was not always reported completely or in detail, resulting in missing values or incomplete data for certain variables. Specifically, the rate of seed-placed nutrients may have been of particular interest for the emergence component of the study, however, only the total fertility rate was reported in many cases.

Response variables related to stand establishment (plant density/percent emergence, growth stage) were all replicated at the sample site level. When several measurements were taken at the same sample site and on the same date, the values were averaged, and the standard deviation was also calculated for final plant density. Explanatory variables were replicated at either the field level or sample site level. A brief description and attributes of each of the explanatory variables ultimately included in the analysis are provided in Table 2.

Table 2. Description and attributes of explanatory variables included in the analysis of the emergence component of the study.

Variable name	Description	Replication
Previous crop	Management factor with 5 levels: Lentil, Field pea, Spring wheat, Canaryseed, Soybean	Field
Previous crop type	Management factor with 2 levels: Cereal, Pulse	Field
Canola rotation	Management factor with 3 levels: 1 in 2, 3, or 4 years	Field
Cereal rotation	Management factor with 2 levels: 1 or 2 in 4 years	Field
Pulse rotation	Management factor with 3 levels: 0, 1, or 2 in 4 years	Field
Variety	Management factor with 7 levels: L233P, L252, L230, L234PC, L255PC, L345PC, P501L	Field
Seed treatment	Management factor with 2 levels: Prosper, Prosper+Lumiderm	Field
Seeding depth	Continuous management variable (producer reported); range 0.5 – 1 in	Field
Seeding speed	Continuous management variable (producer reported); range 4 – 6.5 mph	Field
Residue cover (pre-seed)	Continuous management variable, percent of ground cover that is not bare soil; range 31 - 100%	Sample site
Residue cover (post-seed)	Continuous management variables, percent of ground cover that is not bare soil; range 20 - 91%	Sample site
Seeding date	Continuous management variable; range 5 May – 22 May (125-142 julian)	Field
Seeding rate	Continuous management variable, producer-reported in lbs/ac and coverted to seeds per sq. ft using producer-reported TSW; range 8.3 – 13.4 seeds ft^{-2}	Field
Seed size	Continuous management variable, producer-reported in g per 1000 seeds (TSW); range 4.0 – 6.8 g 1000 $seeds^{-1}$	Field
Hypocotyl length	Continuous management variable, direct measurement of seeding depth; range 9.8 – 19.0 mm	Sample site
N fertilizer rate	Continuous management variable, producer-reported total (all sources, times, placements); range 110 - 157 lbs ac^{-1}	Field
P fertilizer rate	Continuous management variable, producer-reported total (all sources, times, placements); range 25 - 51 lbs ac^{-1}	Field
S fertilizer rate	Continuous management variable, producer-reported total (all sources, times, placements); range 15 - 37 lbs ac^{-1}	Field
Topsoil percent organic matter	Continuous environmental variable; range 2.6 - 6.7%	Sample site
Topsoil nitrate	Continuous environmental variable; range 2.5 - 48 ppm	Sample site
Topsoil P	Continuous environmental variable; range 2 - 31 ppm (Olsen)	Sample site
Topsoil Cation Exchange Capacity	Continuous environmental variable; range 14.2 - 48.9 meq 100 g^{-1}	Sample site
Avg mean air Temp (7 dbs)[1]	Continuous environmental variable, average mean air temperature over the 7 days prior to seeding; range 2.7 - 16.3°C	Field
Avg mean air Temp (7 das)[2]	Continuous environmental variable, average mean air temperature over the 7 days following seeding; range 3.7 - 18.9°C	Field
Avg mean air Temp (14 das)	Continuous environmental variable, average mean air temperature over the 14 days following seeding; range 6.6 - 16.9°C	Field
Avg mean air Temp (21 das)	Continuous environmental variable, average mean air temperature over the 21 days following seeding; range 7.9 - 17.1°C	Field
Cumulative GDD (seeding date)	Continuous environmental variable, total GDD accumulation up to seeding date; range 51 - 179	Field

Total GDD (7 das)	Continuous environmental variable, total GDD accumulation over the 7 days after seeding; range 8 - 98	Field
Total GDD (14 das)	Continuous environmental variable, total GDD accumulation over the 14 days after seeding; range 39 - 166	Field
Total GDD (21 das)	Continuous environmental variable, total GDD accumulation over the 21 days after seeding; range 78 - 255	Field
Soil temp (seeding date)	Continuous environmental variable, soil temperature on the seeding date; range 2.5 - 14.2°C	Sample site
Avg soil temp (7 das)	Continuous environmental variable, average soil temperature over the 7 days following seeding; range 4.6 - 14.6°C	Sample site
Avg soil temp (14 das)	Continuous environmental variable, average soil temperature over the 14 days following seeding; range 6.0 - 15.4°C	Sample site
Avg soil temp (21 das)	Continuous environmental variable, average soil temperature over the 21 days following seeding; range 7.3 - 16.2°C	Sample site
Cumulative precip (seeding date)	Continuous environmental variable, total precipitation up to the seeding date (including snowfall); range 45.6 - 73.1 mm	Field
Total precip (7 das)	Continuous environmental variable, total precipitation over the 7 days following seeding; range 0 - 9.7 mm	Field
Total precip (14 das)	Continuous environmental variable, total precipitation over the 14 days following seeding; range 1.9 - 57.1 mm	Field
Total precip (21 das)	Continuous environmental variable, total precipitation over the 21 days following seeding; range 2.3 – 89.9 mm	Field
Rain gauge (seeding date)	Continuous environmental variable, total precipitation collected in rain gauge up to the seeding date; range 0 – 14.5 mm	Field
Rain gauge (7 das)	Continuous environmental variable, total precipitation collected in rain gauge over the 7 days following seeding; range 0 – 30.1 mm	Field
Rain gauge (14 das)	Continuous environmental variable, total precipitation collected in rain gauge over the 14 days following seeding; range 0 – 50.2 mm	Field
Rain gauge (21 das)	Continuous environmental variable, total precipitation collected in rain gauge over the 21 days following seeding; range 0 – 80.7 mm	Field
Soil moisture (seeding date)	Continuous environmental variable, volumetric soil moisture on the seeding date; range 4.2 – 46.7%	Sample site
Soil moisture (7 das)	Continuous environmental variable, average volumetric soil moisture over the 7 days following seeding; range 6.1 – 43.0%	Sample site
Soil moisture (14 das)	Continuous environmental variable, average volumetric soil moisture over the 14 days following seeding; range 7.2 – 41.2%	Sample site
Soil moisture (21 das)	Continuous environmental variable, average volumetric soil moisture over the 21 days following seeding; range 9.3 – 41.7%	Sample site

[1] dbs=days before seeding
[2] das=days after seeding

Statistical analysis

The multivariate and observational design of this study fundamentally leads to a more explorative analytical approach, with the objective of identifying associations worthy of further investigation. A multiple regression and model selection approach was utilized. Mixed-effect models were used to deal with issues resulting from the unbalanced and nested data structure. With a multivariate study design, the choice of analysis is also limited by the level of replication. As the study was only conducted in a single location over three seasons, replication was low in relation to the number of variables of interest, which limits the number of variables that can be included in a single model. Thus, model selection was achieved via a combination of forward selection (addition of terms) and a competing models approach. Data were analyzed with the R statistical program, version 4.0.4 (R Core Team 2021), using the *lme4* package (Bates et al. 2015) for fitting mixed-effects models, and the *lmerTest* package (Kuznetsova et al. 2017) for assessing model fit and treatment effects. As the methodology varied with each response variable, details of the analysis are provided with the results.

RESULTS AND DISCUSSION

Emergence Rate

The emergence rate was modeled as percent emergence with days after seeding. The emergence rate indicates the speed or timeliness of emergence, or how quickly canola seedlings are reaching the surface, as well as final percent emergence. Rapidly emerging crops are less susceptible to seedling diseases and flea beetle pressure, and are more likely to be uniform in development stage which has implications for disease management and harvest management.

As a base model, a mixed effect model was fitted with linear and quadratic terms for 'Days After Seeding' as fixed effects, and year, operation within year, and field unit within operation within year as nested random effects. To force the curve to a zero intercept, zero percent emergence on the seeding date was included along with the emergence data collected at approximately 2, 3, and 4 weeks after seeding. It was noted that a sigmoid curve may have been more appropriate in modeling this relationship, however considering the increase in complexity of the model(s) and effect on the interpretability of the results, a quadratic relationship was considered equally informative. Both the linear and quadratic relationship were significant (P<0.05) in the base model (Figure 1).

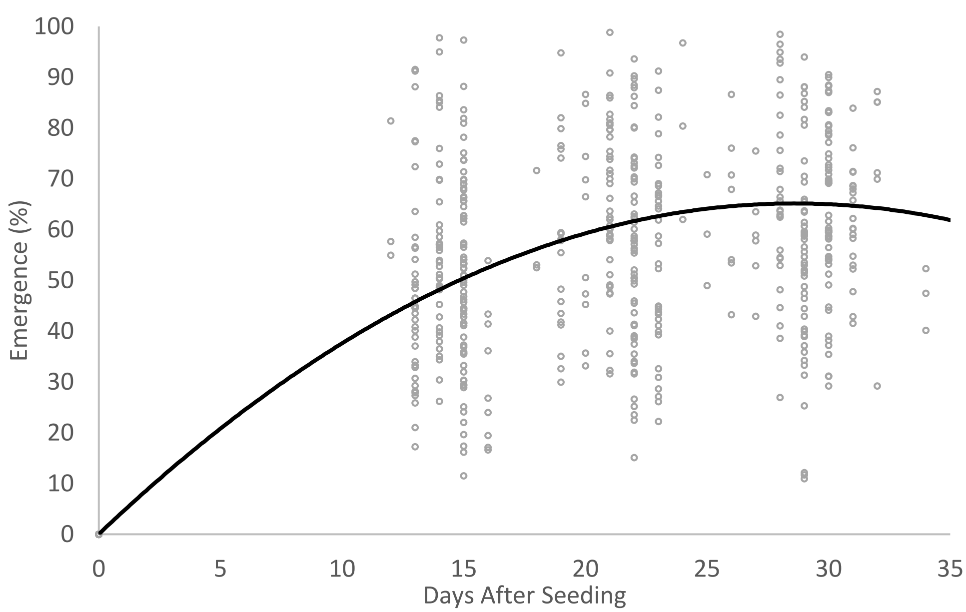


Figure 1. Percent emergence with days after seeding. The linear and quadratic relationship of percent emergence with 'days after seeding' are significant (P<0.05) and comprise the base model from which additional explanatory variables are added via forward selection to assess their effect on the relationship.

Forward selection modeling was then utilized to explore the effect of additional management and environmental variables on the emergence curve. Separate models were fitted for each explanatory variable to examine their individual effect via their interaction with the linear and quadratic terms. A separate intercept was not included for the additional variable, as it was assumed that the emergence curve would always start at zero percent emergence on the seeding date. The addition of interaction terms to the base model was justified if the more complex model had significantly better fit than the base model (χ^2 (chi-square) test, $P<0.05$). To achieve the minimally adequate model, the more complex model could be simplified by removing non-significant interaction terms or combining factor levels, provided the model fit was not significantly less than the more complex model (χ^2, $P>0.05$). Interactions with linear and quadratic terms were considered independent of each other; an interaction with the linear terms is interpreted as affecting the speed of emergence while an interaction with the quadratic term is interpreted as affecting the final percent emergence. Results of this modeling exercise for each variable are shown in Table 3.

