

# The `germinationmetrics` Package: A Brief Introduction

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2023-08-13

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## Overview

The package `germinationmetrics` is a collection of functions which implements various methods for describing the time-course of germination in terms of single-value germination indices as well as fitted curves.

The goal of this vignette is to introduce the users to these functions and get started in describing sequentially recorded germination count data. This document assumes a basic knowledge of R programming language.



## Installation

The package can be installed using the following functions:

```
# Install from CRAN
install.packages('germinationmetrics', dependencies=TRUE)

# Install development version from Github
devtools::install_github("aravind-j/germinationmetrics")
```

Then the package can be loaded using the function

```
library(germinationmetrics)
```

## Version History

The current version of the package is 0.1.7. The previous versions are as follows.

**Table 1.** Version history of `germinationmetrics` R package.

Version	Date
0.1.0	2018-04-17
0.1.1	2018-07-26
0.1.1.1	2018-10-16
0.1.2	2018-10-31
0.1.3	2019-01-19
0.1.4	2020-06-16
0.1.5	2021-02-17
0.1.6	2022-06-15

To know detailed history of changes use `news(package='germinationmetrics')`.

## Germination count data

Typically in a germination test, the germination count data of a fixed number of seeds is recorded at regular intervals for a definite period of time or until all the seeds have germinated. These germination count data can be either partial or cumulative (Table 2).

**Table 2 :** A typical germination count data.

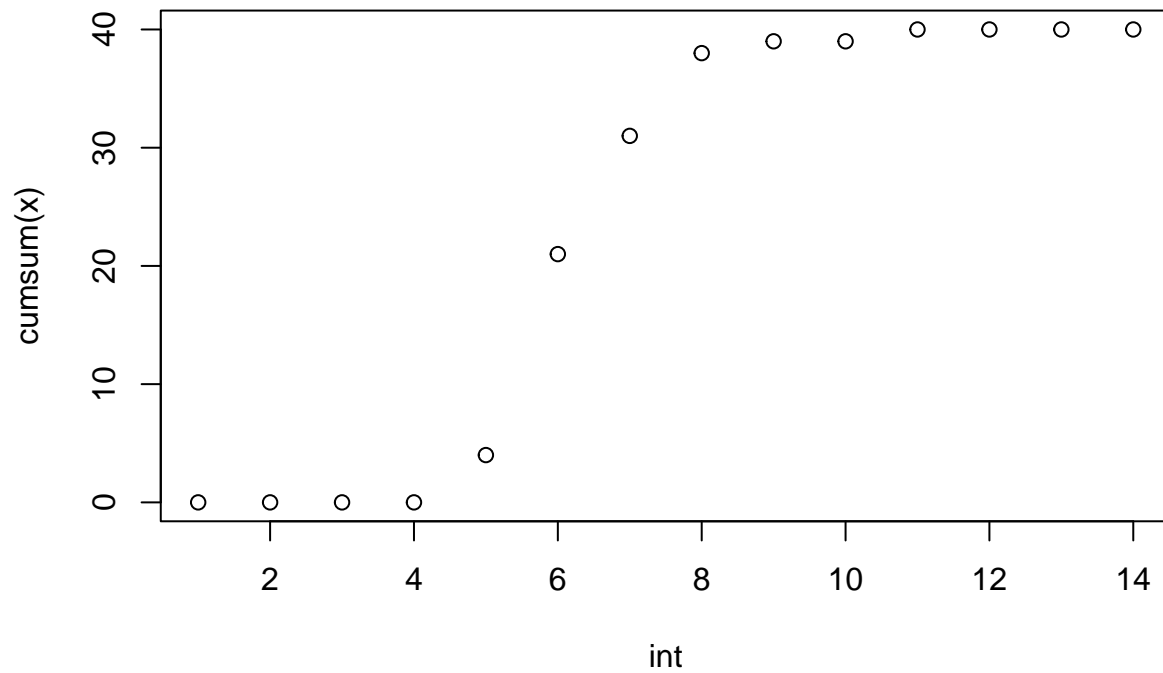
intervals	counts	cumulative.counts
1	0	0
2	0	0
3	0	0
4	0	0
5	4	4
6	17	21
7	10	31
8	7	38
9	1	39
10	0	39
11	1	40
12	0	40
13	0	40
14	0	40

The time-course of germination can be plotted as follows.

```
data <- data.frame(intervals = 1:14,
                  counts = c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0))

# Partial germination counts
x <- data$counts
# Cumulative germination counts
y <- cumsum(x)
# Time intervals of observations
int <- data$intervals
```

```
plot(int, cumsum(x))
```



### Single-value germination indices

The details about the single-value germination indices implemented in `germinationmetrics` are described in Table 3.

**Table 3 :** Single-value germination indices implemented in `germinationmetrics`.

Germination index	Function	Details	Unit	Measures	Reference
Germination percentage or Final germination percentage or Germinability ( $GP$ )	<b>GermPercent</b>	It is computed as follows. $GP = \frac{N_g}{N_t} \times 100$ Where, $N_g$ is the number of germinated seeds and $N_t$ is the total number of seeds.	Percentage (%)	Germination capacity	ISTA (2015)
Peak germination percentage ( $PGP$ )	<b>PeakGermPercent</b>	It is computed as follows. $PGP = \frac{N_{max}}{N_t} \times 100$ Where, $N_{max}$ is the maximum number of seeds germinated per interval.	Percentage (%)	Germination capacity	Vallance (1950); Roh et al. (2004)
Time for the first germination or Germination time lag ( $t_0$ )	<b>FirstGermTime</b>	It is the time for first germination to occur (e.g. First day of germination). $t_0 = \min \{T_i : N_i \neq 0\}$ Where, $T_i$ is the time from the start of the experiment to the $i$ th interval and $N_i$ is the number of seeds germinated in the $i$ th time interval (not the accumulated number, but the number corresponding to the $i$ th interval)	time	Germination time	Edwards (1932); Czabator (1962); Goloff and Bazzaz (1975); Labouriau (1983a); Ranal (1999); Quintanilla et al. (2000)
Time for the last germination ( $t_g$ )	<b>LastGermTime</b>	It is the time for last germination to occur (e.g. Last day of germination) $t_g = \max \{T_i : N_i \neq 0\}$ Where, $T_i$ is the time from the start of the experiment to the $i$ th interval and $N_i$ is the number of seeds germinated in the $i$ th time interval (not the accumulated number, but the number corresponding to the $i$ th interval)	time	Germination time	Edwards (1932)
Time spread of germination or Germination distribution	<b>TimeSpreadGerm</b>	It is the difference between time for last germination ( $t_g$ ) and time for first germination ( $t_0$ ). $Time\ spread\ of\ germination = t_g - t_0$	time	Germination time	Al-Mударis (1998); Schrader and Graves (2000); Kader (2005)
Peak period of germination or Modal time of germination ( $t_{peak}$ )	<b>PeakGermTime</b>	It is the time in which highest frequency of germinated seeds are observed and need not be unique. $t_{peak} = \{T_i : N_i = N_{max}\}$ Where, $T_i$ is the time from the start of the experiment to the $i$ th interval, $N_i$ is the number of seeds germinated in the $i$ th time interval (not the accumulated number, but the number corresponding to the $i$ th interval) and $N_{max}$ is the maximum number of seeds germinated per interval.	time	Germination time	Ranal and Santana (2006)

Germination index	Function	Details	Unit	Measures	Reference
Median germination time ( $t_{50}$ ) (Coolbear)	<b>t50</b>	<p>It is the time to reach 50% of final/maximum germination. With argument <b>method</b> specified as "<b>coolbear</b>", it is computed as follows.</p> $t_{50} = T_i + \frac{(\frac{N+1}{2} - N_i)(T_j - T_i)}{N_j - N_i}$ <p>Where, <math>t_{50}</math> is the median germination time, <math>N</math> is the final number of germinated seeds, and <math>N_i</math> and <math>N_j</math> are the total number of seeds germinated in adjacent counts at time <math>T_i</math> and <math>T_j</math> respectively, when <math>N_i &lt; \frac{N+1}{2} &lt; N_j</math>.</p>	time	Germination time	Coolbear et al. (1984)
Median germination time ( $t_{50}$ ) (Farooq)	<b>t50</b>	<p>With argument <b>method</b> specified as "<b>farooq</b>", it is computed as follows.</p> $t_{50} = T_i + \frac{(\frac{N}{2} - N_i)(T_j - T_i)}{N_j - N_i}$ <p>Where, <math>t_{50}</math> is the median germination time, <math>N</math> is the final number of germinated seeds, and <math>N_i</math> and <math>N_j</math> are the total number of seeds germinated in adjacent counts at time <math>T_i</math> and <math>T_j</math> respectively, when <math>N_i &lt; \frac{N}{2} &lt; N_j</math>.</p>	time	Germination time	Farooq et al. (2005)
Mean germination time or Mean length of incubation time ( $\bar{T}$ ) or Germination resistance ( $GR$ ) or Sprouting index ( $SI$ ) or Emergence index ( $EI$ )	<b>MeanGermTime</b>	<p>It is the average length of time required for maximum germination of a seed lot and is estimated according to the following formula.</p> $\bar{T} = \frac{\sum_{i=1}^k N_i T_i}{\sum_{i=1}^k N_i}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals.</p> <p>It is the inverse of mean germination rate (<math>\bar{V}</math>).</p> $\bar{T} = \frac{1}{\bar{V}}$	time	Germination time	Edmond and Drapala (1958); Czabator (1962); Smith and Millet (1964); Gordon (1969); Gordon (1971); Mock and Eberhart (1972); Ellis and Roberts (1980) Labouriau (1983a); Ranal and Santana (2006)

Germination index	Function	Details	Unit	Measures	Reference
Variance of germination time ( $s_T^2$ )	<b>VarGermTime</b>	<p>It is computed according to the following formula.</p> $s_T^2 = \frac{\sum_{i=1}^k N_i (T_i - \overline{T})^2}{\sum_{i=1}^k N_i - 1}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals.</p>	time <sup>-1</sup>	Germination time	Labouriau (1983a); Ranal and Santana (2006)
Standard error of germination time ( $s_{\overline{T}}$ )	<b>SEGermTime</b>	<p>It signifies the accuracy of the calculation of the mean germination time. It is estimated according to the following formula:</p> $s_{\overline{T}} = \sqrt{\frac{s_T^2}{\sum_{i=1}^k N_i}}$ <p>Where, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval) and <math>k</math> is the total number of time intervals.</p>	time	Germination time	Labouriau (1983a); Ranal and Santana (2006)
Mean germination rate ( $\overline{V}$ )	<b>MeanGermRate</b>	<p>It is computed according to the following formula:</p> $\overline{V} = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k N_i T_i}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals. It is the inverse of mean germination time (<math>\overline{T}</math>).</p> $\overline{V} = \frac{1}{\overline{T}}$	time <sup>-1</sup>	Germination rate	Labouriau and Valadares (1976); Labouriau (1983b); Ranal and Santana (2006)

Germination index	Function	Details	Unit	Measures	Reference
Coefficient of velocity of germination ( <i>CVG</i> ) or Coefficient of rate of germination ( <i>CRG</i> ) or Kotowski's coefficient of velocity	<b>CVG</b>	<p>It is estimated according to the following formula.</p> $CVG = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k N_i T_i} \times 100$ $CVG = \bar{V} \times 100$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals.</p>	% time <sup>-1</sup>	Germination rate	Kotowski (1926), Nichols and Heydecker (1968); Bewley and Black (1994); Labouriau (1983b); Scott et al. (1984)
Variance of germination rate ( $s_V^2$ )	<b>VarGermRate</b>	<p>It is calculated according to the following formula.</p> $s_V^2 = \bar{V}^4 \times s_T^2$ <p>Where, <math>s_T^2</math> is the variance of germination time.</p>	time <sup>-2</sup>	Germination rate	Labouriau (1983b); Ranal and Santana (2006)
Standard error of germination rate ( $s_{\bar{V}}$ )	<b>SEGermRate</b>	<p>It is estimated according to the following formula.</p> $s_{\bar{V}} = \sqrt{\frac{s_V^2}{\sum_{i=1}^k N_i}}$ <p>Where, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals.</p>	time <sup>-1</sup>	Germination rate	Labouriau (1983b); Ranal and Santana (2006)
Germination rate as the reciprocal of the median time ( $v_{50}$ )	<b>GermRateRecip</b>	<p>It is the reciprocal of the median germination time (<math>t_{50}</math>).</p> $v_{50} = \frac{1}{t_{50}}$	time <sup>-1</sup>	Germination rate	Went (1957); Labouriau (1983b); Ranal and Santana (2006)
Speed of germination or Germination rate Index or index of velocity of germination or Emergence rate index (Allan, Vogel and Peterson; Erbach; Hsu and Nelson) or Germination index (AOSA)	<b>GermSpeed</b>	<p>It is the rate of germination in terms of the total number of seeds that germinate in a time interval. It is estimated as follows.</p> $S = \sum_{i=1}^k \frac{N_i}{T_i}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>k</math> is the total number of time intervals. Instead of germination counts, germination percentages may also be used for computation of speed of germination.</p>	% time <sup>-1</sup> or count time <sup>-1</sup>	Mixed	Throneberry and Smith (1955); Maguire (1962); Allan et al. (1962); Kendrick and Frankland (1969); Bouton et al. (1976); Erbach (1982); AOSA (1983); Khandakar and Bradbeer (1983); Hsu and Nelson (1986); Bradbeer (1988); Wardle et al. (1991)