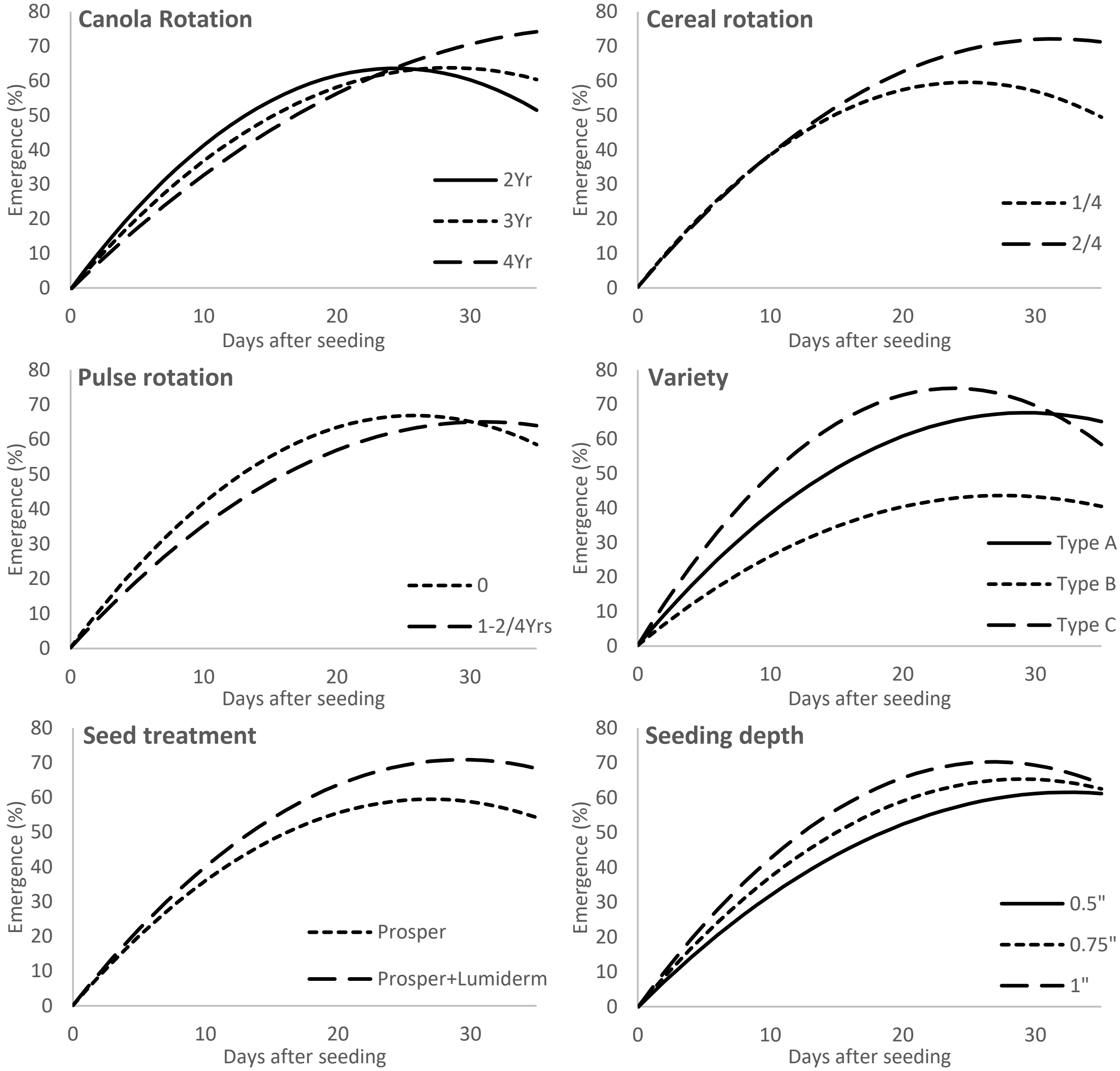
Temperature and moisture measurements were included for conditions prior to/up to seeding, as well as for several post-seeding intervals (7, 14, and 21 days). For each type of measurement, models for each of the three post-seeding intervals were compared using AIC (Akaike's Information Criterion, a measure of model fit), and the best-fitting models (lowest AIC) were chosen for further analysis. For the temperature variables, the 14-day interval provided the best fit, while for moisture variables, the 21-day interval provided the best fit (analysis not shown).

The magnitude of the effect of each significant explanatory variable was examined graphically to assess their relative influence on the emergence curve (Figure 2, Figure 3). The curves shown in the figures are based on the parameter estimates of each separate model (specific values not shown).

Table 3. Results of forward-selection modeling for percent emergence with days after seeding. The base model includes only linear and quadratic terms for 'days after seeding'; interactions with these model terms are added separately for each explanatory variable. The final model is the minimally adequate version of the full interaction model. Tests of significance for interaction terms in the final model are shown if the final model is significantly better than the base model (X^2, $P < 0.05$).

Explanatory variable	χ^2 test (base vs final model)		Final model interactions P(>|t|)	
	χ^2, df	P (>χ^2)	Linear	Quadratic
Previous crop	5.12, 4	0.276	-	-
Previous crop type	1.03, 1	0.309	-	-
Canola rotation	40.9, 4	**<0.001**	<0.001	<0.001
Cereal rotation[1]	32.8, 2	**<0.001**	-	<0.001
Pulse rotation[1,2]	10.7, 2	**0.005**	0.001	0.002
Variety[2]	70.6, 4	**<0.001**	<0.001	0.001
Seed treatment	20.5, 1	**<0.001**	<0.001	-
Seeding depth[1]	13.1, 2	**0.001**	0.001	0.011
Seeding speed[1]	3.66, 1	0.056	-	-
Residue cover (pre-seed)[1]	4.91, 2	0.086	-	-
Residue cover (post-seed)	30.2, 2	**<0.001**	<0.001	<0.001
Seeding date	30.3, 2	**<0.001**	<0.001	<0.001
Seeding rate	25.7, 2	**<0.001**	<0.001	0.016
Seed size[1]	2.37, 1	0.124	-	-
Hypocotyl length[1]	0.70, 1	0.402	-	-
N fertilizer rate	3.25, 1	0.072	-	-
P fertilizer rate	8.43, 1	**0.004**	-	0.003
S fertilizer rate	0.51, 1	0.474	-	-
Topsoil percent organic matter[1]	14.8, 2	**0.001**	0.005	0.038
Topsoil nitrate[1]	13.7, 2	**0.001**	<0.001	<0.001
Topsoil P[1]	0.08, 1	0.772	-	-
Topsoil Cation Exchange Capacity[1]	20.4, 2	**<0.001**	0.002	0.041
Avg mean air Temp (7 dbs[3])	53.1, 2	**<0.001**	<0.001	<0.001
Avg mean air Temp (7 das[4])	80.2, 2	**<0.001**	<0.001	<0.001
Avg mean air Temp (14 das)	98.4, 2	**<0.001**	<0.001	<0.001
Avg mean air Temp (21 das)	70.8, 2	**<0.001**	<0.001	<0.001
Cumulative GDD (seeding date)	73.6, 2	**<0.001**	<0.001	<0.001
Total GDD (7 das)	79.0, 2	**<0.001**	<0.001	<0.001
Total GDD (14 das)	99.1, 2	**<0.001**	<0.001	<0.001
Total GDD (21 das)	72.1, 2	**<0.001**	<0.001	<0.001
Soil temp (seeding date)	47.6, 2	**<0.001**	<0.001	<0.001
Avg soil temp (7 das)	79.2, 2	**<0.001**	<0.001	<0.001
Avg soil temp (14 das)	82.4, 2	**<0.001**	<0.001	<0.001
Avg soil temp (21 das)	62.8, 2	**<0.001**	<0.001	<0.001
Cumulative precip (seeding date)	8.37, 2	**0.015**	0.005	0.004
Total precip (7 das)	9.93, 1	**0.002**	0.002	-
Total precip (14 das)	26.2, 2	**<0.001**	<0.001	<0.001
Total precip (21 das)	44.7, 2	**<0.001**	<0.001	<0.001
Rain gauge (seeding date)	0.61, 1	0.433	-	-
Rain gauge (7 das)	15.1, 2	**0.001**	0.003	0.039
Rain gauge (14 das)	26.6, 2	**<0.001**	<0.001	0.001
Rain gauge (21 das)	38.0, 2	**<0.001**	<0.001	<0.001
Soil moisture (seeding date)	0.44, 1	0.509	-	-
Soil moisture (7 das)	0.14, 1	0.708	-	-
Soil moisture (14 das)	0.74, 1	0.391	-	-
Soil moisture (21 das)	5.47, 1	**0.019**	-	0.018

[1] Data set is incomplete for this variable due to missing entries. [2] Original factor levels were combined to simplify the model, provided the grouping was logical and did not result in a significant increase in deviance. [3] dbs = Days before seeding. [4] das = Days after seeding.



Canola Rotation
2Yr
3Yr
4Yr
Cereal rotation
1/4
2/4
Pulse rotation
0
1-2/4Yrs
Variety
Type A
Type B
Type C
Seed treatment
Prosper
Prosper+Lumiderm
Seeding depth
0.5"
0.75"
1"
Emergence (%)
Days after seeding
0
10
20
30
40
50
60
70
80

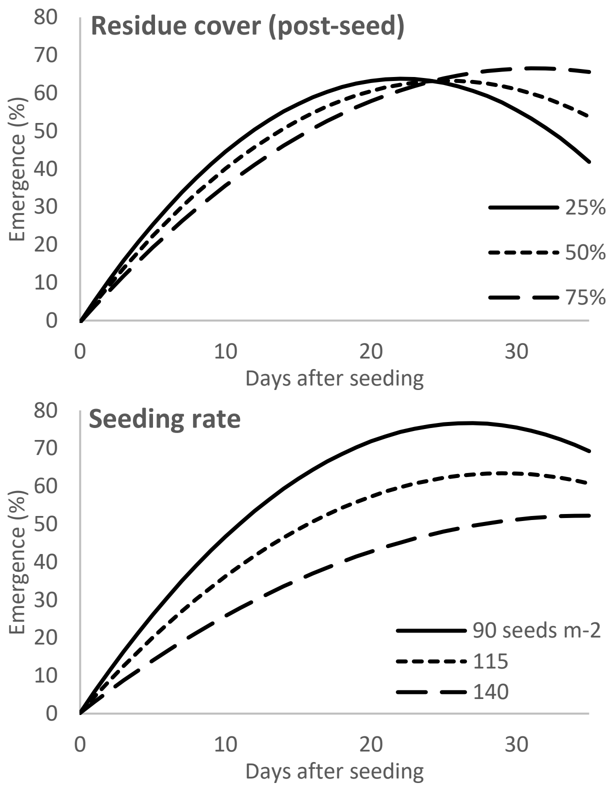
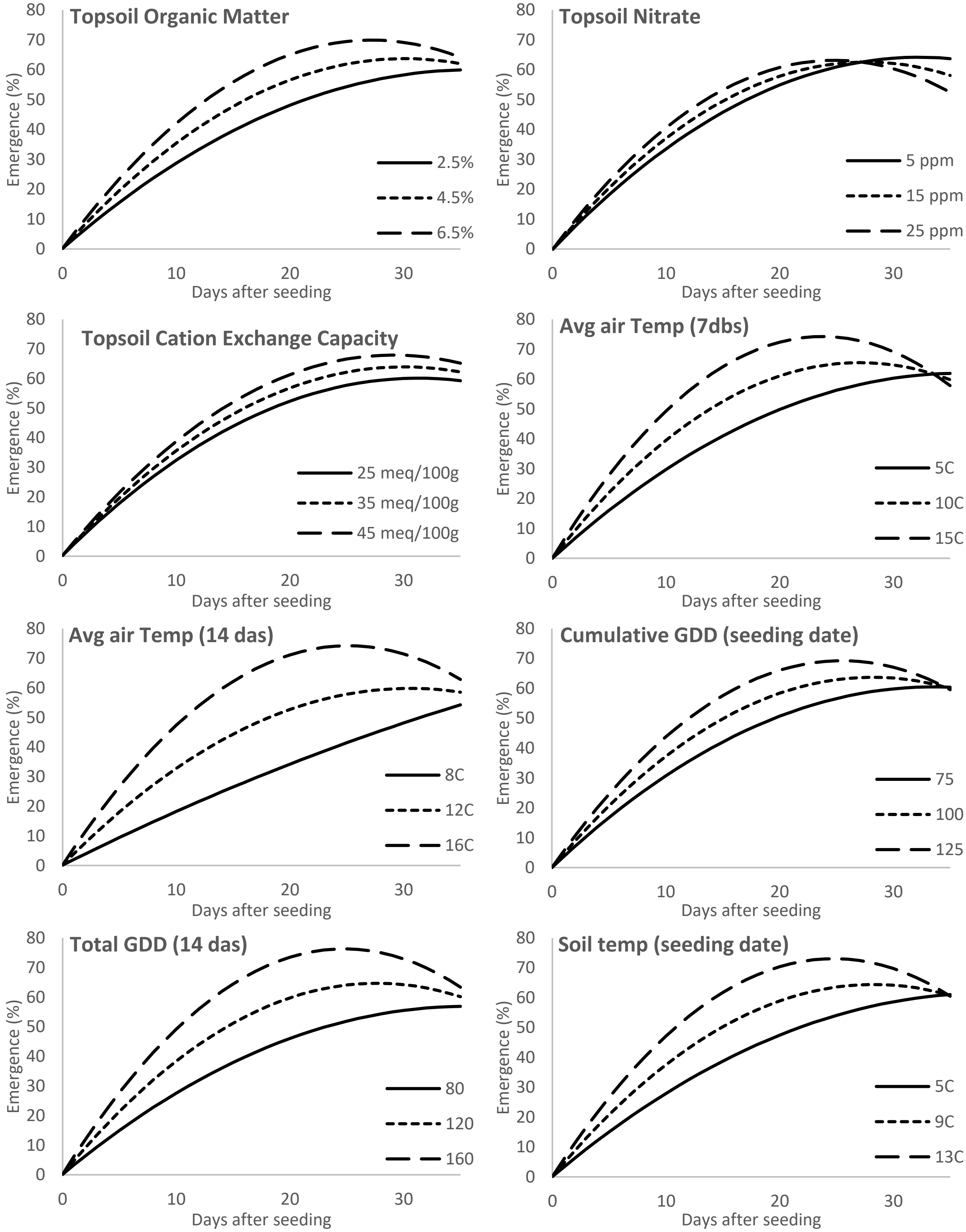