Germination index	Function	Details	Unit	Measures	Reference
Speed of accumulated germination	<b>GermSpeedAccumulate</b>	<p>It is the rate of germination in terms of the accumulated/cumulative total number of seeds that germinate in a time interval.</p> <p>It is estimated as follows.</p> $S_{accumulated} = \sum_{i=1}^k \frac{\sum_{j=1}^i N_j}{T_i}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>\sum_{j=1}^i N_j</math> is the cumulative/accumulated number of seeds germinated in the <math>i</math>th interval, and <math>k</math> is the total number of time intervals.</p> <p>Instead of germination counts, germination percentages may also be used for computation of speed of germination.</p>	% time <sup>-1</sup> or count time <sup>-1</sup>	Mixed	Bradbeer (1988); Wardle et al. (1991); Haugland and Brandsaeter (1996); Santana and Ranal (2004)
Corrected germination rate index	<b>GermSpeedCorrected</b>	<p>It is computed as follows.</p> $S_{corrected} = \frac{S}{FGP}$ <p>Where, <math>S</math> is the germination speed computed with germination percentage instead of counts and <math>FGP</math> is the final germination percentage or germinability.</p>	time <sup>-1</sup>	Mixed	Evetts and Burnside (1972)
Weighted germination percentage ( $WGP$ )	<b>WeightGermPercent</b>	<p>It is estimated as follows.</p> $WGP = \frac{\sum_{i=1}^k (k-i+1)N_i}{k \times N} \times 100$ <p>Where, <math>N_i</math> is the number of seeds that germinated in the time interval <math>i</math> (not cumulative, but partial count), <math>N</math> is the total number of seeds tested, and <math>k</math> is the total number of time intervals.</p>	Percentage (%)	Mixed	Reddy et al. (1985); Reddy (1978)
Mean germination percentage per unit time ( $\overline{GP}$ )	<b>MeanGermPercent</b>	<p>It is estimated as follows.</p> $\overline{GP} = \frac{GP}{T_k}$ <p>Where, <math>GP</math> is the final germination percentage, <math>T_k</math> is the time at the <math>k</math>th time interval, and <math>k</math> is the total number of time intervals required for final germination.</p>	% time <sup>-1</sup>	Mixed	Czabator (1962)
Number of seeds germinated per unit time $\overline{N}$	<b>MeanGermNumber</b>	<p>It is estimated as follows.</p> $\overline{N} = \frac{N_g}{T_k}$ <p>Where, <math>N_g</math> is the number of germinated seeds at the end of the germination test, <math>T_k</math> is the time at the <math>k</math>th time interval, and <math>k</math> is the total number of time intervals required for final germination.</p>	count time <sup>-1</sup>	Mixed	Khamassi et al. (2013)



Germination index	Function	Details	Unit	Measures	Reference
Timson's index [ $\sum 10$ (Ten summation), $\sum 5$ or $\sum 20$ ] or Germination energy index ( <i>GEI</i> )	<b>TimsonsIndex</b>	<p>It is the progressive total of cumulative germination percentage recorded at specific intervals for a set period of time and is estimated in terms of cumulative germination percentage (<math>G_i</math>) as follows.</p> $\Sigma k = \sum_{i=1}^k G_i$ <p>Where, <math>G_i</math> is the cumulative germination percentage in time interval <math>i</math>, and <math>k</math> is the total number of time intervals. It also estimated in terms of partial germination percentage as follows.</p> $\Sigma k = \sum_{i=1}^k g_i(k - j)$ <p>Where, <math>g_i</math> is the germination (not cumulative, but partial germination) in time interval <math>i</math> (<math>i</math> varying from 0 to <math>k</math>), <math>k</math> is the total number of time intervals, and <math>j = i - 1</math>.</p>	Percentage (%)	Mixed	Grose and Zimmer (1958); Timson (1965); ( <b>lyonRapid-MethodDetermining1966?</b> ); Chaudhary and Ghildyal (1970); Negm and Smith (1978); Brown and Mayer (1988); Baskin and Baskin (1998); Goodchild and Walker (1971)
Modified Timson's index ( $\Sigma k_{mod}$ ) (Labouriau)	<b>TimsonsIndex</b>	<p>It is estimated as Timson's index <math>\Sigma k</math> divided by the sum of partial germination percentages.</p> $\Sigma k_{mod} = \frac{\Sigma k}{\sum_{i=1}^k g_i}$	no unit	Mixed	Ranal and Santana (2006)
Modified Timson's index ( $\Sigma k_{mod}$ ) (Khan and Unger)	<b>TimsonsIndex</b>	<p>It is estimated as Timson's index (<math>\Sigma k</math>) divided by the total time period of germination (<math>T_k</math>).</p> $\Sigma k_{mod} = \frac{\Sigma k}{T_k}$	% time <sup>-1</sup>	Mixed	Khan and Ungar (1984)
George's index ( <i>GR</i> )	<b>GermRateGeorge</b>	<p>It is estimated as follows.</p> $GR = \sum_{i=1}^k N_i K_i$ <p>Where <math>N_i</math> is the number of seeds germinated by <math>i</math>th interval and <math>K_i</math> is the number of intervals(eg. days) until the end of the test, and <math>k</math> is the total number of time intervals.</p>	count time	Mixed	George (1961); Tucker and Wright (1965); Nichols and Heydecker (1968);Chopra and Chaudhary (1980)

Germination index	Function	Details	Unit	Measures	Reference
Germination Index ( $GI$ ) (Melville)	<b>GermIndex</b>	<p>It is estimated as follows.</p> $GI = \sum_{i=1}^k \frac{ (T_k - T_i) N_i }{N_t}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval (day for the example), <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), <math>N_t</math> is the total number of seeds used in the test, and <math>k</math> is the total number of time intervals.</p>	time	Mixed	Melville et al. (1980)
Germination Index ( $GI_{mod}$ ) (Melville; Santana and Ranal)	<b>GermIndex</b>	<p>It is estimated as follows.</p> $GI_{mod} = \sum_{i=1}^k \frac{ (T_k - T_i) N_i }{N_g}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval (day for the example), <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), <math>N_g</math> is the total number of germinated seeds at the end of the test, and <math>k</math> is the total number of time intervals.</p>	time	Mixed	Melville et al. (1980); Santana and Ranal (2004); Ranal and Santana (2006)
Emergence Rate Index ( $ERI$ ) or Germination Rate Index (Shmueli and Goldberg)	<b>EmergenceRateIndex</b>	<p>It is estimated as follows.</p> $ERI = \sum_{i=i_0}^{k-1} N_i(k-i)$ <p>Where, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), <math>i_0</math> is the time interval when emergence/germination started, and <math>k</math> is the total number of time intervals.</p>	count	Mixed	Shmueli and Goldberg (1971)
Modified Emergence Rate Index ( $ERI_{mod}$ ) or Modified Germination Rate Index (Shmueli and Goldberg; Santana and Ranal)	<b>EmergenceRateIndex</b>	<p>It is estimated by dividing Emergence rate index (<math>ERI</math>) by total number of emerged seedlings (or germinated seeds).</p> $ERI_{mod} = \frac{\sum_{i=i_0}^{k-1} N_i(k-i)}{N_g} = \frac{ERI}{N_g}$ <p>Where, <math>N_g</math> is the total number of germinated seeds at the end of the test, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), <math>i_0</math> is the time interval when emergence/germination started, and <math>k</math> is the total number of time intervals.</p>	no unit	Mixed	Shmueli and Goldberg (1971); Santana and Ranal (2004); Ranal and Santana (2006)

Germination index	Function	Details	Unit	Measures	Reference
Emergence Rate Index ( <i>ERI</i> ) or Germination Rate Index (Bilbro & Wanjura)	<b>EmergenceRateIndex</b>	<p>It is the estimated as follows.</p> $ERI = \frac{\sum_{i=1}^k N_i}{\bar{T}} = \frac{N_g}{\bar{T}}$ <p>Where, <math>N_g</math> is the total number of germinated seeds at the end of the test, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time interval (not the accumulated number, but the number corresponding to the <math>i</math>th interval), and <math>\bar{T}</math> is the mean germination time or mean emergence time.</p>	count time <sup>-1</sup>	Mixed	Bilbro and Wanjura (1982)
Emergence Rate Index ( <i>ERI</i> ) or Germination Rate Index (Fakorede)	<b>EmergenceRateIndex</b>	<p>It is estimated as follows.</p> $ERI = \frac{\bar{T}}{FGP/100}$ <p>Where, <math>\bar{T}</math> is the Mean germination time and <math>FGP</math> is the final germination time.</p>	time count <sup>-1</sup>	Mixed	Fakorede and Ayoola (1980); Fakorede and Ojo (1981); Fakorede and Agbana (1983)
Peak value( <i>PV</i> ) (Czabator) or Emergence Energy ( <i>EE</i> )	<b>PeakValue</b>	<p>It is the accumulated number of seeds germinated at the point on the germination curve at which the rate of germination starts to decrease. It is computed as the maximum quotient obtained by dividing successive cumulative germination values by the relevant incubation time.</p> $PV = \max \left( \frac{G_1}{T_1}, \frac{G_2}{T_2}, \dots, \frac{G_k}{T_k} \right)$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th interval, <math>G_i</math> is the cumulative germination percentage in the <math>i</math>th time interval, and <math>k</math> is the total number of time intervals.</p>	% time <sup>-1</sup>	Mixed	Czabator (1962); Bonner (1967)
Germination value ( <i>GV</i> ) (Czabator)	<b>GermValue</b>	<p>It is computed as follows.</p> $GV = PV \times MDG$ <p>Where, <math>PV</math> is the peak value and <math>MDG</math> is the mean daily germination percentage from the onset of germination. It can also be computed for other time intervals of successive germination counts, by replacing <math>MDG</math> with the mean germination percentage per unit time (<math>GP</math>). <math>GV</math> value can be modified (<math>GV_{mod}</math>), to consider the entire duration from the beginning of the test instead of just from the onset of germination.</p>	% <sup>2</sup> time <sup>-2</sup>	Mixed	Czabator (1962); Brown and Mayer (1988)

Germination index	Function	Details	Unit	Measures	Reference
Germination value ( <i>GV</i> ) (Diavanshir and Pourbiek)	<b>GermValue</b>	<p>It is computed as follows.</p> $GV = \frac{\sum DGS}{N} \times GP \times c$ <p>Where, <i>DGS</i> is the daily germination speed computed by dividing cumulative germination percentage by the number of days since the onset of germination, <i>N</i> is the frequency or number of DGS calculated during the test, <i>GP</i> is the germination percentage expressed over 100, and <i>c</i> is a constant. The value of <i>c</i> is decided on the basis of average daily speed of germination (<math>\frac{\sum DGS}{N}</math>). If it is less than 10, then <i>c</i> value of 10 can be used and if it is more than 10, then value of 7 or 8 can be used for <i>c</i>.  <i>GV</i> value can be modified (<i>GV<sub>mod</sub></i>), to consider the entire duration from the beginning of the test instead of just from the onset of germination.</p>	% <sup>2</sup> time <sup>-1</sup>	Mixed	Djavanshir and Pourbeik (1976); Brown and Mayer (1988)
Coefficient of uniformity of germination ( <i>CUG</i> )	<b>CUGerm</b>	<p>It is computed as follows.</p> $CUG = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k (\bar{T} - T_i)^2 N_i}$ <p>Where, <math>\bar{T}</math> is the the mean germination time, <i>T<sub>i</sub></i> is the time from the start of the experiment to the <i>i</i>th interval (day for the example), <i>N<sub>i</sub></i> is the number of seeds germinated in the <i>i</i>th time interval (not the accumulated number, but the number corresponding to the <i>i</i>th interval), and <i>k</i> is the total number of time intervals.</p>	time <sup>-2</sup>	Germination unifromity	Heydecker (1972); Bewley and Black (1994)
Coefficient of variation of the germination time ( <i>CV<sub>T</sub></i> )	<b>CVGermTime</b>	<p>It is estimated as follows.</p> $CV_T = \sqrt{\frac{s_T^2}{\bar{T}}}$ <p>Where, <i>s<sub>T</sub><sup>2</sup></i> is the variance of germination time and <math>\bar{T}</math> is the mean germination time.</p>	no unit	Germination unifromity	Gomes (1960); Ranal and Santana (2006)
Synchronization index ( $\bar{E}$ ) or Uncertainty of the germination process ( <i>U</i> ) or informational entropy ( <i>H</i> )	<b>GermUncertainty</b>	<p>It is estimated as follows.</p> $\bar{E} = - \sum_{i=1}^k f_i \log_2 f_i$ <p>Where, <i>f<sub>i</sub></i> is the relative frequency of germination (<math>f_i = \frac{N_i}{\sum_{i=1}^k N_i}</math>), <i>N<sub>i</sub></i> is the number of seeds germinated on the <i>i</i>th time interval, and <i>k</i> is the total number of time intervals.</p>	bit	Germination synchrony	Shannon (1948); Labouriau and Valadares (1976); Labouriau (1983b)

Germination index	Function	Details	Unit	Measures	Reference
Synchrony of germination ( $Z$ index)	<b>GermSynchrony</b>	<div>It is computed as follows.</div> $Z = \frac{\sum_{i=1}^k C_{N_i,2}}{C_{\Sigma N_i,2}}$ <div>Where, <math>C_{N_i,2}</math> is the partial combination of the two germinated seeds from among <math>N_i</math>, the number of seeds germinated on the <math>i</math>th time interval (estimated as <math>C_{N_i,2} = \frac{N_i(N_i-1)}{2}</math>), and <math>C_{\Sigma N_i,2}</math> is the partial combination of the two germinated seeds from among the total number of seeds germinated at the final count, assuming that all seeds that germinated did so simultaneously.</div>	no unit	Germination synchrony	Primack (1985); Ranal and Santana (2006)

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
z <- c(0, 0, 0, 0, 11, 11, 9, 7, 1, 0, 1, 0, 0, 0)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
GermPercent(germ.counts = x, total.seeds = 50)
```

```
GermPercent()
```

```
[1] 80
```

```
PeakGermPercent(germ.counts = x, intervals = int, total.seeds = 50)
```

```
[1] 34
```

```
# For multiple peak germination times
```

```
PeakGermPercent(germ.counts = z, intervals = int, total.seeds = 50)
```

Warning in `PeakGermPercent(germ.counts = z, intervals = int, total.seeds = 50)`: Multiple peak germination times exist.

```
[1] 22
```

```
# From cumulative germination counts
```

```
#-----
```

```
GermPercent(germ.counts = y, total.seeds = 50, partial = FALSE)
```

```
[1] 80
```

```
PeakGermPercent(germ.counts = y, intervals = int, total.seeds = 50,
                 partial = FALSE)
```

```
[1] 34
```

```
# For multiple peak germination times
```

```
PeakGermPercent(germ.counts = cumsum(z), intervals = int, total.seeds = 50,
                 partial = FALSE)
```

Warning in `PeakGermPercent(germ.counts = cumsum(z), intervals = int, total.seeds = 50, : Multiple peak germination times exist.`

```
[1] 22
```

```
# From number of germinated seeds
```

```
#-----
```

```
GermPercent(germinated.seeds = 40, total.seeds = 50)
```

```
[1] 80
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
z <- c(0, 0, 0, 0, 11, 11, 9, 7, 1, 0, 1, 0, 0, 0)
int <- 1:length(x)
```

```
# From partial germination counts
```

```

#-----
FirstGermTime(germ.counts = x, intervals = int)

FirstGermTime(), LastGermTime(), PeakGermTime(), TimeSpreadGerm()

[1] 5
LastGermTime(germ.counts = x, intervals = int)

[1] 11
TimeSpreadGerm(germ.counts = x, intervals = int)

[1] 6
PeakGermTime(germ.counts = x, intervals = int)

[1] 6
# For multiple peak germination times
PeakGermTime(germ.counts = z, intervals = int)

Warning in PeakGermTime(germ.counts = z, intervals = int): Multiple peak germination times exist.

[1] 5 6
# From cumulative germination counts
#-----
FirstGermTime(germ.counts = y, intervals = int, partial = FALSE)

[1] 5
LastGermTime(germ.counts = y, intervals = int, partial = FALSE)

[1] 11
TimeSpreadGerm(germ.counts = y, intervals = int, partial = FALSE)

[1] 6
PeakGermTime(germ.counts = y, intervals = int, partial = FALSE)

[1] 6
# For multiple peak germination time
PeakGermTime(germ.counts = cumsum(z), intervals = int, partial = FALSE)

Warning in PeakGermTime(germ.counts = cumsum(z), intervals = int, partial = FALSE): Multiple peak germination times exist.

[1] 5 6

x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
t50(germ.counts = x, intervals = int, method = "coolbear")

t50()

```

```
[1] 5.970588
```

```
t50(germ.counts = x, intervals = int, method = "farooq")
```

```
[1] 5.941176
```

```
# From cumulative germination counts
```

```
#-----
```

```
t50(germ.counts = y, intervals = int, partial = FALSE, method = "coolbear")
```

```
[1] 5.970588
```

```
t50(germ.counts = y, intervals = int, partial = FALSE, method = "farooq")
```

```
[1] 5.941176
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
MeanGermTime(germ.counts = x, intervals = int)
```

```
MeanGermTime(), VarGermTime(), SEGermTime(), CVGermTime()
```

```
[1] 6.7
```

```
VarGermTime(germ.counts = x, intervals = int)
```

```
[1] 1.446154
```

```
SEGermTime(germ.counts = x, intervals = int)
```

```
[1] 0.1901416
```

```
CVGermTime(germ.counts = x, intervals = int)
```

```
[1] 0.1794868
```

```
# From cumulative germination counts
```

```
#-----
```

```
MeanGermTime(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 6.7
```

```
VarGermTime(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 19.04012
```

```
SEGermTime(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 0.2394781
```

```
CVGermTime(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 0.6512685
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
```



```

int <- 1:length(x)

# From partial germination counts
#-----
MeanGermRate(germ.counts = x, intervals = int)

MeanGermRate(), CVG(), VarGermRate(), SEGermRate(), GermRateRecip()

[1] 0.1492537
CVG(germ.counts = x, intervals = int)

[1] 14.92537
VarGermRate(germ.counts = x, intervals = int)

[1] 0.0007176543
SEGermRate(germ.counts = x, intervals = int)

[1] 0.004235724
GermRateRecip(germ.counts = x, intervals = int, method = "coolbear")

[1] 0.1674877
GermRateRecip(germ.counts = x, intervals = int, method = "farooq")

[1] 0.1683168

# From cumulative germination counts
#-----
MeanGermRate(germ.counts = y, intervals = int, partial = FALSE)

[1] 0.1492537
CVG(germ.counts = y, intervals = int, partial = FALSE)

[1] 14.92537
VarGermRate(germ.counts = y, intervals = int, partial = FALSE)

[1] 0.009448666
SEGermRate(germ.counts = y, intervals = int, partial = FALSE)

[1] 0.005334776
GermRateRecip(germ.counts = y, intervals = int,
              method = "coolbear", partial = FALSE)

[1] 0.1674877
GermRateRecip(germ.counts = y, intervals = int,
              method = "farooq", partial = FALSE)

[1] 0.1683168

x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

```

```

# From partial germination counts
#-----
GermSpeed(germ.counts = x, intervals = int)

GermSpeed(), GermSpeedAccumulated(), GermSpeedCorrected()

[1] 6.138925
GermSpeedAccumulated(germ.counts = x, intervals = int)

[1] 34.61567
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                    method = "normal")

[1] 0.1534731
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                    method = "accumulated")

[1] 0.8653917
# From partial germination counts (with percentages instead of counts)
#-----
GermSpeed(germ.counts = x, intervals = int,
          percent = TRUE, total.seeds = 50)

[1] 12.27785
GermSpeedAccumulated(germ.counts = x, intervals = int,
                     percent = TRUE, total.seeds = 50)

[1] 69.23134
# From cumulative germination counts
#-----
GermSpeed(germ.counts = y, intervals = int, partial = FALSE)

[1] 6.138925
GermSpeedAccumulated(germ.counts = y, intervals = int, partial = FALSE)

[1] 34.61567
GermSpeedCorrected(germ.counts = y, intervals = int,
                   partial = FALSE, total.seeds = 50, method = "normal")

[1] 0.1534731
GermSpeedCorrected(germ.counts = y, intervals = int,
                   partial = FALSE, total.seeds = 50, method = "accumulated")

[1] 0.8653917
# From cumulative germination counts (with percentages instead of counts)
#-----
GermSpeed(germ.counts = y, intervals = int, partial = FALSE,
          percent = TRUE, total.seeds = 50)

[1] 12.27785

```

```
GermSpeedAccumulated(germ.counts = y, intervals = int, partial = FALSE,
                      percent = TRUE, total.seeds = 50)
```

```
[1] 69.23134
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
WeightGermPercent(germ.counts = x, total.seeds = 50, intervals = int)
```

```
WeightGermPercent()
```

```
[1] 47.42857
```

```
# From cumulative germination counts
```

```
#-----
```

```
WeightGermPercent(germ.counts = y, total.seeds = 50, intervals = int,
                  partial = FALSE)
```

```
[1] 47.42857
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
MeanGermPercent(germ.counts = x, total.seeds = 50, intervals = int)
```

```
MeanGermPercent(), MeanGermNumber()
```

```
[1] 5.714286
```

```
MeanGermNumber(germ.counts = x, intervals = int)
```

```
[1] 2.857143
```

```
# From cumulative germination counts
```

```
#-----
```

```
MeanGermPercent(germ.counts = y, total.seeds = 50, intervals = int, partial = FALSE)
```

```
[1] 5.714286
```

```
MeanGermNumber(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 2.857143
```

```
# From number of germinated seeds
```

```
#-----
```

```
MeanGermPercent(germinated.seeds = 40, total.seeds = 50, intervals = int)
```

```
[1] 5.714286
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
# Without max specified
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50)
```

```
TimsonsIndex(), GermRateGeorge()
```

```
[1] 664
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              modification = "none")
```

```
[1] 664
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              modification = "labouriau")
```

```
[1] 8.3
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              modification = "khanungar")
```

```
[1] 47.42857
```

```
GermRateGeorge(germ.counts = x, intervals = int)
```

```
[1] 332
```

```
# With max specified
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50, max = 10)
```

```
[1] 344
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              max = 10, modification = "none")
```

```
[1] 344
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              max = 10, modification = "labouriau")
```

```
[1] 4.410256
```

```
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
              max = 10, modification = "khanungar")
```

```
[1] 24.57143
```

```
GermRateGeorge(germ.counts = x, intervals = int, max = 10)
```

```
[1] 172
```

```
GermRateGeorge(germ.counts = x, intervals = int, max = 14)
```

```
[1] 332
```

```
# From cumulative germination counts
```

```
#-----
```

```
# Without max specified
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50)
```

```
[1] 664
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              modification = "none")
```

```
[1] 664
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              modification = "labouriau")
```

```
[1] 8.3
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              modification = "khanungar")
```

```
[1] 47.42857
```

```
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,)
```

```
[1] 332
```

```
# With max specified
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50, max = 10)
```

```
[1] 344
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              max = 10, modification = "none")
```

```
[1] 344
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              max = 10, modification = "labouriau")
```

```
[1] 4.410256
```

```
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,  
              total.seeds = 50,  
              max = 10, modification = "khanungar")
```

```
[1] 24.57143
```

```
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,  
                max = 10)
```

```
[1] 172
```

```
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,  
                max = 14)
```

```
[1] 332
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
GermIndex(germ.counts = x, intervals = int, total.seeds = 50)
```

```
GermIndex()
```

```
[1] 5.84
```

```
GermIndex(germ.counts = x, intervals = int, total.seeds = 50,
           modification = "none")
```

```
[1] 5.84
```

```
GermIndex(germ.counts = x, intervals = int, total.seeds = 50,
           modification = "santanaranal")
```

```
[1] 7.3
```

```
# From cumulative germination counts
#-----
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
           total.seeds = 50)
```

```
[1] 5.84
```

```
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
           total.seeds = 50,
           modification = "none")
```

```
[1] 5.84
```

```
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
           total.seeds = 50,
           modification = "santanaranal")
```

```
[1] 7.3
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
EmergenceRateIndex(germ.counts = x, intervals = int)
```

```
EmergenceRateIndex()
```

```
[1] 292
```

```
EmergenceRateIndex(germ.counts = x, intervals = int,
                    method = "shmueligoldberg")
```

[1] 292

```
EmergenceRateIndex(germ.counts = x, intervals = int,
  method = "sgsantanaranal")
```

[1] 7.3

```
EmergenceRateIndex(germ.counts = x, intervals = int,
  method = "bilbrowanjura")
```

[1] 5.970149

```
EmergenceRateIndex(germ.counts = x, intervals = int,
  total.seeds = 50, method = "fakorede")
```

[1] 8.375

```
# From cumulative germination counts
#-----
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,)
```

[1] 292

```
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "shmueligoldberg")
```

[1] 292

```
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "sgsantanaranal")
```

[1] 7.3

```
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "bilbrowanjura")
```

[1] 5.970149

```
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50, method = "fakorede")
```

[1] 8.375

```
x <- c(0, 0, 34, 40, 21, 10, 4, 5, 3, 5, 8, 7, 7, 6, 6, 4, 0, 2, 0, 2)
y <- c(0, 0, 34, 74, 95, 105, 109, 114, 117, 122, 130, 137, 144, 150,
  156, 160, 160, 162, 162, 164)
int <- 1:length(x)
total.seeds = 200
```

```
# From partial germination counts
#-----
PeakValue(germ.counts = x, intervals = int, total.seeds = 200)
```

```
PeakValue(), GermValue()
```

[1] 9.5

```
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
  method = "czabator")
```

```
$`Germination Value`
[1] 38.95
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS
3	34	3	34	17.0	5.666667
4	40	4	74	37.0	9.250000
5	21	5	95	47.5	9.500000
6	10	6	105	52.5	8.750000
7	4	7	109	54.5	7.785714
8	5	8	114	57.0	7.125000
9	3	9	117	58.5	6.500000
10	5	10	122	61.0	6.100000
11	8	11	130	65.0	5.909091
12	7	12	137	68.5	5.708333
13	7	13	144	72.0	5.538462
14	6	14	150	75.0	5.357143
15	6	15	156	78.0	5.200000
16	4	16	160	80.0	5.000000
17	0	17	160	80.0	4.705882
18	2	18	162	81.0	4.500000
19	0	19	162	81.0	4.263158
20	2	20	164	82.0	4.100000

```
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
           method = "dp", k = 10)
```

```
$`Germination Value`
[1] 53.36595
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS	SumDGSbyN	GV
3	34	3	34	17.0	5.666667	5.666667	9.633333
4	40	4	74	37.0	9.250000	7.458333	27.595833
5	21	5	95	47.5	9.500000	8.138889	38.659722
6	10	6	105	52.5	8.750000	8.291667	43.531250
7	4	7	109	54.5	7.785714	8.190476	44.638095
8	5	8	114	57.0	7.125000	8.012897	45.673512
9	3	9	117	58.5	6.500000	7.796769	45.611097
10	5	10	122	61.0	6.100000	7.584673	46.266503
11	8	11	130	65.0	5.909091	7.398497	48.090230
12	7	12	137	68.5	5.708333	7.229481	49.521942
13	7	13	144	72.0	5.538462	7.075752	50.945411
14	6	14	150	75.0	5.357143	6.932534	51.994006
15	6	15	156	78.0	5.200000	6.799262	53.034246
16	4	16	160	80.0	5.000000	6.670744	53.365948
17	0	17	160	80.0	4.705882	6.539753	52.318022
18	2	18	162	81.0	4.500000	6.412268	51.939373
19	0	19	162	81.0	4.263158	6.285850	50.915385
20	2	20	164	82.0	4.100000	6.164414	50.548194

```
$testend
[1] 16
```



```
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
           method = "czabator", from.onset = FALSE)
```