Figure 2. Percent emergence with days after seeding, as affected by the addition of management variables to the base model. The management variables include those that were shown to significantly affect the emergence curve (see Table 3). For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.


Topsoil Organic Matter
2.5%
4.5%
6.5%
Topsoil Nitrate
5 ppm
15 ppm
25 ppm
Topsoil Cation Exchange Capacity
25 meq/100g
35 meq/100g
45 meq/100g
Avg air Temp (7dbs)
5C
10C
15C
Avg air Temp (14 das)
8C
12C
16C
Cumulative GDD (seeding date)
75
100
125
Total GDD (14 das)
80
120
160
Soil temp (seeding date)
5C
9C
13C
Emergence (%)
Days after seeding
0
10
20
30
40
50
60
70
80

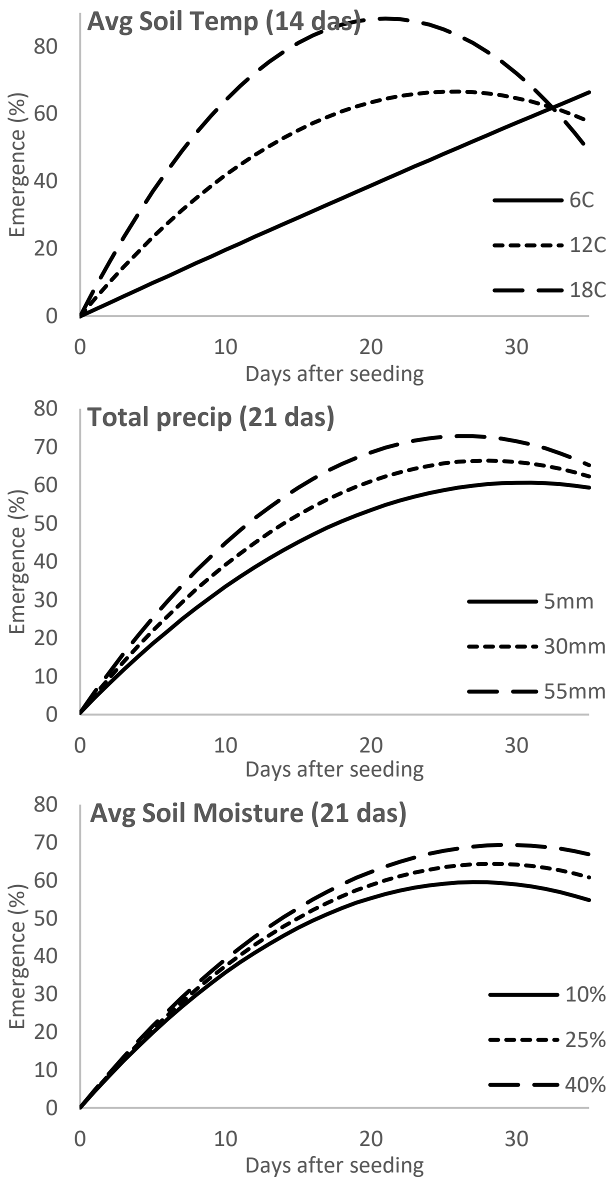


Figure 3. Percent emergence with days after seeding, as affected by the addition of environmental variables to the base model. The environmental variables include those that were shown to significantly affect the emergence curve (see Table 3). For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.

Overall, effects of single factors on canola emergence rate were as would be expected. Greater frequency of cereals and reduced frequency of canola and pulses in rotation were associated with better emergence, and could have been related to the prevalence of soil-borne diseases affecting canola seedlings. The effect of genetics (variety) on canola emergence has not been studied extensively and was greater than would be expected. An additional insecticidal active ingredient in the seed treatment was associated with better emergence. Greater seeding depth was associated with better emergence, though this may have been a function of soil conditions in the years studied (see discussion). Greater residue cover was associated with a slower speed of emergence but higher final percent emergence. Earlier seeding dates were associated with a more rapid emergence but final percent emergence was similar among seeding dates. Lower seeding rates were associated with a greater emergence rate overall. Higher fertility (P fertilizer rate, topsoil nitrate) and better soil quality overall (higher topsoil organic matter, higher topsoil cation exchange capacity) were associated with better emergence. In general, higher temperature and heat units, and greater precipitation and soil moisture before and after seeding were associated with better emergence.

A correlation matrix of all the significant continuous explanatory variables was calculated (Table 4). Canola, cereal, and pulse rotation were included as continuous variables because of their numeric values, and other significant factor variables (variety, seed treatment) were not included. Many of the variables were highly correlated, especially management variables with other management variables and environmental variables with other environmental variables.

As many of the explanatory variables were inter-correlated and because there was low replication (thus a risk of overparameterization), the relative influence of each variable and their interactions was assessed using a competing models approach, comparing several candidate models which comprise the base model plus a maximum of two additional variables and their interactions. A simple and modified version of the competing models approach presented by Symonds & Moussalli (2011) was followed, in consideration of the issues introduced via the inclusion of random effects, interactions, and polynomial terms in the models (Grueber et al. 2011). Considering the potential effect of removing a number of observations from the data set, variables with missing values were not included in the candidate set of competing models (cereal rotation, pulse rotation, seeding depth, topsoil organic matter, topsoil nitrate, and topsoil CEC). Thus, as the objective was to examine the influence of management variables relative to environmental variables, and to identify interactions between them, the candidate set of models included each variable on their own (17 models), plus pairwise combinations of each management variable with each environmental variable (7 management x 10 environmental = 70 models). The models included only the significant two-way interactions with each variable, as identified in Table 3, and any relevant three-way interactions. All models included a single intercept (zero percent emergence at 0 days after seeding). The candidate models were simplified via stepwise deletion of non-significant terms, provided the final model did not result in significantly poorer model fit (χ^2, P>0.05). The minimally adequate (all model terms significant) candidate models were ranked from lowest to highest AIC, and the Aikaike weight was calculated for each model. The Akaike weight is a value between 0 and 1, with the sum of Akaike weights of all models in the candidate set being 1, and indicates the probability that the model provides the best representation of the true relationship, relative to other models in the candidate set. The 15 top-ranked models out of the candidate set of 87 models are listed in Table 5 along with their Akaike weights. For each individual variable, predictor weights were calculated by adding the Akaike weights from all the models in which that variable was included, and the best-ranked model for each variable was determined (Table 6). Predictor weights indicate the probability that the variable would be involved in the true relationship, relative to the other variables in the candidate model set.

Table 4. Intercorrelations among continuous management and environmental variables that were shown to significantly affect the emergence curve (see Table 3). 'NS' indicates non-significant correlations. Correlation coefficients greater than 0.50 are bolded for emphasis.

	Canola rotation	Cereal rotation	Pulse rotation	Seeding depth	Residue cover	Seeding date	Seeding rate	P fertilizer rate	Topsoil % OM	Topsoil nitrate	Topsoil CEC	Avg air Temp (7 dbs)	Avg air Temp (14 das)	Cum. GDD (seed date)	Total GDD (14 das)	Soil temp (seed date)	Avg soil temp (14 das)	Cum. precip (seed date)	Total precip (21 das)	Rain gauge (21 das)	Soil moisture (21 das)
Canola rotation	1.00																				
Cereal rotation	0.18	1.00																			
Pulse rotation	**0.58**	**-0.53**	1.00																		
Seeding depth	ns	-0.14	0.24	1.00																	
Residue cover	0.15	0.30	ns	ns	1.00																
Seeding date	ns	-0.21	0.12	0.26	ns	1.00															
Seeding rate	ns	-0.33	0.11	-0.30	ns	ns	1.00														
P fertilizer rate	ns	0.12	ns	**0.64**	0.19	0.29	-0.31	1.00													
Topsoil % OM	ns	-0.09	0.16	0.39	0.10	0.11	ns	0.10	1.00												
Topsoil nitrate	0.10	-0.32	0.14	ns	-0.24	0.24	0.24	-0.21	0.16	1.00											
Topsoil CEC	ns	ns	ns	0.45	ns	0.19	ns	0.42	0.46	0.17	1.00										
Avg air Temp (7 dbs)	0.15	ns	0.13	0.35	0.16	**0.55**	-0.26	0.16	0.42	0.33	0.29	1.00									
Avg air Temp (14 das)	0.09	ns	0.21	0.27	ns	0.38	-0.26	-0.09	0.48	0.22	0.20	**0.59**	1.00								
Cum. GDD (seed date)	ns	-0.09	0.12	0.37	ns	**0.77**	-0.26	0.11	0.44	0.21	0.22	**0.83**	**0.67**	1.00							
Total GDD (14 das)	0.08	ns	0.21	0.26	ns	0.36	-0.25	-0.10	0.48	0.22	0.19	**0.58**	**1.00**	**0.67**	1.00						
Soil temp (seed date)	0.10	ns	0.13	0.15	ns	**0.52**	-0.24	-0.15	0.14	0.11	-0.19	**0.58**	**0.58**	**0.72**	**0.57**	1.00					
Avg soil temp (14 das)	-0.08	ns	ns	0.11	ns	**0.51**	-0.14	-0.17	0.20	0.16	ns	**0.60**	**0.67**	**0.73**	**0.67**	**0.81**	1.00				
Cum. precip (seed date)	-0.12	-0.12	ns	0.08	-0.31	**0.66**	-0.15	0.37	-0.27	0.11	ns	ns	0.11	0.35	0.11	0.10	0.12	1.00			
Total precip (21 das)	ns	ns	0.20	0.19	0.12	ns	-0.11	-0.39	0.40	ns	0.09	0.41	**0.65**	0.43	**0.66**	0.49	**0.54**	**-0.53**	1.00		
Rain gauge (21 das)	0.18	0.10	0.18	0.13	0.19	-0.18	-0.17	-0.34	0.40	ns	ns	0.43	**0.64**	0.34	**0.65**	0.42	0.46	**-0.58**	**0.91**	1.00	
Soil moisture (21 das)	0.10	ns	0.11	**0.53**	0.15	0.22	-0.16	**0.50**	0.35	ns	**0.70**	0.15	-0.11	0.19	-0.11	-0.13	-0.24	0.14	-0.11	-0.15	1.00

Table 5. Top ranked models out of the candidate set of 87 competing models for emergence rate. All models include a single intercept, and linear and quadratic terms for ‘Days after seeding’, and the additional interaction terms as listed. ΔAIC is the difference in AIC between each model and the top ranked model. The Akaike weight indicates the probability that the model provides the best representation of the true relationship, relative to other models in the candidate set.