```
$`Germination Value`
```

```
[1] 38.95
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS
1	0	1	0	0.0	0.000000
2	0	2	0	0.0	0.000000
3	34	3	34	17.0	5.666667
4	40	4	74	37.0	9.250000
5	21	5	95	47.5	9.500000
6	10	6	105	52.5	8.750000
7	4	7	109	54.5	7.785714
8	5	8	114	57.0	7.125000
9	3	9	117	58.5	6.500000
10	5	10	122	61.0	6.100000
11	8	11	130	65.0	5.909091
12	7	12	137	68.5	5.708333
13	7	13	144	72.0	5.538462
14	6	14	150	75.0	5.357143
15	6	15	156	78.0	5.200000
16	4	16	160	80.0	5.000000
17	0	17	160	80.0	4.705882
18	2	18	162	81.0	4.500000
19	0	19	162	81.0	4.263158
20	2	20	164	82.0	4.100000

```
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
           method = "dp", k = 10, from.onset = FALSE)
```

```
$`Germination Value`
```

```
[1] 46.6952
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS	SumDGSbyN	GV
1	0	1	0	0.0	0.000000	0.000000	0.000000
2	0	2	0	0.0	0.000000	0.000000	0.000000
3	34	3	34	17.0	5.666667	1.888889	3.211111
4	40	4	74	37.0	9.250000	3.729167	13.797917
5	21	5	95	47.5	9.500000	4.883333	23.195833
6	10	6	105	52.5	8.750000	5.527778	29.020833
7	4	7	109	54.5	7.785714	5.850340	31.884354
8	5	8	114	57.0	7.125000	6.009673	34.255134
9	3	9	117	58.5	6.500000	6.064153	35.475298
10	5	10	122	61.0	6.100000	6.067738	37.013202
11	8	11	130	65.0	5.909091	6.053316	39.346552
12	7	12	137	68.5	5.708333	6.024567	41.268285
13	7	13	144	72.0	5.538462	5.987174	43.107655
14	6	14	150	75.0	5.357143	5.942172	44.566291
15	6	15	156	78.0	5.200000	5.892694	45.963013
16	4	16	160	80.0	5.000000	5.836901	46.695205
17	0	17	160	80.0	4.705882	5.770370	46.162961

18	2	18	162	81.0	4.500000	5.699794	46.168331
19	0	19	162	81.0	4.263158	5.624182	45.555871
20	2	20	164	82.0	4.100000	5.547972	45.493374

```
$testend
```

```
[1] 16
```

```
# From cumulative germination counts
```

```
#-----
```

```
PeakValue(germ.counts = y, interval = int, total.seeds = 200,
           partial = FALSE)
```

```
[1] 9.5
```

```
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
           partial = FALSE, method = "czabator")
```

```
$`Germination Value`
```

```
[1] 38.95
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS
3	34	3	34	17.0	5.666667
4	40	4	74	37.0	9.250000
5	21	5	95	47.5	9.500000
6	10	6	105	52.5	8.750000
7	4	7	109	54.5	7.785714
8	5	8	114	57.0	7.125000
9	3	9	117	58.5	6.500000
10	5	10	122	61.0	6.100000
11	8	11	130	65.0	5.909091
12	7	12	137	68.5	5.708333
13	7	13	144	72.0	5.538462
14	6	14	150	75.0	5.357143
15	6	15	156	78.0	5.200000
16	4	16	160	80.0	5.000000
17	0	17	160	80.0	4.705882
18	2	18	162	81.0	4.500000
19	0	19	162	81.0	4.263158
20	2	20	164	82.0	4.100000

```
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
           partial = FALSE, method = "dp", k = 10)
```

```
$`Germination Value`
```

```
[1] 53.36595
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS	SumDGSbyN	GV
3	34	3	34	17.0	5.666667	5.666667	9.633333
4	40	4	74	37.0	9.250000	7.458333	27.595833
5	21	5	95	47.5	9.500000	8.138889	38.659722
6	10	6	105	52.5	8.750000	8.291667	43.531250
7	4	7	109	54.5	7.785714	8.190476	44.638095
8	5	8	114	57.0	7.125000	8.012897	45.673512
9	3	9	117	58.5	6.500000	7.796769	45.611097

10	5	10	122	61.0	6.100000	7.584673	46.266503
11	8	11	130	65.0	5.909091	7.398497	48.090230
12	7	12	137	68.5	5.708333	7.229481	49.521942
13	7	13	144	72.0	5.538462	7.075752	50.945411
14	6	14	150	75.0	5.357143	6.932534	51.994006
15	6	15	156	78.0	5.200000	6.799262	53.034246
16	4	16	160	80.0	5.000000	6.670744	53.365948
17	0	17	160	80.0	4.705882	6.539753	52.318022
18	2	18	162	81.0	4.500000	6.412268	51.939373
19	0	19	162	81.0	4.263158	6.285850	50.915385
20	2	20	164	82.0	4.100000	6.164414	50.548194

```
$testend
```

```
[1] 16
```

```
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
           partial = FALSE, method = "czabator", from.onset = FALSE)
```

```
$`Germination Value`
```

```
[1] 38.95
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS
1	0	1	0	0.0	0.000000
2	0	2	0	0.0	0.000000
3	34	3	34	17.0	5.666667
4	40	4	74	37.0	9.250000
5	21	5	95	47.5	9.500000
6	10	6	105	52.5	8.750000
7	4	7	109	54.5	7.785714
8	5	8	114	57.0	7.125000
9	3	9	117	58.5	6.500000
10	5	10	122	61.0	6.100000
11	8	11	130	65.0	5.909091
12	7	12	137	68.5	5.708333
13	7	13	144	72.0	5.538462
14	6	14	150	75.0	5.357143
15	6	15	156	78.0	5.200000
16	4	16	160	80.0	5.000000
17	0	17	160	80.0	4.705882
18	2	18	162	81.0	4.500000
19	0	19	162	81.0	4.263158
20	2	20	164	82.0	4.100000

```
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
           partial = FALSE, method = "dp", k = 10, from.onset = FALSE)
```

```
$`Germination Value`
```

```
[1] 46.6952
```

```
[[2]]
```

	germ.counts	intervals	Cumulative.germ.counts	Cumulative.germ.percent	DGS	SumDGSbyN	GV
1	0	1	0	0.0	0.000000	0.000000	0.000000
2	0	2	0	0.0	0.000000	0.000000	0.000000
3	34	3	34	17.0	5.666667	1.888889	3.211111

4	40	4	74	37.0	9.250000	3.729167	13.797917
5	21	5	95	47.5	9.500000	4.883333	23.195833
6	10	6	105	52.5	8.750000	5.527778	29.020833
7	4	7	109	54.5	7.785714	5.850340	31.884354
8	5	8	114	57.0	7.125000	6.009673	34.255134
9	3	9	117	58.5	6.500000	6.064153	35.475298
10	5	10	122	61.0	6.100000	6.067738	37.013202
11	8	11	130	65.0	5.909091	6.053316	39.346552
12	7	12	137	68.5	5.708333	6.024567	41.268285
13	7	13	144	72.0	5.538462	5.987174	43.107655
14	6	14	150	75.0	5.357143	5.942172	44.566291
15	6	15	156	78.0	5.200000	5.892694	45.963013
16	4	16	160	80.0	5.000000	5.836901	46.695205
17	0	17	160	80.0	4.705882	5.770370	46.162961
18	2	18	162	81.0	4.500000	5.699794	46.168331
19	0	19	162	81.0	4.263158	5.624182	45.555871
20	2	20	164	82.0	4.100000	5.547972	45.493374

```
$testend
```

```
[1] 16
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
CUGerm(germ.counts = x, intervals = int)
```

```
CUGerm()
```

```
[1] 0.7092199
```

```
# From cumulative germination counts
```

```
#-----
```

```
CUGerm(germ.counts = y, intervals = int, partial = FALSE)
```

```
[1] 0.05267935
```

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
```

```
# From partial germination counts
```

```
#-----
```

```
GermSynchrony(germ.counts = x, intervals = int)
```

```
GermSynchrony(), GermUncertainty()
```

```
[1] 0.2666667
```

```
GermUncertainty(germ.counts = x, intervals = int)
```

```
[1] 2.062987
```

```
# From cumulative germination counts
#-----
GermSynchrony(germ.counts = y, intervals = int, partial = FALSE)

[1] 0.2666667

GermUncertainty(germ.counts = y, intervals = int, partial = FALSE)

[1] 2.062987
```

## Non-linear regression analysis

Several mathematical functions have been used to fit the cumulative germination count data and describe the germination process by non-linear regression analysis. They include functions such as Richard's, Weibull, logistic, log-logistic, gaussian, four-parameter hill function etc. Currently `germinationmetrics` implements the four-parameter hill function to fit the count data and computed various associated metrics.

### Four-parameter hill function

The four-parameter hill function defined as follows (El-Kassaby et al., 2008).

$$f(x) = y = y_0 + \frac{ax^b}{x^b + c^b}$$

Where,  $y$  is the cumulative germination percentage at time  $x$ ,  $y_0$  is the intercept on the y axis,  $a$  is the asymptote,  $b$  is a mathematical parameter controlling the shape and steepness of the germination curve and  $c$  is the “half-maximal activation level”.

this function can also be reparameterized by substituting  $b$  with  $e^\beta$  to constraint  $b$  to positive values only.

$$y = y_0 + \frac{ax^{e^\beta}}{c^{e^\beta} + x^{e^\beta}}$$

Where,  $b = e^\beta$  and  $\beta = \log_e(b)$ .

The details of various parameters that are computed from this function are given in Table 4.

**Table 4** Germination parameters estimated from the four-parameter hill function.

Germination parameters	Details	Unit	Measures
y intercept ( $y_0$ )	The intercept on the y axis.		
Asymptote ( $a$ )	It is the maximum cumulative germination percentage, which is equivalent to germination capacity.	%	Germination capacity
Shape and steepness ( $b$ )	Mathematical parameter controlling the shape and steepness of the germination curve. The larger the $b$ , the steeper the rise toward the asymptote $a$ , and the shorter the time between germination onset and maximum germination.		Germination rate
Half-maximal activation level ( $c$ )	Time required for 50% of viable seeds to germinate.	time	Germination time

Germination parameters	Details	Unit	Measures
<i>lag</i>	It is the time at germination onset and is computed by solving four-parameter hill function after setting $y$ to 0 as follows. $lag = b\sqrt{\frac{-y_0c^b}{a+y_0}}$	time	Germination time
<i>D<sub>lag-50</sub></i>	The duration between the time at germination onset ( <i>lag</i> ) and that at 50% germination ( <i>c</i> ).	time	Germination time
<i>t<sub>50total</sub></i>	Time required for 50% of total seeds to germinate.	time	Germination time
<i>t<sub>50germinated</sub></i>	Time required for 50% of viable/germinated seeds to germinate	time	Germination time
<i>t<sub>xtotal</sub></i>	Time required for $x\%$ of total seeds to germinate.	time	Germination time
<i>t<sub>xgerminated</sub></i>	Time required for $x\%$ of viable/germinated seeds to germinate	time	Germination time
Uniformity ( $U_{t_{max}-t_{min}}$ )	It is the time interval between the percentages of viable seeds specified in the arguments <b>umin</b> and <b>umin</b> to germinate.	time	Germination time
Time at maximum germination rate ( <i>TMGR</i> )	The partial derivative of the four-parameter hill function gives the instantaneous rate of germination ( $s$ ) as follows. $s = \frac{\partial y}{\partial x} = \frac{abc^b x^{b-1}}{(c^b + x^b)^2}$ From this function for instantaneous rate of germination, <i>TMGR</i> can be estimated as follows. $TMGR = b\sqrt{\frac{c^b(b-1)}{b+1}}$ It represents the point in time when the instantaneous rate of germination starts to decline.	time	Germination time
Area under the curve ( <i>AUC</i> )	It is obtained by integration of the fitted curve between time 0 and time specified in the argument <b>tmax</b> .		Mixed
<i>MGT</i>	Calculated by integration of the fitted curve and proper normalisation.	time	Germination time
<i>Skewness</i>	It is computed as follows. $\frac{MGT}{t_{50germinated}}$		

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
total.seeds = 50
```

```
# From partial germination counts
```

```
#-----
FourPHFfit(germ.counts = x, intervals = int, total.seeds = 50, tmax = 20)
```

```
FourPHFfit()
```

```
Warning in FourPHFfit(germ.counts = x, intervals = int, total.seeds = 50, : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"
```

```
$data
```

	gp	csgp	intervals
1	0	0	1
2	0	0	2
3	0	0	3
4	0	0	4
5	8	8	5
6	34	42	6
7	20	62	7
8	14	76	8
9	2	78	9
10	0	78	10
11	2	80	11
12	0	80	12
13	0	80	13
14	0	80	14

```
$Parameters
```

	term	estimate	std.error	statistic	p.value
1	a	NA	NA	NA	NA
2	b	NA	NA	NA	NA
3	c	NA	NA	NA	NA
4	y0	NA	NA	NA	NA

```
$Fit
```

	sigma	isConv	finTol	logLik	AIC	BIC	deviance	df.residual	nobs
1	NA	NA	NA	NA	NA	NA	NA	NA	NA

```
$a
```

```
[1] NA
```

```
$b
```

```
[1] NA
```

```
$c
```

```
[1] NA
```

```
$y0
```

```
[1] NA
```

```

$lag
[1] NA

$Dlag50
[1] NA

$t50.total
[1] NA

$txp.total
10 60
NA NA

$t50.Germinated
[1] NA

$txp.Germinated
10 60
NA NA

$Uniformity
      90      10 uniformity
      NA      NA          NA

$TMGR
[1] NA

$AUC
[1] NA

$MGT
[1] NA

$Skewness
[1] NA

$msg
[1] "#1. failed to evaluate 'fn' at starting values: could not find function \"FourPHF_fixa_fixy0\" "

$isConv
[1] NA

$model
<simpleError in gsl_nls.formula(csgp ~ FourPHF_fixa_fixy0(x = intervals, a = max(csgp),      bta, c), da
attr(,"class")
[1] "FourPHFfit" "list"
# From cumulative germination counts
#-----
FourPHFfit(germ.counts = y, intervals = int, total.seeds = 50, tmax = 20,
partial = FALSE)

```

```

Warning in FourPHFfit(germ.counts = y, intervals = int, total.seeds = 50, : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"

```



```

$data
  gp csgp intervals
1  0    0         1
2  0    0         2
3  0    0         3
4  0    0         4
5  8    8         5
6 34   42         6
7 20   62         7
8 14   76         8
9  2   78         9
10 0   78        10
11 2   80        11
12 0   80        12
13 0   80        13
14 0   80        14

$Parameters
  term estimate std.error statistic p.value
1    a         NA         NA         NA     NA
2    b         NA         NA         NA     NA
3    c         NA         NA         NA     NA
4   y0         NA         NA         NA     NA

$Fit
  sigma isConv finTol logLik AIC BIC deviance df.residual nobs
1    NA    NA    NA    NA NA  NA         NA         NA   NA

$a
[1] NA

$b
[1] NA

$c
[1] NA

$y0
[1] NA

$lag
[1] NA

$Dlag50
[1] NA

$t50.total
[1] NA

$txp.total
10 60
NA NA

$t50.Germinated