	Minimal adequate model interaction terms						
Rank	Linear	Quadratic	Linear	Quadratic	Linear (3-way)	ΔAIC	Model weight
1	Variety	Variety	Avg soil temp (14 das)	Avg soil temp (14 das)	Variety:Avg soil temp (14 das)	0	0.795
2	Variety	-	Total GDD (14 das)	Total GDD (14 das)	-	3	0.167
3	Variety	Variety	Avg air Temp (14 das)	Avg air Temp (14 das)	-	6	0.036
4	Variety	Variety	Avg air Temp (7 dbs)	Avg air Temp (7 dbs)	-	12	0.002
5	Seed treatment	-	Avg air Temp (14 das)	Avg air Temp (14 das)	-	17	<0.001
6	Canola rotation	Canola rotation	Avg air Temp (14 das)	Avg air Temp (14 das)	Canola rotation:Avg air Temp (14 das)	20	<0.001
7	-	-	Avg air Temp (14 das)	Avg air Temp (14 das)	-	23	<0.001
8	Seed treatment	-	Total GDD (14 das)	Total GDD (14 das)	-	26	<0.001
9	Seed treatment	-	Avg soil temp (14 das)	Avg soil temp (14 das)	-	29	<0.001
10	Residue cover	Residue cover	Avg air Temp (14 das)	Avg air Temp (14 das)	-	30	<0.001
11	Seeding rate	-	Avg air Temp (14 das)	Avg air Temp (14 das)	Seeding rate:Avg air Temp (14 das)	31	<0.001
12	-	-	Total GDD (14 das)	Total GDD (14 das)	-	33	<0.001
13	-	P fertilizer rate	Avg air Temp (14 das)	Avg air Temp (14 das)	-	34	<0.001
14	Variety	Variety	Soil temp (seed date)	Soil temp (seed date)	-	35	<0.001
15	-	-	Avg soil temp (14 das)	Avg soil temp (14 das)	-	38	<0.001

Table 6. Predictor weights for each explanatory variable included in the candidate competing models set for emergence rate. Predictor weights indicate the probability that the variable would be involved in the true relationship, relative to the other variables in the candidate model set.

Variable	Predictor weight	Best ranked model
Variety	1.00	1
Avg soil temp (14 das)	0.80	1
Total GDD (14 das)	0.17	2
Avg air Temp (14 das)	0.04	3
Avg air Temp (7 dbs)	0.002	4
Seed treatment	<0.001	5
Canola rotation	<0.001	6
Residue cover	<0.001	10
Seeding rate	<0.001	11
P fertilizer rate	<0.001	13
Soil temp (seed date)	<0.001	14
Rain gauge (21 das)	<0.001	22
Total precip (21 das)	<0.001	23
Seeding date	<0.001	24
Cum. GDD (seed date)	<0.001	25
Cum. precip (seed date)	<0.001	40
Soil moisture (21 das)	<0.001	64

The top-ranked model was weighted significantly higher than the other models, indicating that there was 80% probability that variety and average soil temperature 14 days after seeding were the most influential management and environmental variables on canola emergence rate, respectively (Table 5). Variety also had the highest predictor weight overall and was included in the top four models, in combination with four of the different temperature variables (Table 6). The four temperature variables included in the top ranked models were all highly inter-correlated (***r*** > 0.59 for all pairwise correlations, Table 4), but they were not weighted equally. Notably, the highest weighted, soil temperature, was measured at the sample site level of replication, while other temperature variables were measured at the field level. This indicates that a significant amount of variability in response to temperature was occurring within fields. The top-ranked model also included a significant interaction between variety and soil temperature, indicating that different varieties were differentially affected by soil temperature, and more generally, that interactions between management and environmental variables are occurring and measurable. All other management variables were weighted much lower and were always included in combination with one of the top four temperature variables. The results of the competing models fairly complemented the effect sizes seen with the single additional variable models (Figure 2, Figure 3), apart from a few exceptions. Interestingly, seeding date was not one of the top-weighted management variables, even though there was a substantial effect size. This indicates that the effect of seeding date was largely encompassed by the environmental variables that were included in the analysis, and this is supported by the significant correlations between seeding date and many of the temperature environmental variables (Table 4). Seeding rate also appeared to have a significant effect size in the single additional variable model but was not a highly weighted management variable. Seeding rate had a significant interaction with temperature in the top-ranked model including this management variable.

Emergence Growth Rate

The emergence growth rate was modeled as the average growth stage (BBCH scale) with days after seeding. The emergence growth rate indicates how quickly seedlings are developing as they come out of the ground. Rapidly developing plants are less susceptible to environmental stresses, pests, and diseases, especially in consideration of the window of effectiveness of seed treatments. Growth rate also has implications for crop-weed competition.

For the base model, a mixed effect model for average growth stage was fitted with only the linear term for 'Days After Seeding' as a fixed effect, and year, operation within year, and field unit within operation within year as nested random effects. The linear relationship was significant ($P<0.05$) in the base model (Figure 4).

Forward selection modeling was then utilized to explore the effect of additional management and environmental variables on the growth rate. Separate models were fitted for each explanatory variable to examine their individual effect via their interaction with the intercept and linear regression terms. Interaction with the intercept was interpreted as affecting the days to emergence (growth stage records begin at BBCH 10 which represents the cotyledon stage), while interactions with the linear regression term were interpreted as affecting the growth rate. The addition of interaction terms to the base model was justified if the more complex model had significantly better fit than the base model (χ^2 (chi-square) test, $P<0.05$). To achieve the minimally adequate model, the more complex model could be simplified by removing non-significant terms or combining factor levels, provided the model fit was not significantly less than the more complex model (χ^2, $P>0.05$). Results of this modeling exercise for each variable are shown in Table 7.

Temperature and moisture measurements were included for conditions prior to/up to seeding, as well as for several post-seeding intervals (7, 14, and 21 days). For each type of measurement, models for each of the three post-seeding intervals were compared using AIC (Akaike's Information Criterion, a measure of model fit), and the best-fitting models (lowest AIC) were chosen for further analysis. For the temperature variables, the 21-day interval provided the best fit. Both of the significant moisture variables were chosen for further analysis.

The magnitude of the effect of each significant explanatory variable was examined graphically to assess their relative influence on the growth rate (Figure 5, Figure 6). The curves shown in the figures are based on the parameter estimates of each separate model (values not shown).

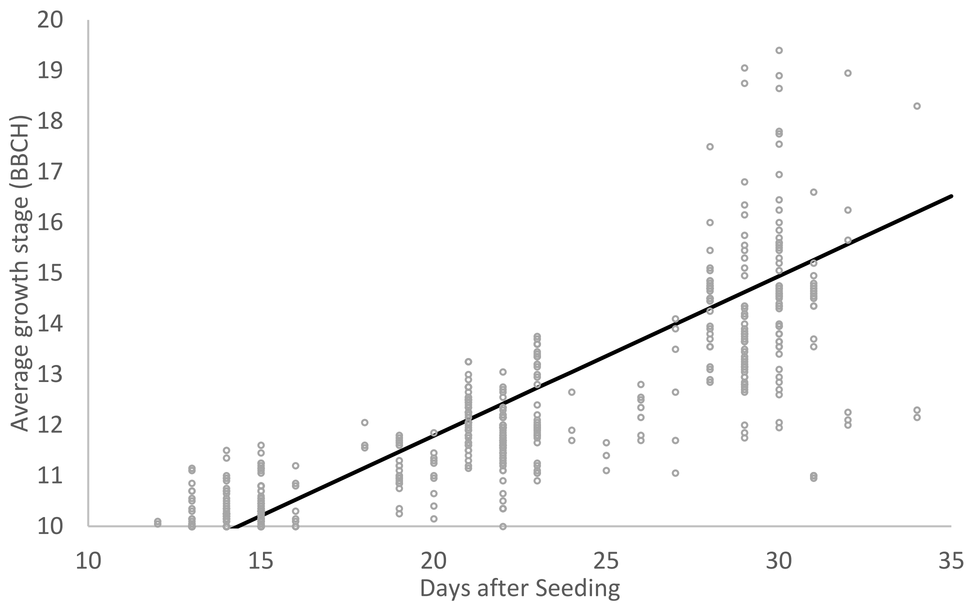


Figure 4. Average growth stage (BBCH decimal scale) with days after seeding. Records begin at growth stage 10 which represents the cotyledon stage. The linear relationship is significant (P<0.05) and comprises the base model from which additional explanatory variables are added via forward selection to assess their effect on the relationship.

Table 7. Results of forward-selection modeling for average growth stage with days after seeding. The base model included only the linear term for 'days after seeding'; models assessing interactions with the intercept and linear term were fitted for each explanatory variable separately. The final model is the minimally adequate version of the full interaction model. Tests of significance for interaction terms in the final model are shown if the final model is significantly better than the base model (X^2, $P < 0.05$).

Explanatory variable	χ^2 (base vs final model)		Final model terms P(>|t|)	
	χ^2, df	P (> χ^2)	Intercept	Linear interaction
Previous crop	4.21, 4	0.378	-	-
Previous crop type	0.12, 1	0.733	-	-
Canola rotation[2]	8.16, 1	**0.004**	-	0.005
Cereal rotation[1,2]	4.37, 1	**0.037**	-	0.040
Pulse rotation[1,2]	0.29, 1	0.589	-	-
Variety[2]	31.1, 4	**<0.001**	0.004	<0.001
Seed treatment	3.08, 1	0.079	-	-
Seeding depth	1.34, 1	0.247	-	-
Seeding speed	3.15, 1	0.076	-	-
Residue cover (pre-seed)[1]	0.13, 1	0.716	-	-
Residue cover (post-seed)	1.49, 1	0.222	-	-
Seeding date	34.3, 1	**<0.001**	-	<0.001
Seeding rate	10.9, 2	**0.004**	0.008	0.001
Seed size[1]	0.26, 1	0.608	-	-
Hypocotyl length[1]	2.99, 1	0.084	-	-
N fertilizer rate	5.10, 1	**0.024**	-	0.026
P fertilizer rate	13.9, 2	**0.001**	0.023	0.001
S fertilizer rate	0.86, 1	0.354	-	-
Topsoil percent organic matter[1]	0.37, 1	0.540	-	-
Topsoil nitrate[1]	6.13, 1	**0.013**	-	0.013
Topsoil P[1]	0.81, 1	0.367	-	-
Topsoil CEC[1]	4.11, 1	**0.043**	-	0.044
Avg mean air Temp (7 dbs[3])	13.1, 1	**<0.001**	-	<0.001
Avg mean air Temp (7 das[4])	5.19, 1	**0.023**	0.026	-
Avg mean air Temp (14 das)	10.4, 1	**0.001**	<0.001	-
Avg mean air Temp (21 das)	21.1, 1	**<0.001**	-	<0.001
Cumulative GDD (seeding date)	10.5, 1	**0.001**	-	0.001
Total GDD (7 das)	4.59, 1	**0.032**	0.036	-
Total GDD (14 das)	10.4, 1	**0.001**	<0.001	-
Total GDD (21 das)	21.3, 1	**<0.001**	-	<0.001
Soil temp (seeding date)	24.8, 1	**<0.001**	-	<0.001
Avg soil temp (7 das)	33.7, 1	**<0.001**	-	<0.001
Avg soil temp (14 das)	38.7, 2	**<0.001**	0.018	<0.001
Avg soil temp (21 das)	37.9, 2	**<0.001**	0.001	<0.001
Cumulative precip (seeding date)	1.90, 1	0.168	-	-
Total precip (7 das)	2.47, 1	0.116	-	-
Total precip (14 das)	1.31, 1	0.252	-	-
Total precip (21 das)	1.87, 1	0.172	-	-
Rain gauge (seeding date)	26.6, 2	**<0.001**	0.004	<0.001
Rain gauge (7 das)	0.04, 1	0.849	-	-
Rain gauge (14 das)	0.14, 1	0.711	-	-
Rain gauge (21 das)	0.80, 1	0.370	-	-
Soil moisture (seeding date)	0.25, 1	0.616	-	-
Soil moisture (7 das)	1.46, 1	0.226	-	-
Soil moisture (14 das)	3.75, 1	0.053	-	-
Soil moisture (21 das)	6.06, 1	**0.014**	-	0.015

[1] Data set is incomplete for this variable due to missing entries. [2] Original factor levels were combined to simplify the model, provided the grouping was logical and did not result in a significant increase in deviance. [3] dbs = Days before seeding. [4] das = Days after seeding.