```

```

[1] NA

$txp.Germinated
10 60
NA NA

$Uniformity
      90      10 uniformity
      NA      NA          NA

$TMGR
[1] NA

$AUC
[1] NA

$MGT
[1] NA

$Skewness
[1] NA

$msg
[1] "#1. failed to evaluate 'fn' at starting values: could not find function \"FourPHF_fixa_fixy0\" "

$isConv
[1] NA

$model
<simpleError in gsl_nls.formula(csgp ~ FourPHF_fixa_fixy0(x = intervals, a = max(csgp),      bta, c), da

attr(,"class")
[1] "FourPHFfit" "list"
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
total.seeds = 50

# From partial germination counts
#-----
fit1 <- FourPHFfit(germ.counts = x, intervals = int,
                  total.seeds = 50, tmax = 20)

Warning in FourPHFfit(germ.counts = x, intervals = int, total.seeds = 50, : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"

# From cumulative germination counts
#-----
fit2 <- FourPHFfit(germ.counts = y, intervals = int,
                  total.seeds = 50, tmax = 20, partial = FALSE)

Warning in FourPHFfit(germ.counts = y, intervals = int, total.seeds = 50, : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"

```

```
# Default plots
plot(fit1)
```

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

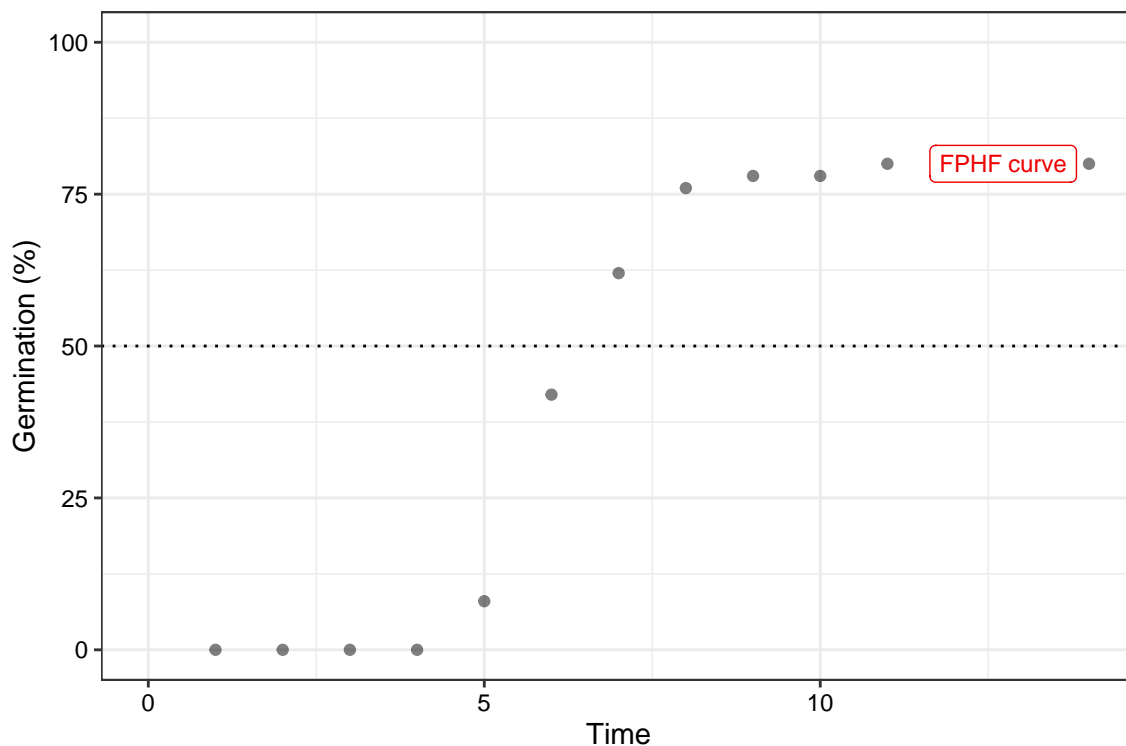
Removed 1 rows containing missing values (``geom_vline()``).

Warning: Removed 14 rows containing missing values (``geom_segment()``).

Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

Removed 1 rows containing missing values (``geom_vline()``).



```
plot(fit2)
```

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

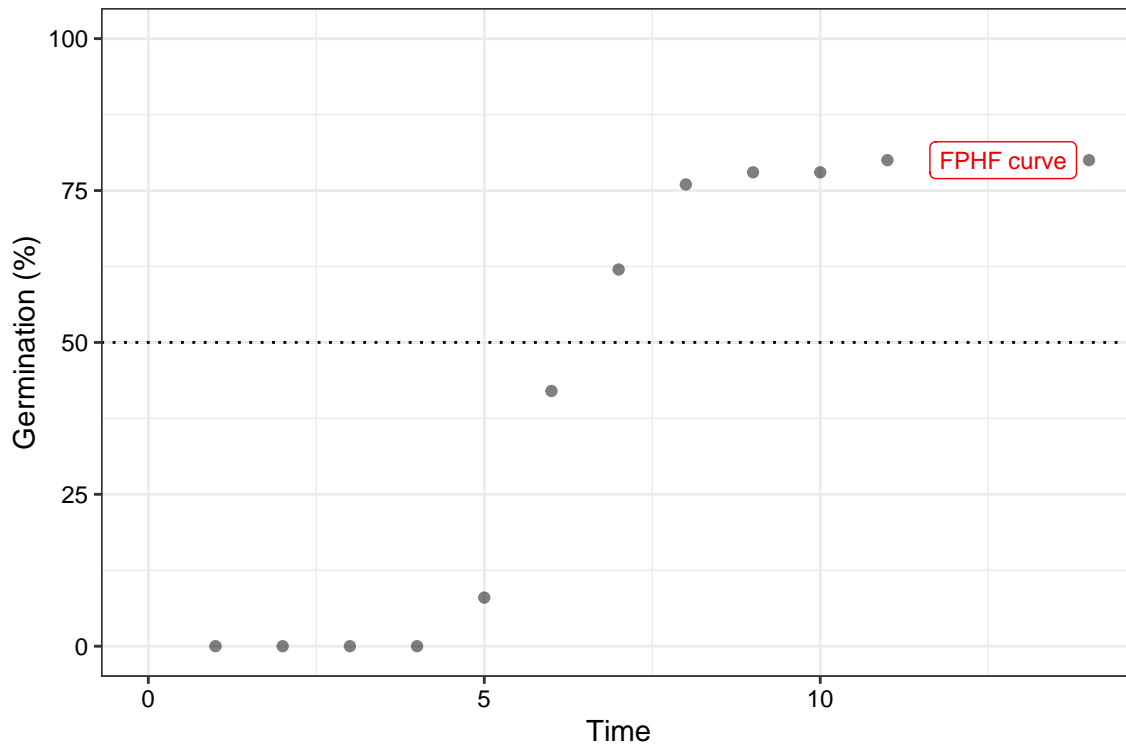
Removed 1 rows containing missing values (``geom_vline()``).

Warning: Removed 14 rows containing missing values (``geom_segment()``).

Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

Removed 1 rows containing missing values (``geom_vline()``).



```
# No labels
plot(fit1, plotlabels = FALSE)
```

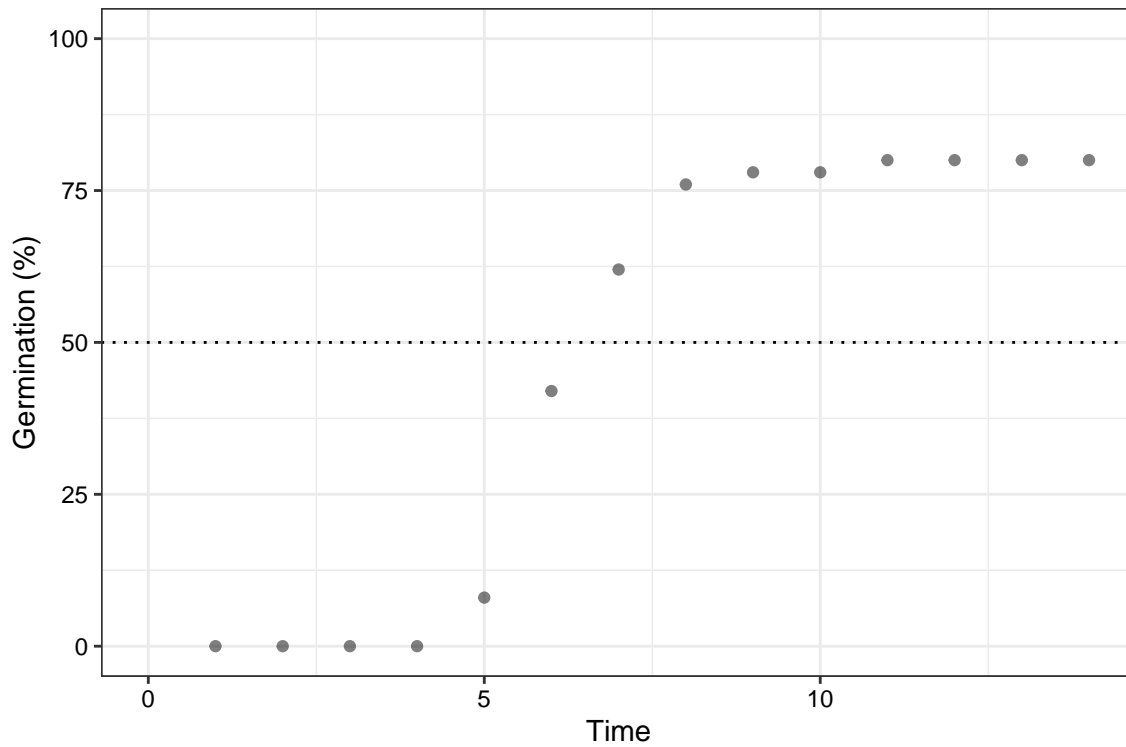
Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).

Warning: Removed 14 rows containing missing values (``geom_segment()``).  
 Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).



```
plot(fit2, plotlabels = FALSE)
```

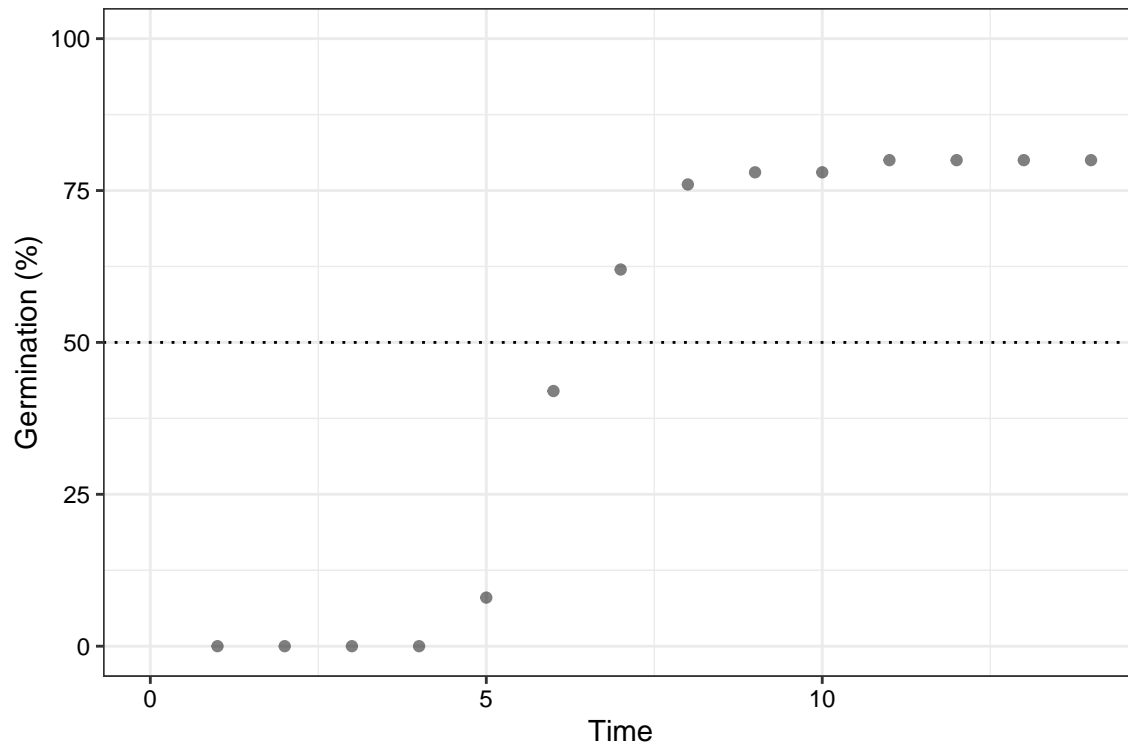
Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).

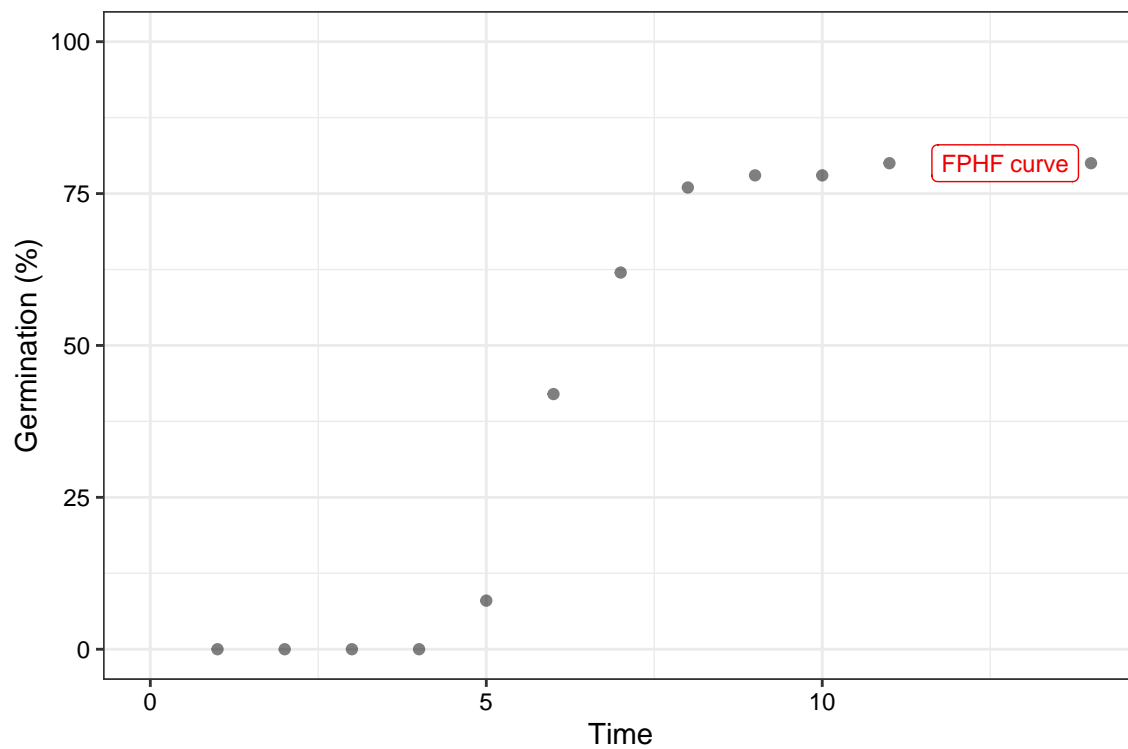
Warning: Removed 14 rows containing missing values (``geom_segment()``).  
 Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).



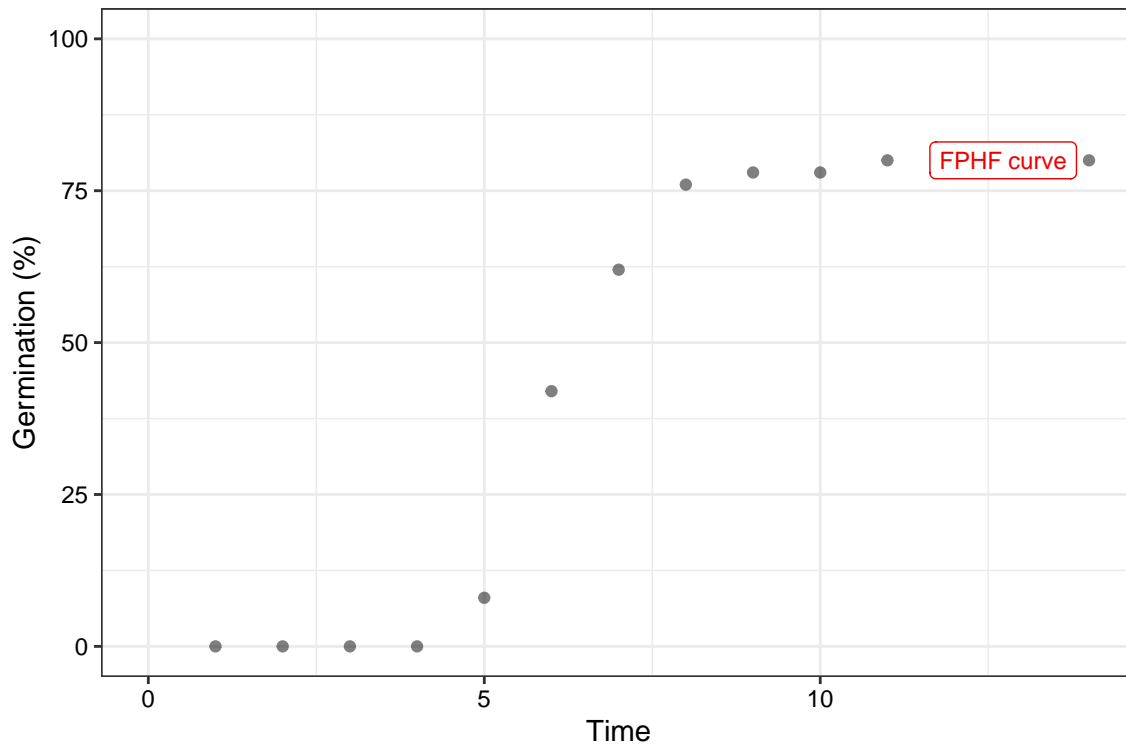
```
# Only the FPHF curve
plot(fit1, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
     tmgr = FALSE, mgt = FALSE, uniformity = FALSE)
```

Warning: Removed 101 rows containing missing values (``geom_function()``).



```
plot(fit2, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
     tmgr = FALSE, mgt = FALSE, uniformity = FALSE)
```

Warning: Removed 101 rows containing missing values (``geom_function()``).



```
# Without y axis limits adjustment
plot(fit1, limits = FALSE)
```

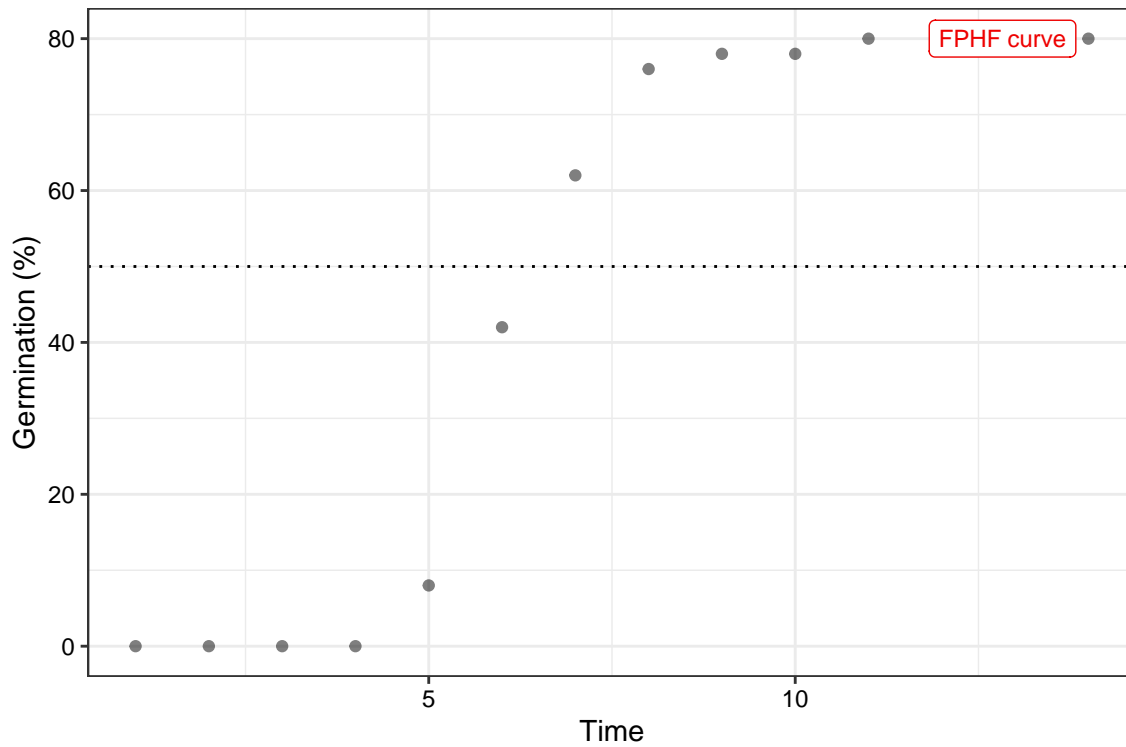
Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).

Warning: Removed 14 rows containing missing values (``geom_segment()``).  
 Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).  
 Removed 1 rows containing missing values (``geom_vline()``).



```
plot(fit2, limits = FALSE)
```

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 101 rows containing missing values (``geom_function()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

Removed 1 rows containing missing values (``geom_vline()``).

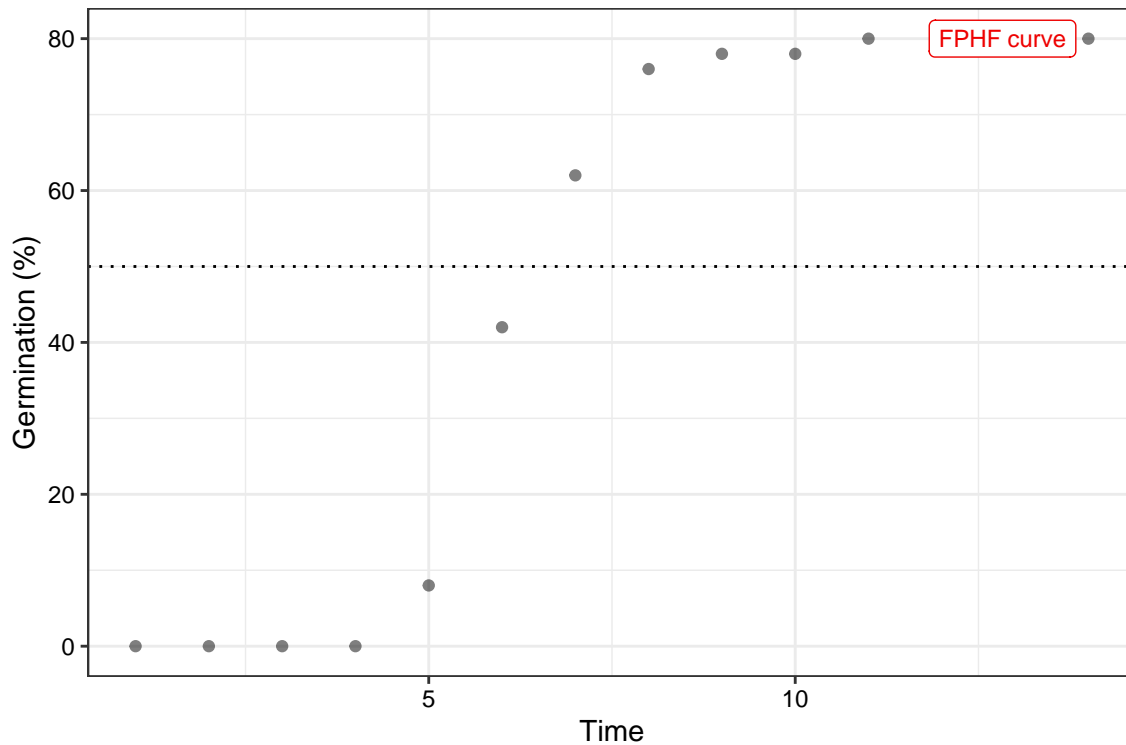
Warning: Removed 14 rows containing missing values (``geom_segment()``).

Removed 14 rows containing missing values (``geom_segment()``).

Warning: Removed 1 rows containing missing values (``geom_vline()``).

Removed 1 rows containing missing values (``geom_vline()``).





## Wrapper functions

Wrapper functions `germination.indices()` and `FourPHFfit.bulk()` are available in the package for computing results for multiple samples in batch from a data frame of germination counts recorded at specific time intervals.

**`germination.indices()`** This wrapper function can be used to compute several germination indices simultaneously for multiple samples in batch.

```
data(gcdata)
```

```
counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")
germination.indices(gcdata, total.seeds.col = "Total Seeds",
                   counts.intervals.cols = counts.per.intervals,
                   intervals = 1:14, partial = TRUE, max.int = 5)
```

	Genotype	Rep	Day01	Day02	Day03	Day04	Day05	Day06	Day07	Day08	Day09	Day10	Day11	Day12	Day13	Day14	Tot.
1	G1	1	0	0	0	0	4	17	10	7	1	0	1	0	0	0	
2	G2	1	0	0	0	1	3	15	13	6	2	1	0	1	0	0	
3	G3	1	0	0	0	2	3	18	9	8	2	1	1	1	0	0	
4	G4	1	0	0	0	0	4	19	12	6	2	1	1	1	0	0	
5	G5	1	0	0	0	0	5	20	12	8	1	0	0	1	1	0	
6	G1	2	0	0	0	0	3	21	11	7	1	1	1	1	0	0	
7	G2	2	0	0	0	0	4	18	11	7	1	0	1	0	0	0	
8	G3	2	0	0	0	1	3	14	12	6	2	1	0	1	0	0	
9	G4	2	0	0	0	1	3	19	10	8	1	1	1	1	0	0	
10	G5	2	0	0	0	0	4	18	13	6	2	1	0	1	0	0	
11	G1	3	0	0	0	0	5	21	11	8	1	0	0	1	1	0	