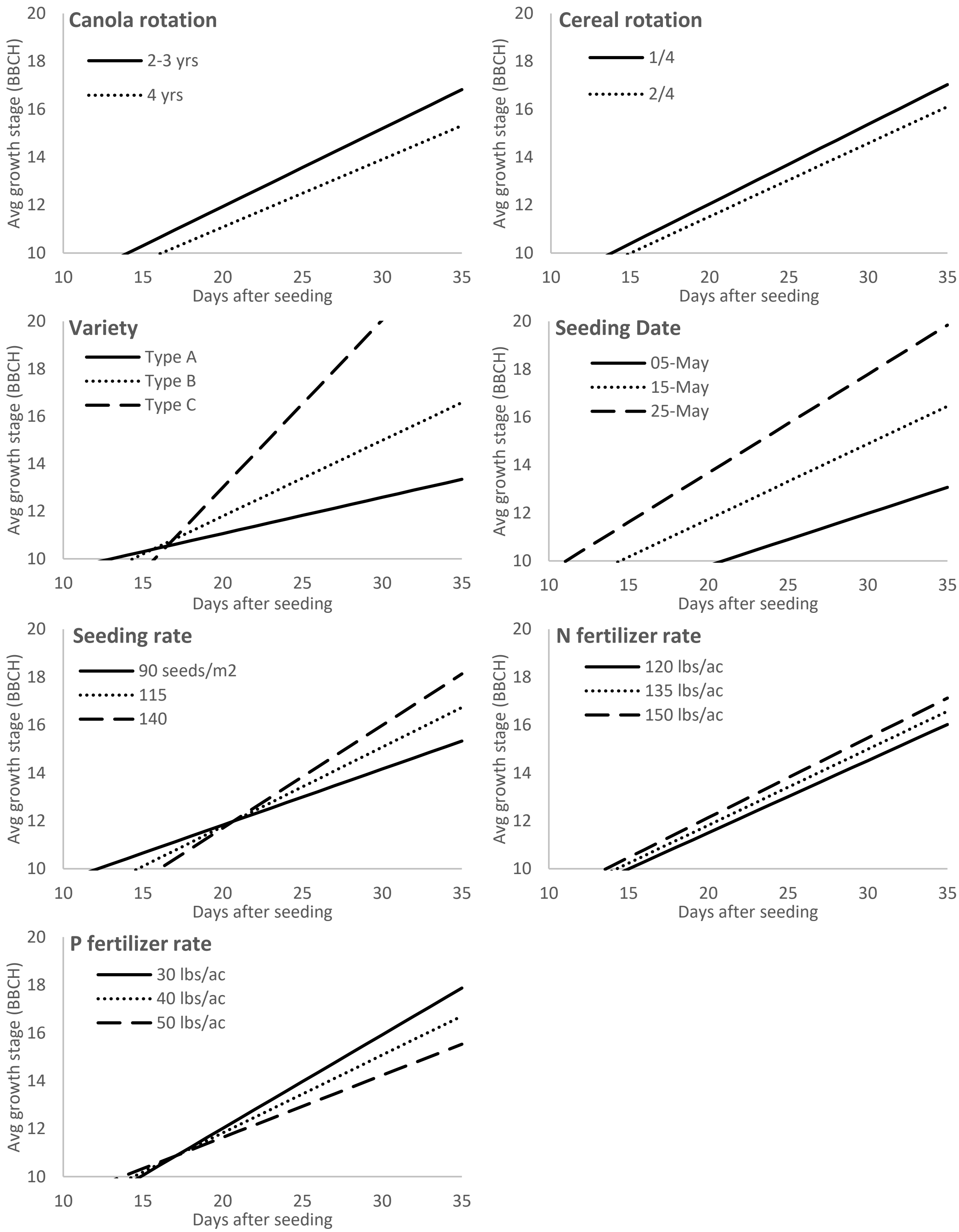
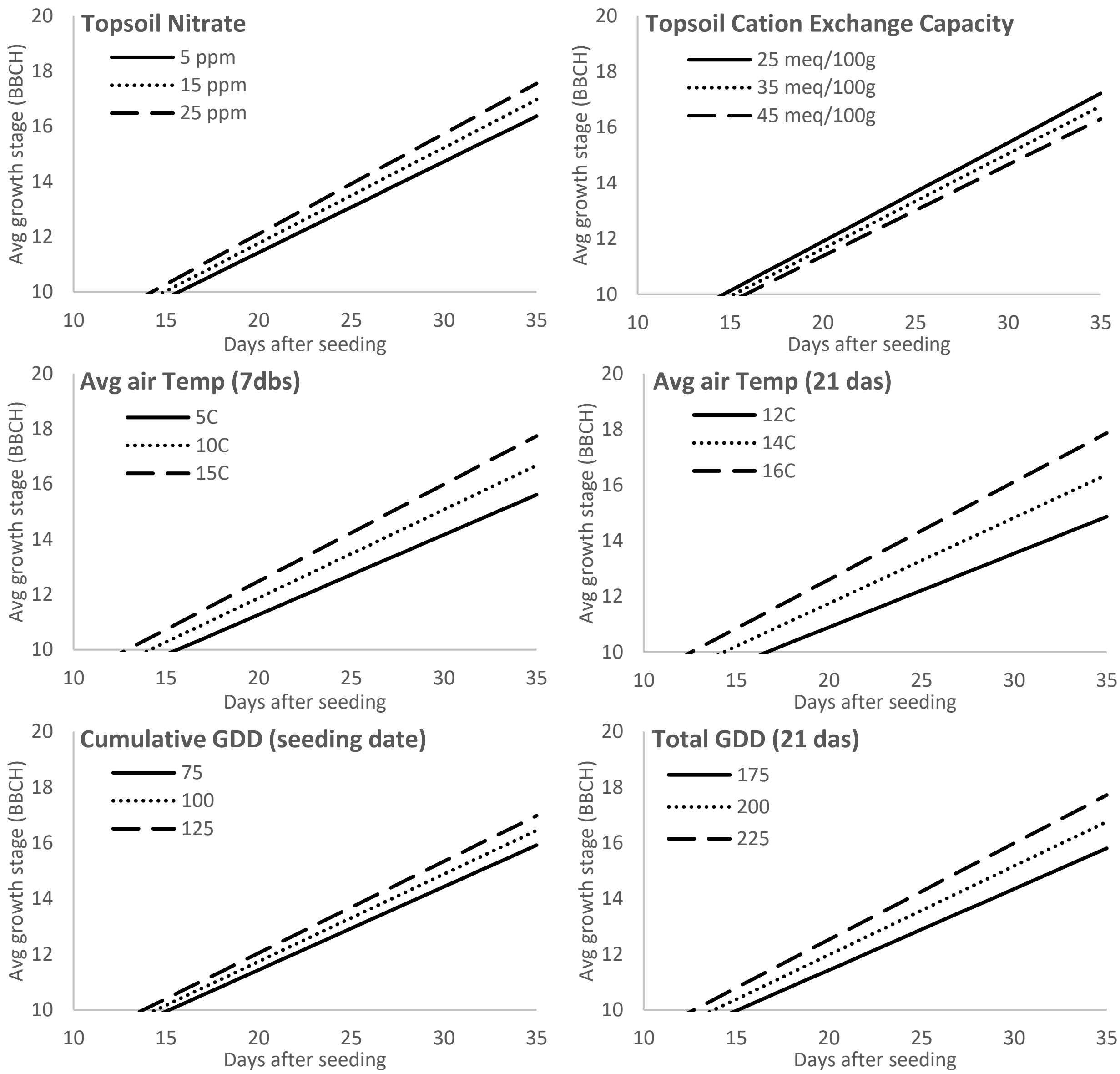


Figure 5. Average growth stage with days after seeding, as affected by the addition of management variables to the base model. The management variables include those that were shown to significantly affect the growth rate (see Table 7). For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.


Topsoil Nitrate
5 ppm
15 ppm
25 ppm
Topsoil Cation Exchange Capacity
25 meq/100g
35 meq/100g
45 meq/100g
Avg air Temp (7dbs)
5C
10C
15C
Avg air Temp (21 das)
12C
14C
16C
Cumulative GDD (seeding date)
75
100
125
Total GDD (21 das)
175
200
225
Avg growth stage (BBCH)
Days after seeding
10
12
14
16
18
20
15
25
30
35

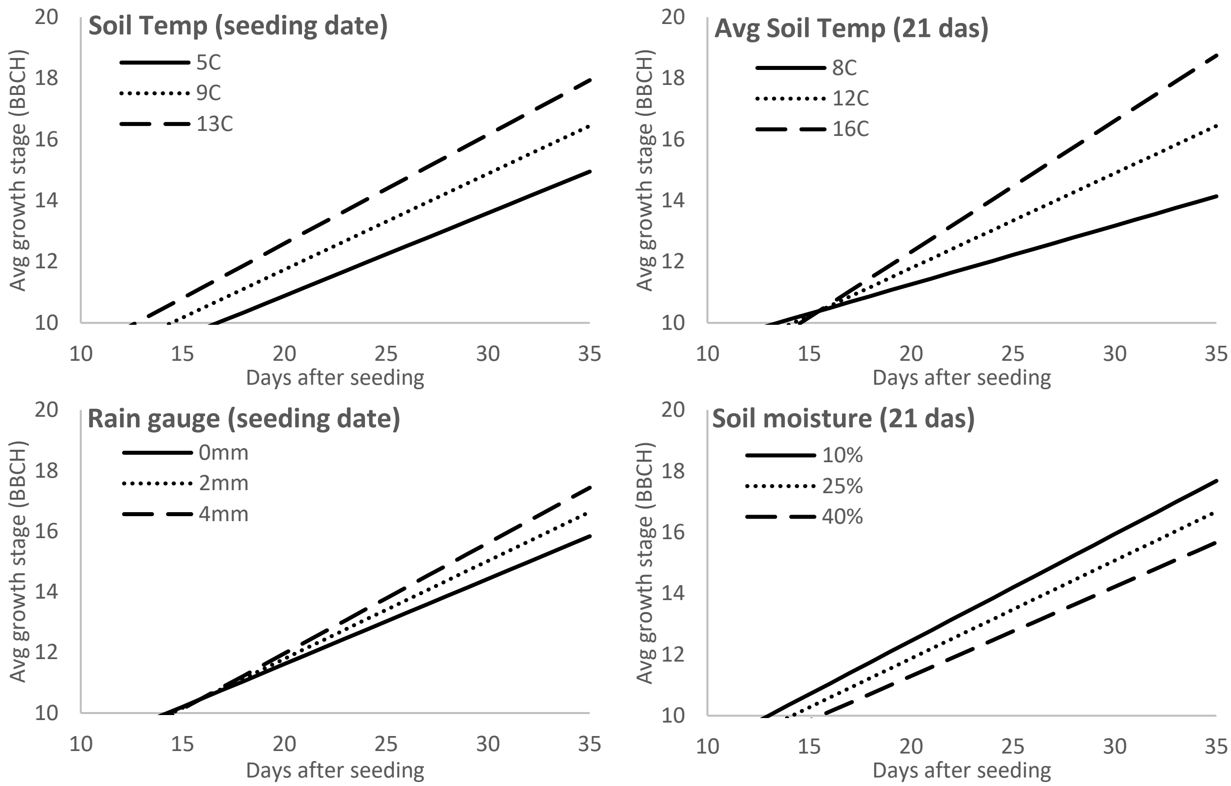


Figure 6. Average growth stage with days after seeding, as affected by the addition of environmental variables to the base model. The environmental variables include those that were shown to significantly affect the growth rate curve (see Table 7). For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.