12	G2	3	0	0	0	0	3	20	10	7	1	1	1	1	0	0
13	G3	3	0	0	0	0	4	19	12	8	1	1	0	1	1	0
14	G4	3	0	0	0	0	3	21	11	6	1	0	1	1	0	0
15	G5	3	0	0	0	0	4	17	10	8	1	1	1	0	0	0
	GermPercent	PeakGermPercent	FirstGermTime	LastGermTime	PeakGermTime	TimeSpreadGerm	t50_Coolbear	t50_								
1	80.00000	34.00000	5	11	6	6	5.970588	5.9								
2	82.35294	29.41176	4	12	6	8	6.192308	6.1								
3	93.75000	37.50000	4	12	6	8	6.000000	5.9								
4	90.19608	37.25490	5	12	6	7	6.041667	6.0								
5	96.00000	40.00000	5	13	6	8	5.975000	5.9								
6	93.87755	42.85714	5	12	6	7	5.976190	5.9								
7	87.50000	37.50000	5	11	6	6	5.972222	5.9								
8	85.10638	29.78723	4	12	6	8	6.208333	6.1								
9	86.53846	36.53846	4	12	6	8	6.000000	5.9								
10	90.00000	36.00000	5	12	6	7	6.076923	6.0								
11	94.11765	41.17647	5	13	6	8	5.928571	5.9								
12	86.27451	39.21569	5	12	6	7	5.975000	5.9								
13	95.91837	38.77551	5	13	6	8	6.083333	6.0								
14	91.66667	43.75000	5	12	6	7	5.928571	5.9								
15	87.50000	35.41667	5	11	6	6	6.050000	6.0								
	MeanGermTime	VarGermTime	SEGermTime	CVGermTime	MeanGermRate	VarGermRate	SEGermRate	CVGermRate								
1	6.700000	1.446154	0.1901416	0.1794868	0.1492537	0.0007176543	0.004235724	14.92537								
2	6.857143	2.027875	0.2197333	0.2076717	0.1458333	0.0009172090	0.004673148	14.58333								
3	6.866667	2.572727	0.2391061	0.2335882	0.1456311	0.0011572039	0.005071059	14.56311								
4	6.891304	2.187923	0.2180907	0.2146419	0.1451104	0.0009701218	0.004592342	14.51104								
5	6.812500	2.368351	0.2221275	0.2259002	0.1467890	0.0010995627	0.004786184	14.67890								
6	6.869565	2.071498	0.2122088	0.2095140	0.1455696	0.0009301809	0.004496813	14.55696								
7	6.690476	1.389663	0.1818989	0.1761967	0.1494662	0.0006935558	0.004063648	14.94662								
8	6.875000	2.112179	0.2297923	0.2113940	0.1454545	0.0009454531	0.004861721	14.54545								
9	6.866667	2.300000	0.2260777	0.2208604	0.1456311	0.0010345321	0.004794747	14.56311								
10	6.822222	1.831313	0.2017321	0.1983606	0.1465798	0.0008453940	0.004334343	14.65798								
11	6.791667	2.381206	0.2227295	0.2272072	0.1472393	0.0011191581	0.004828643	14.72393								
12	6.886364	2.149577	0.2210295	0.2129053	0.1452145	0.0009558577	0.004660905	14.52145								
13	6.936170	2.539315	0.2324392	0.2297410	0.1441718	0.0010970785	0.004831366	14.41718								
14	6.772727	1.900634	0.2078370	0.2035568	0.1476510	0.0009033254	0.004531018	14.76510								
15	6.809524	1.670151	0.1994129	0.1897847	0.1468531	0.0007767634	0.004300508	14.68531								
	GermRateRecip_Farooq	GermSpeed_Count	GermSpeed_Percent	GermSpeedAccumulated_Count	GermSpeedAccumulated_Percent											
1	0.1683168	6.138925	12.27785	34.61567												
2	0.1625000	6.362698	12.47588	35.54058												
3	0.1674419	6.882179	14.33787	38.29725												
4	0.1666667	6.927417	13.58317	38.68453												
5	0.1680672	7.318987	14.63797	41.00786												
6	0.1680000	6.931782	14.14649	38.77620												
7	0.1682243	6.448449	13.43427	36.38546												
8	0.1621622	6.053175	12.87909	33.77079												
9	0.1674009	6.830592	13.13575	38.11511												
10	0.1656051	6.812698	13.62540	38.19527												
11	0.1693548	7.342796	14.39764	41.17452												
12	0.1680672	6.622258	12.98482	37.00640												
13	0.1655172	7.052320	14.39249	39.29399												
14	0.1693548	6.706782	13.97246	37.69490												
15	0.1666667	6.363925	13.25818	35.69697												
	GermSpeedCorrected_Normal	GermSpeedCorrected_Accumulated	WeightGermPercent	MeanGermPercent	MeanGermNormal											
1	0.1534731	0.8653917	47.42857	5.714286	2.8											

2	0.1514928	0.8462043	47.89916	5.882353	3.00		
3	0.1529373	0.8510501	54.46429	6.696429	3.20		
4	0.1505960	0.8409680	52.24090	6.442577	3.20		
5	0.1524789	0.8543303	56.14286	6.857143	3.40		
6	0.1506909	0.8429608	54.51895	6.705539	3.20		
7	0.1535345	0.8663205	51.93452	6.250000	3.00		
8	0.1513294	0.8442698	49.39210	6.079027	2.80		
9	0.1517909	0.8470024	50.27473	6.181319	3.20		
10	0.1513933	0.8487837	52.57143	6.428571	3.20		
11	0.1529749	0.8578026	55.18207	6.722689	3.40		
12	0.1505059	0.8410547	50.00000	6.162465	3.10		
13	0.1500494	0.8360424	55.24781	6.851312	3.30		
14	0.1524269	0.8567022	53.86905	6.547619	3.10		
15	0.1515220	0.8499278	51.19048	6.250000	3.00		
	TimsonsIndex	TimsonsIndex_Labouriau	TimsonsIndex_KhanUngar	GermRateGeorge	GermIndex	GermIndex_mod	
1	8.000000	1.00	0.5714286	4	5.840000	7.300000	
2	9.803922	1.25	0.7002801	5	5.882353	7.142857	
3	14.583333	1.40	1.0416667	7	6.687500	7.133333	
4	7.843137	1.00	0.5602241	4	6.411765	7.108696	
5	10.000000	1.00	0.7142857	5	6.900000	7.187500	
6	6.122449	1.00	0.4373178	3	6.693878	7.130435	
7	8.333333	1.00	0.5952381	4	6.395833	7.309524	
8	10.638298	1.25	0.7598784	5	6.063830	7.125000	
9	9.615385	1.25	0.6868132	5	6.173077	7.133333	
10	8.000000	1.00	0.5714286	4	6.460000	7.177778	
11	9.803922	1.00	0.7002801	5	6.784314	7.208333	
12	5.882353	1.00	0.4201681	3	6.137255	7.113636	
13	8.163265	1.00	0.5830904	4	6.775510	7.063830	
14	6.250000	1.00	0.4464286	3	6.625000	7.227273	
15	8.333333	1.00	0.5952381	4	6.291667	7.190476	
	EmergenceRateIndex_SG	EmergenceRateIndex_SG_mod	EmergenceRateIndex_BilbroWanjura	EmergenceRateIndex_L			
1	292	7.300000	5.970149	8			
2	300	7.142857	6.125000	8			
3	321	7.133333	6.553398	7			
4	327	7.108696	6.675079	7			
5	345	7.187500	7.045872	7			
6	328	7.130435	6.696203	7			
7	307	7.309524	6.277580	7			
8	285	7.125000	5.818182	8			
9	321	7.133333	6.553398	7			
10	323	7.177778	6.596091	7			
11	346	7.208333	7.067485	7			
12	313	7.113636	6.389439	7			
13	332	7.063830	6.776074	7			
14	318	7.227273	6.496644	7			
15	302	7.190476	6.167832	7			
	PeakValue	GermValue_Czabator	GermValue_DP	GermValue_Czabator_mod	GermValue_DP_mod	CUGerm	GermSync
1	9.500000	54.28571	57.93890	54.28571	39.56076	0.7092199	0.26
2	9.313725	54.78662	52.58713	54.78662	40.99260	0.5051546	0.23
3	10.416667	69.75446	68.62289	69.75446	53.42809	0.3975265	0.22
4	10.049020	64.74158	70.43331	64.74158	48.86825	0.4672113	0.25
5	11.250000	77.14286	80.16914	77.14286	56.23935	0.4312184	0.26
6	10.714286	71.84506	76.51983	71.84506	53.06435	0.4934701	0.27
7	10.416667	65.10417	69.41325	65.10417	47.37690	0.7371500	0.27

8	9.574468	58.20345	56.00669	58.20345	43.67948	0.4855842	0.22
9	9.855769	60.92165	58.13477	60.92165	45.30801	0.4446640	0.24
10	10.250000	65.89286	70.91875	65.89286	49.10820	0.5584666	0.25
11	11.029412	74.14731	77.39782	74.14731	54.27520	0.4288905	0.26
12	9.803922	60.41632	64.44988	60.41632	44.71582	0.4760266	0.27
13	10.969388	75.15470	78.16335	75.15470	54.94192	0.4023679	0.25
14	10.677083	69.90947	74.40140	69.90947	51.41913	0.5383760	0.29
15	10.156250	63.47656	67.62031	63.47656	46.48043	0.6133519	0.24
GermUncertainty							
1	2.062987						
2	2.321514						
3	2.462012						
4	2.279215						
5	2.146051						
6	2.160545						
7	2.040796						
8	2.357249						
9	2.321080						
10	2.187983						
11	2.128670						
12	2.185245						
13	2.241181						
14	2.037680						
15	2.185028						

**FourPHFfit.bulk()** This wrapper function can be used to fit the four-parameter hill function for multiple samples in batch.

```
data(gcddata)

counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")

FourPHFfit.bulk(gcddata, total.seeds.col = "Total Seeds",
                counts.intervals.cols = counts.per.intervals,
                intervals = 1:14, partial = TRUE,
                fix.y0 = TRUE, fix.a = TRUE, xp = c(10, 60),
                tmax = 20, tries = 3, umax = 90, umin = 10)
```

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error  
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

	Genotype	Rep	Day01	Day02	Day03	Day04	Day05	Day06	Day07	Day08	Day09	Day10	Day11	Day12	Day13	Day14	Tot.
1	G1	1	0	0	0	0	4	17	10	7	1	0	1	0	0	0	
2	G2	1	0	0	0	1	3	15	13	6	2	1	0	1	0	0	
3	G3	1	0	0	0	2	3	18	9	8	2	1	1	1	0	0	
4	G4	1	0	0	0	0	4	19	12	6	2	1	1	1	0	0	
5	G5	1	0	0	0	0	5	20	12	8	1	0	0	1	1	0	
6	G1	2	0	0	0	0	3	21	11	7	1	1	1	1	0	0	
7	G2	2	0	0	0	0	4	18	11	7	1	0	1	0	0	0	
8	G3	2	0	0	0	1	3	14	12	6	2	1	0	1	0	0	
9	G4	2	0	0	0	1	3	19	10	8	1	1	1	1	0	0	
10	G5	2	0	0	0	0	4	18	13	6	2	1	0	1	0	0	
11	G1	3	0	0	0	0	5	21	11	8	1	0	0	1	1	0	
12	G2	3	0	0	0	0	3	20	10	7	1	1	1	1	0	0	
13	G3	3	0	0	0	0	4	19	12	8	1	1	0	1	1	0	
14	G4	3	0	0	0	0	3	21	11	6	1	0	1	1	0	0	
15	G5	3	0	0	0	0	4	17	10	8	1	1	1	0	0	0	
	b	c	y0	lag	Dlag50	t50.total	txp.total_10	txp.total_60	t50.Germinated	txp.Germinated_10	txp.						
1	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
2	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
3	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
4	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
5	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
6	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						
7	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>						

[illegible][illegible]

46

14	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>
15	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>	<NA>

Multiple fitted curves generated in batch can also be plotted.

```
data(gcdata)

counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")

fits <- FourPHFfit.bulk(gcdata, total.seeds.col = "Total Seeds",
                       counts.intervals.cols = counts.per.intervals,
                       intervals = 1:14, partial = TRUE,
                       fix.y0 = TRUE, fix.a = TRUE, xp = c(10, 60),
                       tmax = 20, tries = 3, umax = 90, umin = 10)
```

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

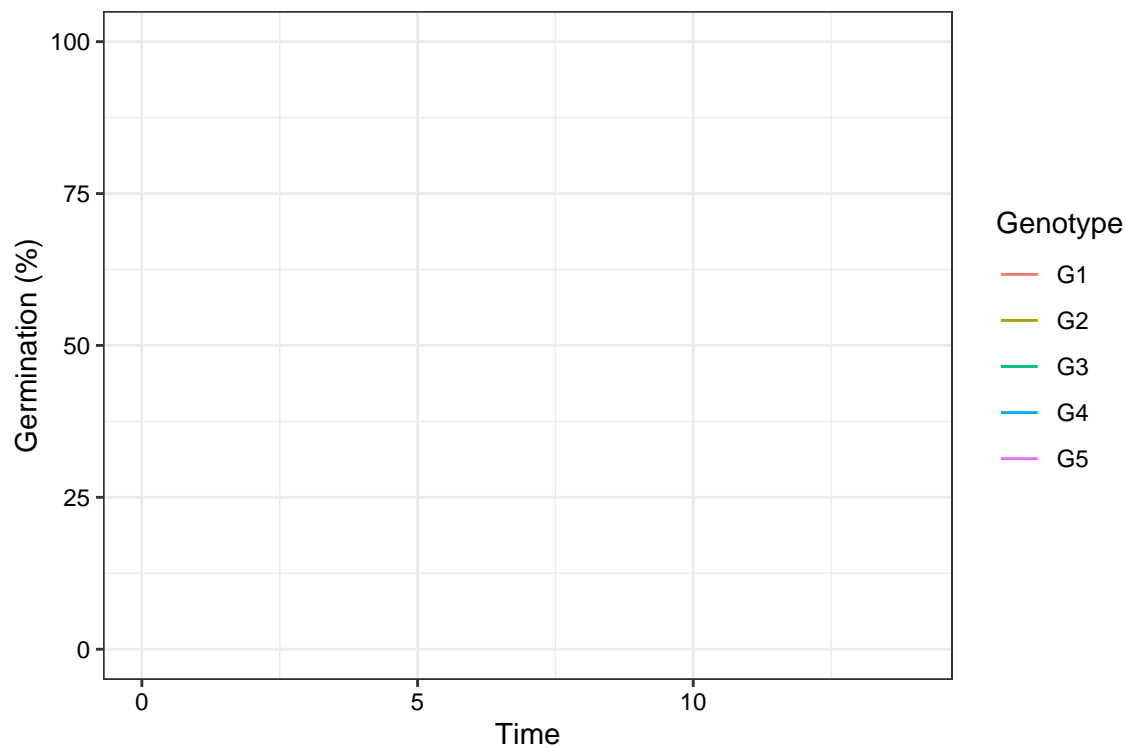
Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error #1. failed to evaluate 'fn' at starting values: could not find function "FourPHF\_fixa\_fixy0"

```
Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"
```

```
Warning in FourPHFfit(germ.counts = unlist(mget(counts.intervals.cols)), : Convergence Error
#1. failed to evaluate 'fn' at starting values: could not find function "FourPHF_fixa_fixy0"
```

```
# Plot FPHF curves
plot(fits, group.col = "Genotype")
```