Variables which significantly affected growth rate of canola were similar to the variables affecting emergence rate. Overall, the effects of single factors on canola growth rate were as would be expected. In contrast to the emergence rate, a greater frequency of canola and lower frequency of cereals were associated with fewer days to emergence and a slightly higher growth rate. As with emergence rate, variety had a surprisingly large effect on the growth rate. Later seeding dates were associated with fewer days to emergence and much higher growth rates. Higher seeding rates were associated with increased days to emergence but higher growth rate. The effect of seeding rate could be a function of plant density and could have implications for intra-crop competition. A higher rate of both N fertilizer and topsoil nitrate were associated with a slightly earlier start and slightly higher growth rate over the emergence period, while a higher rate of P fertilizer had little effect on days to emergence but was associated with a lower growth rate over the emergence period. In contrast to emergence rate, topsoil CEC had a negative influence on the early growth rate of canola. As with emergence rate, higher temperatures or heat units before and after seeding were associated with earlier emergence and higher growth rates overall. Greater precipitation before seeding was associated with higher growth rate, however, greater soil moisture was associated with a delayed start and lower growth rate. Volumetric soil moisture is a function of soil texture, thus this result is consistent with the negative association of growth rate with topsoil cation exchange capacity (CEC). A potential explanation could be that a certain level of moisture was necessary to promote germination, but that sustained higher soil moisture could result in lower soil temperature early in the growing season and thus a reduced growth rate.

A correlation matrix of all the significant explanatory variables was calculated (Table 8). Canola and cereal rotation were included as continuous variables because of their numeric values, and other significant factor variables (variety) are not included.

The competing models approach was conducted as with the percent emergence data. Variables with missing values were not included in the candidate set of competing models (cereal rotation, topsoil nitrate, and topsoil CEC). The candidate set of models included each variable on their own (14 models), plus pairwise combinations of each management variable with each environmental variable (6 management x 8 environmental = 48 models). The models include only the significant model terms as identified in Table 7, and the three-way interaction with 'Days after seeding'. The candidate models were simplified via stepwise deletion of non-significant terms, provided the final model did not result in significantly poorer model fit (χ^2, $P>0.05$). The minimally adequate (all model terms significant) candidate models were ranked from lowest to highest AIC, and the Akaike weight was calculated for each model. The 15 top-ranked models out of the candidate set of 62 models are listed in Table 9 along with their Akaike weights. For each individual variable, predictor weights were calculated by adding the Akaike weights from all the models in which that variable was included, and the best-ranked model for each variable was determined (Table 10).

Table 8. Intercorrelations among continuous management and environmental variables that were shown to significantly affect the growth rate (see Table 7). 'NS' indicates non-significant correlations. Correlation coefficients greater than 0.50 are bolded for emphasis.

	Canola rotation	Cereal rotation	Seeding date	Seeding rate	N fertilizer rate	P fertilizer rate	Topsoil nitrate	Topsoil CEC	Avg air Temp (7 dbs)	Avg air Temp (21 das)	Cum. GDD (seed date)	Total GDD (21 das)	Soil temp (seed date)	Avg soil temp (21 das)	Rain gauge (seed date)	Soil moisture (21 das)
Canola rotation	1.00															
Cereal rotation	0.18	1.00														
Seeding date	ns	-0.21	1.00													
Seeding rate	ns	-0.33	ns	1.00												
N fertilizer rate	-0.18	-0.30	0.39	-0.09	1.00											
P fertilizer rate	ns	0.12	0.29	-0.32	0.39	1.00										
Topsoil nitrate	ns	-0.32	0.24	0.24	ns	-0.21	1.00									
Topsoil CEC	ns	ns	0.19	ns	0.23	0.41	0.17	1.00								
Avg air Temp (7 dbs)	0.15	ns	**0.55**	-0.26	0.26	0.16	0.33	0.29	1.00							
Avg air Temp (21 das)	0.09	ns	0.35	-0.21	0.17	ns	0.27	0.25	**0.59**	1.00						
Cum. GDD (seed date)	ns	-0.09	**0.77**	-0.26	0.40	0.12	0.21	0.22	**0.83**	**0.57**	1.00					
Total GDD (21 das)	ns	ns	0.34	-0.20	0.17	ns	0.28	0.25	**0.59**	**1.00**	**0.57**	1.00				
Soil temp (seed date)	0.10	ns	**0.52**	-0.24	0.17	-0.15	0.11	-0.19	**0.58**	**0.53**	**0.72**	**0.52**	1.00			
Avg soil temp (21 das)	-0.09	ns	0.36	ns	ns	-0.17	0.20	ns	**0.54**	**0.55**	**0.55**	**0.55**	**0.66**	1.00		
Rain gauge (seed date)	-0.14	-0.33	0.17	0.13	0.25	-0.14	0.20	ns	ns	ns	ns	ns	ns	0.09	1.00	
Soil moisture (21 das)	0.10	ns	0.22	-0.16	0.43	**0.50**	ns	**0.70**	0.15	-0.09	0.19	-0.10	-0.13	-0.26	0.17	1.00

Table 9. Top ranked models out of the candidate set of 62 competing models for growth rate. All models include the linear term for 'Days after seeding', and the additional model terms as listed. ΔAIC is the difference in AIC between each model and the top ranked model. The Akaike weight indicates the probability that the model provides the best representation of the true relationship, relative to other models in the candidate set.

	Minimal adequate model interaction terms						
Rank	intercept	linear interaction	intercept	linear interaction	3-way linear interaction	ΔAIC	Model weight
1	Variety	Variety	Avg soil temp (21 das)	Avg soil temp (21 das)	yes	0	0.999
2	Variety	Variety	-	Soil temp (seed date)	yes	15	0.001
3	Variety	Variety	Rain gauge (seed date)	Rain gauge (seed date)	-	24	<0.001
4	Variety	Variety	-	Avg air Temp (21 das)	-	27	<0.001
5	-	Seeding date	-	Soil moisture (21 das)	-	30	<0.001
6	-	Seeding date	-	-	-	30	<0.001
7	-	-	Avg soil temp (21 das)	Avg soil temp (21 das)	-	31	<0.001
8	Variety	Variety	-	-	-	32	<0.001
9	-	Canola rotation	Avg soil temp (21 das)	Avg soil temp (21 das)	-	33	<0.001
10	Variety	Variety	-	Total GDD (21 das)	-	33	<0.001
11	Variety	Variety	-	Avg air Temp (7 dbs)	-	34	<0.001
12	-	Seeding date	Avg soil temp (21 das)	Avg soil temp (21 das)	yes	34	<0.001
13	-	Seeding date	-	Avg air Temp (21 das)	-	36	<0.001
14	-	Canola rotation	-	Soil temp (seed date)	-	37	<0.001
15	-	-	-	Soil temp (seed date)	-	40	<0.001

Table 10. Predictor weights for each explanatory variable included in the candidate competing models set for growth rate. Predictor weights indicate the probability that the variable would be involved in the true relationship, relative to the other variables in the candidate model set.

Variable	Predictor weight	1st ranked model
Variety	1.000	1
Avg soil temp (21 das)	0.999	1
Soil temp (seed date)	0.001	2
Rain gauge (seed date)	<0.001	3
Avg air Temp (21 das)	<0.001	4
Seeding date	<0.001	5
Soil moisture (21 das)	<0.001	5
Canola rotation	<0.001	9
Total GDD (21 das)	<0.001	10
Avg air Temp (7 dbs)	<0.001	11
Cum. GDD (seed date)	<0.001	17
Seeding rate	<0.001	21
N fert rate	<0.001	24
P fert rate	<0.001	32

The top-ranked model was very heavily weighted, indicating that there was 99% probability that variety and average soil temperature 21 days after seeding were the most influential management and environmental variables on canola growth rate, respectively (Table 9). Variety and soil temperature 21 days after seeding also had the highest predictor weights overall, with all other variables being weighted significantly lower (Table 10). Similar to percent emergence, soil temperature, measured at the sample site level, accounted for a greater level of variability in growth stage response than variables measured at the field level. Again, the two top-ranked model included significant interactions between variety and soil temperature.

Relative to percent emergence, environmental conditions leading up to and on the seeding date seemed to be more influential on growth rate. Further, seeding date was the second-highest weighted management variable, and was the highest-ranked model that included only a single additional variable (6th), ahead of both average soil temperature 21 days after seeding (7th) and variety (8th). The magnitude of the effect of seeding date was apparent in the single additional variable plots as well (Figure 5). As was noted before, seeding date was highly correlated with many of the temperature variables, and so it is notable that the highest-ranked model for seeding date included a moisture variable (soil moisture 21 days after seeding), and that this was the only top-ranked model including a moisture variable. This indicates that soil moisture is likely fairly influential on early growth rate, albeit less so than temperature.

Spatial uniformity of emergence

Spatial distribution of canola plants has significant implications for pest and harvest management as they relate to uniformity of crop development, as well as crop-weed competition, and ultimately affects the yield potential of canola (Yang et al. 2014). The standard deviation of plant density can be used as an estimation of the spatial uniformity of emergence. However, the values are not independent of plant density. Thus, a base model was fitted with only plant density as a fixed effect, and year, operation within year, and field unit within operation within year as nested random effects. The linear relationship was significant ($P<0.05$) in the base model (Figure 7).

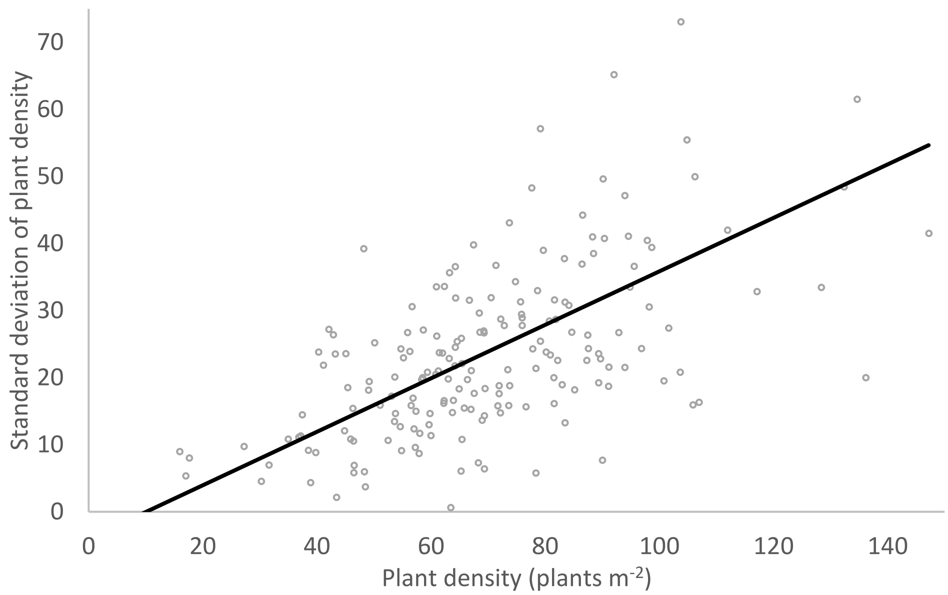


Figure 7. The relationship between plant density and standard deviation of plant density comprises the base model from which additional explanatory variables are added via forward selection to assess their effect on the spatial uniformity of emergence.

Again, forward selection modeling was then utilized to explore the effect of additional management and environmental variables on spatial uniformity. Separate models were fitted for each explanatory variable to examine their individual effect via their interaction with the plant density relationship. Interactions with the intercept only were interpreted as affecting the spatial uniformity equally across plant densities, while an interaction with the linear term was interpreted as affecting the spatial uniformity differentially across plant densities. Greater standard deviation values indicate lower spatial uniformity. The addition of terms to the base model was justified if the more complex model had significantly better fit than the base model (χ^2 test, $P<0.05$). To achieve the minimally adequate model, the more complex model could be simplified by removing non-significant terms or combining factor levels, provided the model fit was not significantly less than the more complex model (χ^2, $P>0.05$). Results of this modeling exercise for each variable are shown in Table 11.

Temperature and moisture measurements were included for conditions prior to/up to seeding, as well as for several post-seeding intervals (7, 14, and 21 days). For each type of measurement, models for each of the three post-seeding intervals were compared using AIC (Akaike's Information Criterion, a measure of model fit), and the best-fitting models (lowest AIC) were chosen for further analysis. For the air temperature and GDD, the 21-day interval provided the best fit. For soil temperature, the 7-day interval provided the best fit, and for soil moisture, the 21-day interval provided the best fit (not shown).

The magnitude of the effect of each significant explanatory variable was examined graphically to assess their relative influence on the spatial uniformity of emergence (Figure 8, Figure 9). The curves shown in the figures are based on the parameter estimates of each separate model (values not shown).

Table 11. Results of forward-selection modeling for spatial uniformity. The base model includes only the linear relationship between plant density and standard deviation of plant density; interactions with the intercept and linear term are added separately for each explanatory variable. The final model is the minimally adequate version of the full interaction model. Tests of significance for interaction terms in the final model are shown if the final model is significantly better than the base model (X^2, $P < 0.05$).

Explanatory variable	χ^2 (base vs final model)		Final model terms P(>|t|)	
	χ^2, df	P (>χ^2)	Intercept	Linear interaction
Previous crop	3.69, 4	0.450	-	-
Previous crop type	1.05, 1	0.305	-	-
Canola rotation[2]	0.69, 1	0.407	-	-
Cereal rotation[1,2]	0.06, 1	0.800	-	-
Pulse rotation[1,2]	1.51, 1	0.219	-	-
Variety[2]	10.2, 2	**0.006**	-	0.009
Seed treatment	9.29, 1	**0.002**	-	0.002
Seeding depth[1]	1.57, 1	0.211	-	-
Seeding speed[1]	3.51, 1	0.061	-	-
Residue cover (pre-seed)[1]	4.45, 2	0.108	-	-
Residue cover (post-seed)	2.08, 1	0.149	-	-
Seeding date	1.04, 1	0.307	-	-
Seeding rate	0.45, 1	0.501	-	-
Seed size[1]	3.24, 1	0.072	-	-
Hypocotyl length[1]	7.46, 1	**0.006**	-	0.005
N fertilizer rate	5.46, 1	**0.019**	0.042	-
P fertilizer rate	0.03, 1	0.855	-	-
S fertilizer rate	0.20, 1	0.651	-	-
Topsoil percent organic matter[1]	0.10, 1	0.755	-	-
Topsoil nitrate[1]	1.03, 1	0.311	-	-
Topsoil P[1]	6.21, 2	**0.045**	0.100	0.042
Topsoil CEC[1]	0.19, 1	0.663	-	-
Avg mean air Temp (7 dbs[3])	0.01, 1	0.943	-	-
Avg mean air Temp (7 das[4])	10.5, 1	**0.001**	-	0.006
Avg mean air Temp (14 das)	14.7, 1	**<0.001**	-	<0.001
Avg mean air Temp (21 das)	18.7, 2	**<0.001**	0.028	0.001
Cumulative GDD (seeding date)	1.30, 1	0.254	-	-
Total GDD (7 das)	10.1, 1	**0.002**	-	0.007
Total GDD (14 das)	14.6, 1	**<0.001**	-	<0.001
Total GDD (21 das)	18.5, 2	**<0.001**	0.034	0.001
Soil temp (seeding date)	14.4, 2	**0.001**	0.018	0.002
Avg soil temp (7 das)	16.6, 2	**<0.001**	0.010	<0.001
Avg soil temp (14 das)	12.7, 2	**0.002**	0.011	0.001
Avg soil temp (21 das)	12.6, 2	**0.002**	0.006	0.001
Cumulative precip (seeding date)	1.11, 1	0.293	-	-
Total precip (7 das)	0.43, 1	0.514	-	-
Total precip (14 das)	0.65, 1	0.421	-	-
Total precip (21 das)	3.30, 1	0.069	-	-
Rain gauge (seeding date)	0.21, 1	0.650	-	-
Rain gauge (7 das)	0.85, 1	0.356	-	-
Rain gauge (14 das)	0.40, 1	0.529	-	-
Rain gauge (21 das)	0.69, 1	0.404	-	-
Soil moisture (seeding date)	6.54, 2	**0.038**	0.059	0.018
Soil moisture (7 das)	8.41, 2	**0.015**	0.015	0.005
Soil moisture (14 das)	8.41, 2	**0.015**	0.007	0.004
Soil moisture (21 das)	8.58, 2	**0.014**	0.006	0.004

[1] Data set is incomplete for this variable due to missing entries. [2] Original factor levels were combined to simplify the model, provided the grouping was logical and did not result in a significant increase in deviance. [3] dbs = Days before seeding. [4] das = Days after seeding.

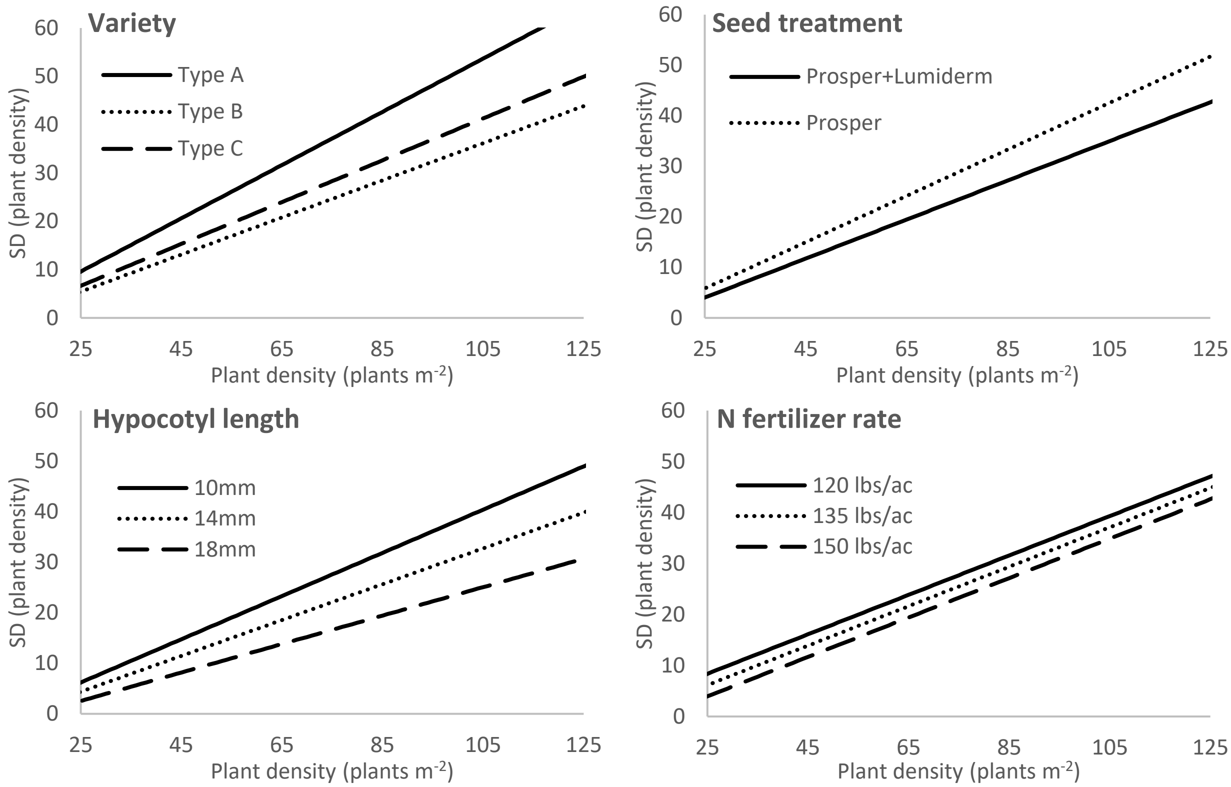


Figure 8. The effect of individual management variables on spatial uniformity of emergence. The management variables include those that were shown to significantly affect the standard deviation of plant density, as a function of plant density (see Table 11). Greater standard deviation values indicates lower spatial uniformity. For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.

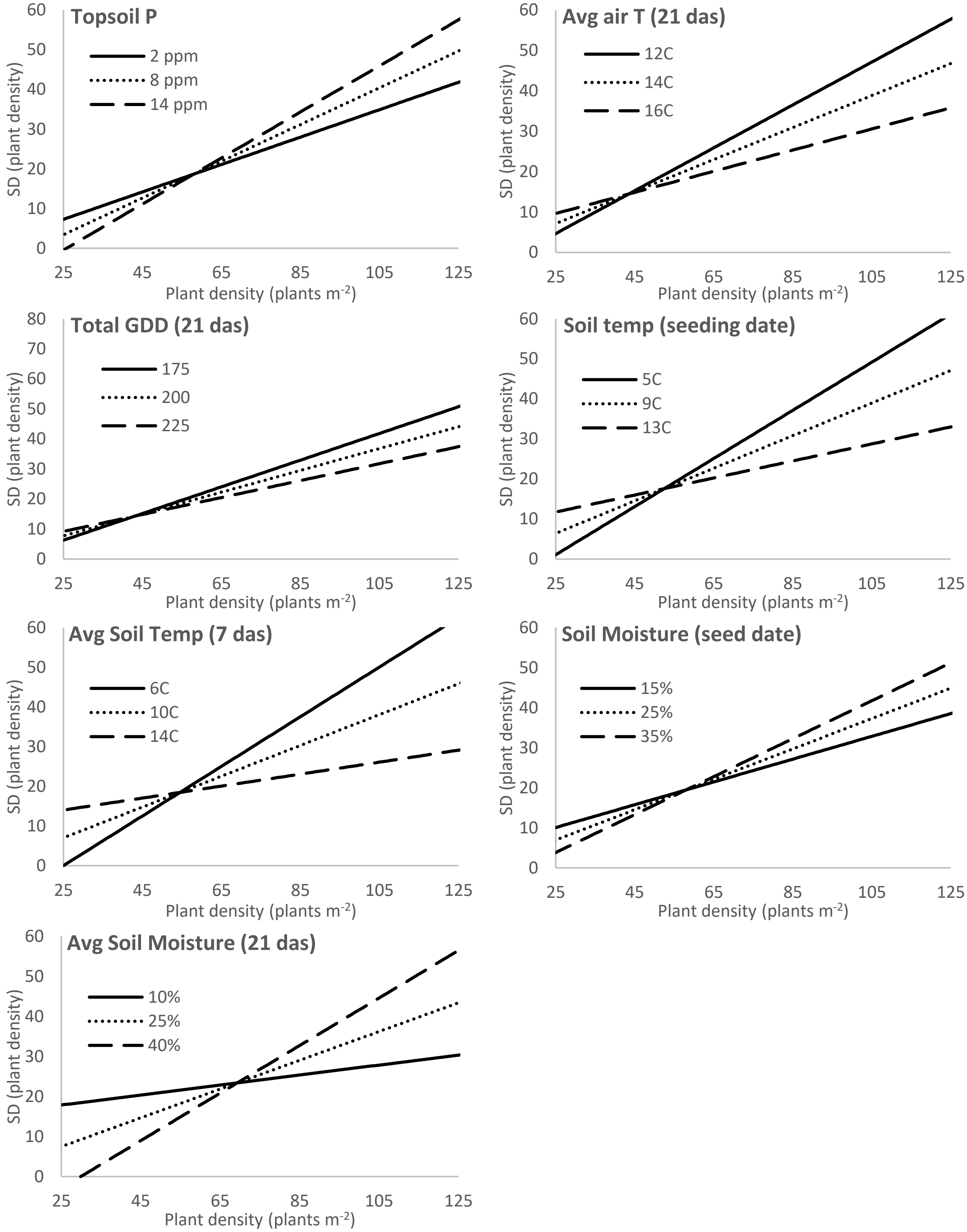


Figure 9. The effect of individual environmental variables on spatial uniformity of emergence. The environmental variables include those that were shown to significantly affect the standard deviation of plant density, as a function of plant density (see Table 11). Greater standard deviation values indicated lower spatial uniformity. For continuous variables, the three curves represent the range of values that are 1) within the minimum and lower quartile, 2) approximately the mean/median, and 3) within the maximum and upper quartile.

Again, variety had a surprisingly large effect on spatial uniformity of emergence. As with percent emergence, an additional insecticidal active ingredient in the seed treatment had a positive effect on spatial uniformity. Also consistent with percent emergence, longer hypocotyl length (deeper seeding depth) had a positive effect on spatial uniformity. A higher N fertilizer rate resulted in higher spatial uniformity, but higher topsoil P resulted in lower spatial uniformity. Again, greater temperature and heat units had a positive effect and were associated with greater spatial uniformity. Consistent with the effect on growth stage, higher soil moisture had a negative effect and was associated with lower spatial uniformity.

A correlation matrix of all the significant explanatory variables was calculated (Table 12). Factor variables (variety and seed treatment) were not included.

The competing models approach was followed for spatial uniformity as well. Variables with missing values were not included in the candidate set of competing models (hypocotyl length, topsoil P). The candidate set of models included each variable on their own (9 models), plus pairwise combinations of each management variable with each environmental variable (3 management x 6 environmental = 18 models). The models included only the significant model terms as identified in Table 11, plus their interactions. The candidate models were simplified via stepwise deletion of non-significant terms, provided the final model did not result in significantly poorer model fit (χ^2, P>0.05). The minimally adequate candidate models were ranked from lowest to highest AIC, and the Akaike weight was calculated for each model.

The 10 top-ranked models out of the candidate set of 27 models are listed in Table 13 along with their Akaike weights. For each individual variable, predictor weights were calculated by adding the Akaike weights from all the models in which that variable was included, and the best-ranked model for each variable was determined (Table 14).

Table 12. Intercorrelations among continuous management and environmental variables that were shown to significantly affect the spatial uniformity of emergence. 'NS' indicates non-significant correlations. Correlation coefficients greater than 0.50 are bolded for emphasis.

	Hypocotyl length	N fertilizer rate	Topsoil P	Avg air Temp (21 das)	Total GDD (21 das)	Soil temp (seed date)	Avg soil temp (7 das)	Soil moisture (seed date)	Avg soil moisture (21 das)
Hypocotyl length	1.00								
N fertilizer rate	-0.25	1.00							
Topsoil P	ns	0.28	1.00						
Avg air Temp (21 das)	-0.32	0.15	-0.22	1.00					
Total GDD (21 das)	-0.32	0.15	-0.22	**1.00**	1.00				
Soil temp (seed date)	-0.33	0.17	ns	**0.52**	**0.51**	1.00			
Avg soil temp (7 das)	-0.37	0.21	ns	**0.61**	**0.61**	**0.94**	1.00		
Soil moisture (seed date)	ns	0.30	0.19	-0.39	-0.41	-0.23	-0.29	1.00	
Avg soil moisture (21 das)	ns	0.43	ns	ns	ns	ns	-0.18	**0.72**	1.00

Table 13. Top ranked models out of the candidate set of 27 competing models for spatial uniformity of emergence. All models include plant density, and the additional model terms as listed. The 3-way interaction was not significant in any of the minimal adequate models. ΔAIC is the difference in AIC between each model and the top ranked model. The Akaike weight indicates the probability that the model provides the best representation of the true relationship, relative to other models in the candidate set.

	Minimal adequate model interaction terms					
Rank	intercept	linear interaction	Intercept	linear interaction	ΔAIC	Model weight
1	-	-	Avg air Temp (21 das)	Avg air Temp (21 das)	0.0	0.347
2	N fertilizer rate	-	Avg air Temp (21 das)	Avg air Temp (21 das)	0.5	0.266
3	-	-	Avg soil temp (7 das)	Avg soil temp (7 das)	2.0	0.130
4	N fertilizer rate	-	Avg soil temp (7 das)	Avg soil temp (7 das)	2.8	0.084
5			Soil temp (seed date)	Soil temp (seed date)	4.5	0.037
6	N fertilizer rate	-	Soil temp (seed date)	Soil temp (seed date)	5.0	0.028
7	-	Seed treatment	-	Avg air Temp (21 das)	5.4	0.024
8	-	Seed treatment	-	-	5.5	0.022
9	-	Seed treatment	Avg soil temp (7 das)	Avg soil temp (7 das)	5.6	0.021
10	-	Variety	Avg air Temp (21 das)	Avg air Temp (21 das)	5.8	0.019

Table 14. Predictor weights for each explanatory variable included in the candidate competing models set for spatial uniformity of emergence. Predictor weights indicate the probability that the variable would be involved in the true relationship, relative to the other variables in the candidate model set.

Variable	Predictor weight	1st ranked model
Avg air Temp (21 das)	0.656	1
N fertilizer rate	0.387	2
Avg soil Temp (7 das)	0.235	3
Seed treatment	0.076	7
Soil temp (seed date)	0.074	5
Variety	0.022	10
Total GDD (21 das)	0.002	16
Avg soil moisture (21 das)	0.001	17
Soil moisture (seed date)	<0.001	21

There was significant model uncertainty in the prediction of spatial uniformity, indicating that several variables were more equally influential on spatial uniformity of canola emergence. The top-ranked environmental variables were ranked higher on their own than in combination with management variables, indicating management overall was not particularly influential on spatial uniformity. Temperature appeared to have a greater influence than moisture, based on predictor weights (Table 14), though average soil moisture 21 days after seeding appeared to have a large effect size (Figure 9).

Discussion

The competing models analysis has allowed us to look at the relative influence of both management variables and environmental variables simultaneously. The candidate models were chosen such that we could more specifically compare the relative influence of the same type of variable (environmental or management) relative to each other, and whether management and environment had additive or interactive effects. The method followed was most appropriate considering the low level of replication and considering the intercorrelation of the variables included in the study, though the inclusion of random effects does address these issues to a certain degree. Importantly, the direction of the effect (positive or negative) as identified with single additional variable models and illustrated in the figures were fairly consistent with what would be expected based on previous research and experience, which helps to validate the study design and demonstrate the potential for future studies with similar methodology.

For management variables, it is interesting to note that several variables consistently had a significant effect on the emergence response variables, regardless of whether they were the most influential. Variety, or more appropriately, cultivar, was shown to influence emergence consistently and substantially. In previous agronomic studies, emergence of open-pollinated and hybrid canola cultivars was often compared, but the differential response of hybrid cultivars has not been studied extensively. It is also possible that there may be a seed lot effect, considering the low replication of some varieties in this study. In contrast, some management variables consistently did not have a significant influence on the emergence response. Previous crop and residue cover were both well replicated, and values of residue cover adequately represented the potential range of the variable, however neither reliably influenced the emergence response. Crop rotational effects were also small and inconsistent. Other management variables had a significant effect on one or more, but not all the response variables. It is possible that the range of these variables was not widely represented (e.g., seed size, seeding speed), or that the measurement was not accurate enough (e.g., producer-reported seeding depth). Some variables surprisingly had a significant effect even with very little data (e.g., hypocotyl length) and some missing data (soil quality, e.g., CEC).

For environmental variables, temperature and heat units were consistently more influential than precipitation and soil moisture in the years and location studied. Precipitation and soil moisture were also consistently influential, and previous research has often shown that moisture can have a greater effect on emergence than temperature (Harker et al. 2012). As with the management factors, the relative influence of different environmental variables could be a function of the range that was represented in the study. As the study was only conducted in a single location over 3 years, it is possible that the range of precipitation and moisture conditions was too narrow to elucidate an emergence response. Additional replication, especially the expansion of the study to additional locations, will provide better representation of the range of environmental conditions. Further, a better representation of the range of environmental conditions will make it more likely to identify interactive effects between environmental and management factors. For example, a seeding depth and soil moisture interaction is more likely to be observed if there is a combination of typically high and low values of each of the variables. Such an interaction could potentially explain unexpected results such as the positive effect of increased seeding depth on canola emergence.

In future analyses, it will be insightful to include several non-correlated variables of the same type (e.g., temperature and moisture), or even several inter-correlated variables simultaneously in the same model. However, more replication will be needed for this to be possible statistically, especially to validate the use of more advanced and favourable multivariate analytical approaches such as structural equation modeling. Additional replication would also justify the inclusion of variables with missing values in the multivariate analysis; at this point, including those variables would result in an unacceptable level of data loss. Overall, an extension of the study to provide additional replication, with a focus on particular variables of interest, would be beneficial in achieving the objectives of the study.

The analysis shown in this report is fairly explorative but illustrates the potential that could be achieved with this type of observational study, utilizing on-farm data collection. In addition to addressing the topic of disease development as per the objectives of this study, further exploration of the effect of stand establishment on the canola production system would be possible utilizing the data collected as part of this study. Potential relationships that could be explored include: 1) the influence of speed and uniformity of emergence on the uniformity of crop development, especially, flowering and maturity; 2) the influence of speed and uniformity of emergence on yield directly, or indirectly through effects on crop development; 3) the relationship between spring plant density and fall stubble density and the influence of environmental factors on in-season mortality; and 4) the relationship between fall stubble density and canola production. With greater replication and expansion of this data set, these relationships could conceivably be explored simultaneously utilizing a structural equation modeling approach.

A secondary objective of this study was to develop relationships between research organizations and producers to facilitate future research collaborations and help applied research organizations transition to more field-scale agronomic trials. The present study has also demonstrated the usefulness of new and different study designs that have been more common in ecological research, where experimental manipulations can be challenging. Observational studies eliminate the requirement for producers to implement and maintain field trials which are time-consuming and logistically demanding.

CONCLUSIONS AND RECOMMENDATIONS

The additive and interactive effects of management and environment on the speed, temporal uniformity, and spatial uniformity of canola emergence were examined. Several management variables were found to be significantly influencing the emergence response at the location and in the years studied. Canola cultivar was the most influential management variable and had a consistent and surprisingly large effect on all emergence response variables. Seeding date was also consistently and significantly influential on emergence, however the effect was not additive when combined with environmental variables. This indicates that the effect of seeding date was mainly a function of environmental conditions. Nearly all the environmental variables measured consistently influenced the emergence response and had additive and sometimes interactive effects with the management variables. Temperature and heat units were consistently more influential on emergence than precipitation and moisture.

The analysis and findings of the study were limited by the level of replication. In particular, conducting the study in a single location limited the range of certain environmental conditions represented in the study. An extension of the study to provide additional replication at several locations would be insightful and would allow for the interpolation of the results to different agricultural production regions. Yet, the study was useful in demonstrating the potential of on-farm observational studies in agronomic research. An extension of the study could focus on particular variables of interest, as identified by canola industry stakeholders.

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APPENDICES

None.

EXTENSION AND ADMINISTRATION

Extension

Results have not been presented to the public at this time but will be communicated via oral presentations, and online and printed reference material and publications in the near future. Media representatives have been in contact and will be involved in sharing the results of the study with the public.

Financial Report

Provided in a separate document.