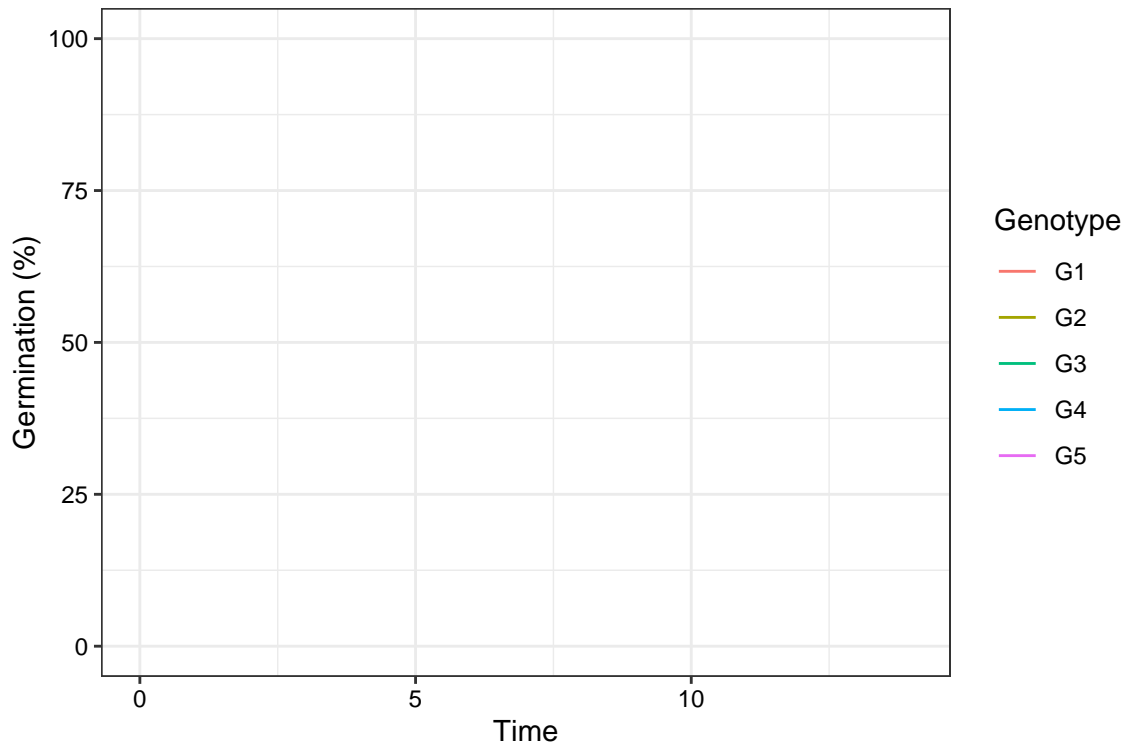
```
Warning: Removed 1965 rows containing missing values (`geom_line()`).
```



```
# Plot ROG curves
plot(fits, rog = TRUE, group.col = "Genotype")
```

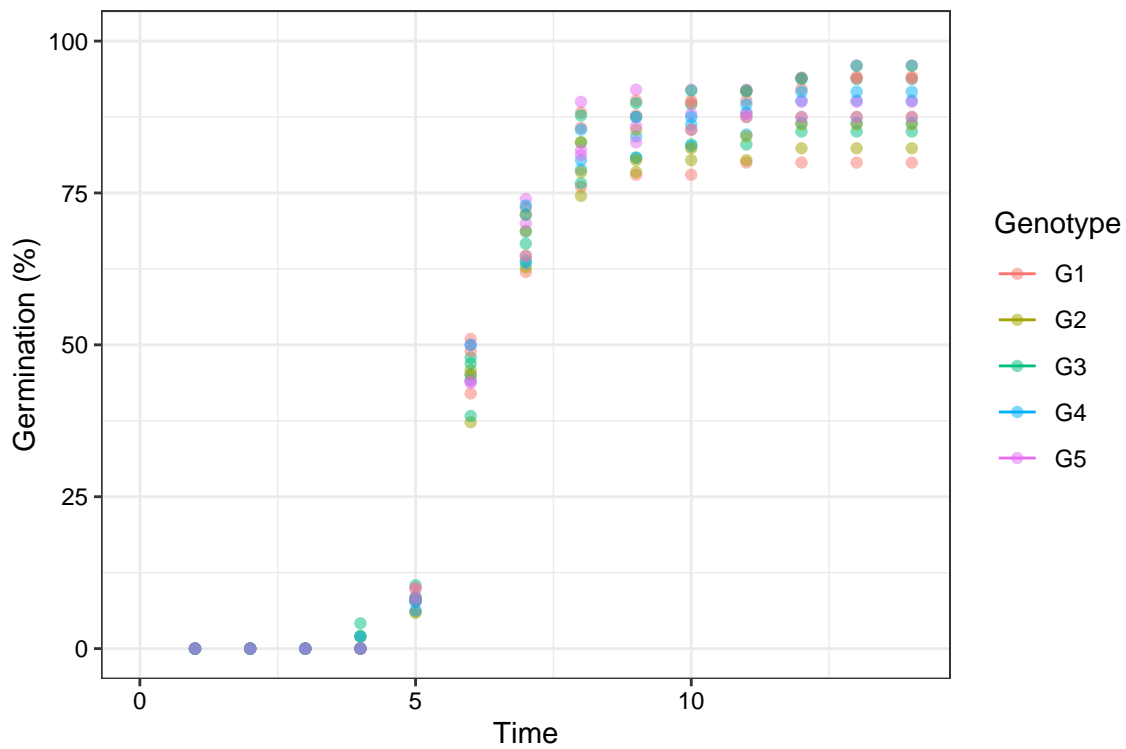
```
Warning: Removed 1965 rows containing missing values (`geom_line()`).
```





```
# Plot FPHF curves with points
plot(fits, group.col = "Genotype", show.points = TRUE)
```

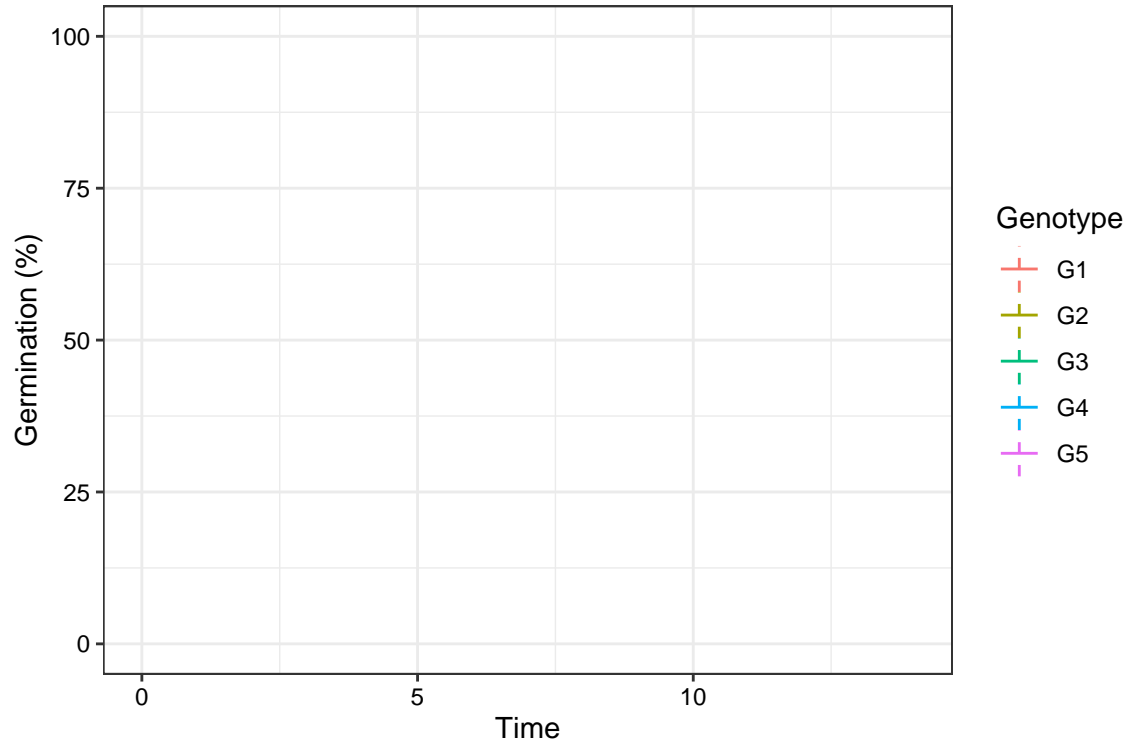
Warning: Removed 1965 rows containing missing values (``geom_line()``).



```
# Plot FPHF curves with annotations
plot(fits, group.col = "Genotype", annotate = "t50.total")
```

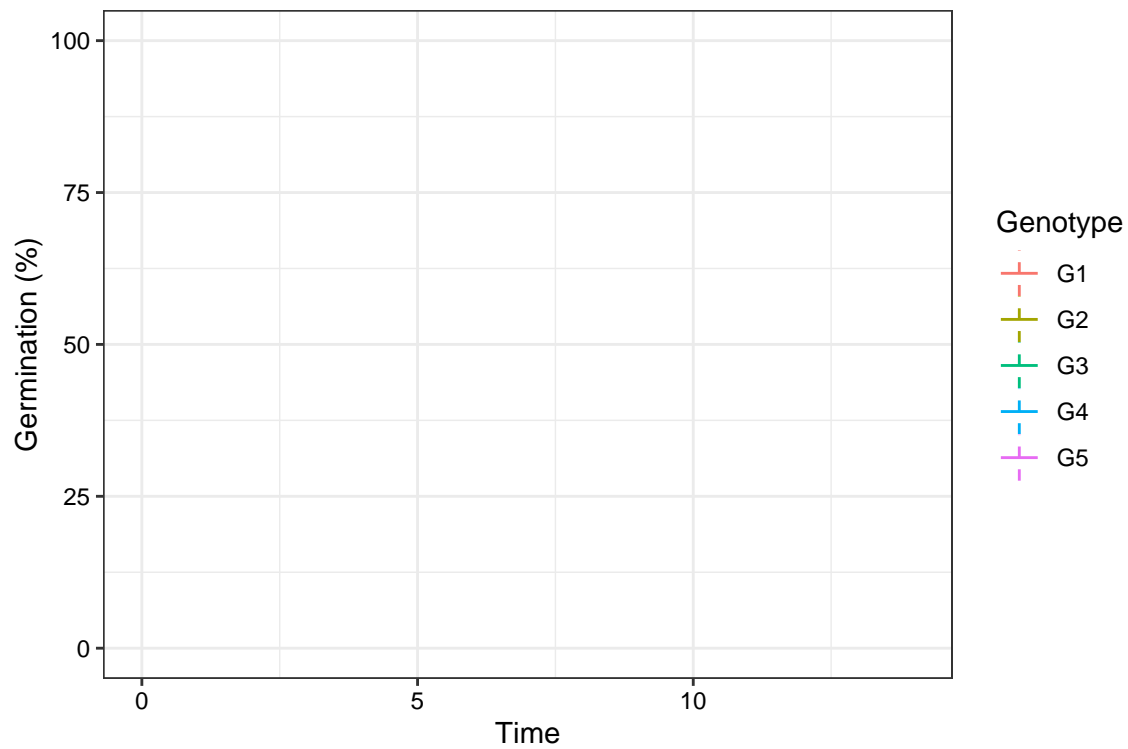
Warning: Removed 1965 rows containing missing values (``geom_line()``).

Warning: Removed 15 rows containing missing values (``geom_vline()``).



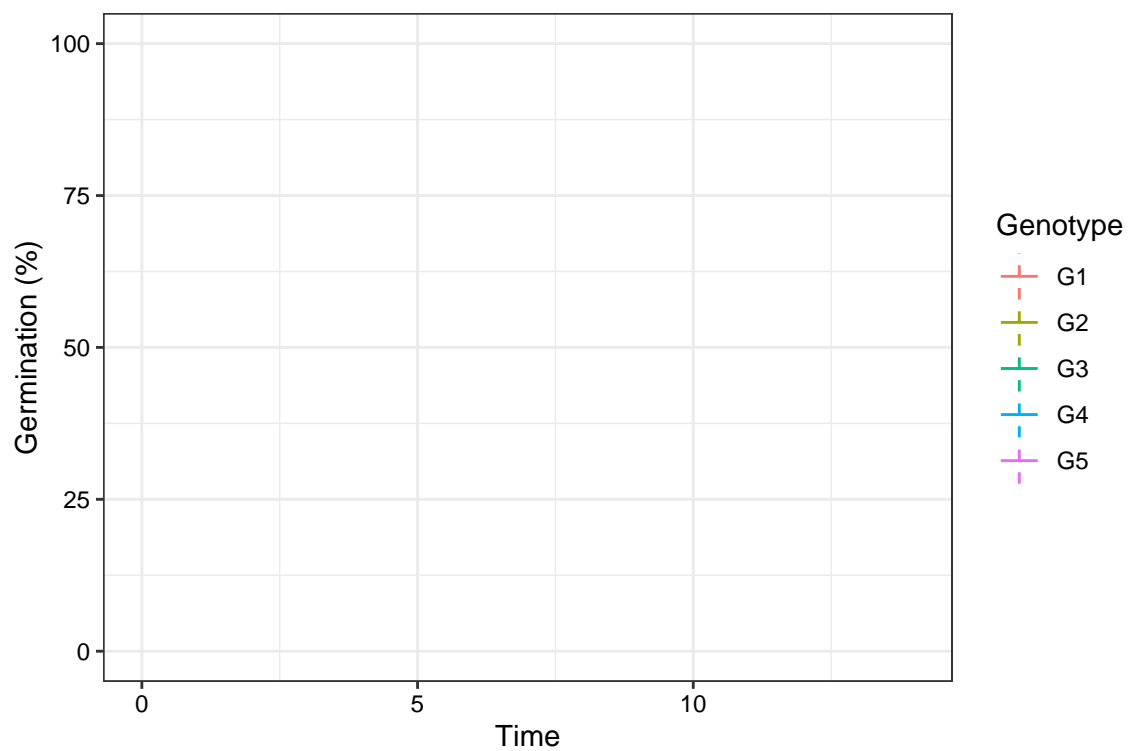
```
plot(fits, group.col = "Genotype", annotate = "t50.germ")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).



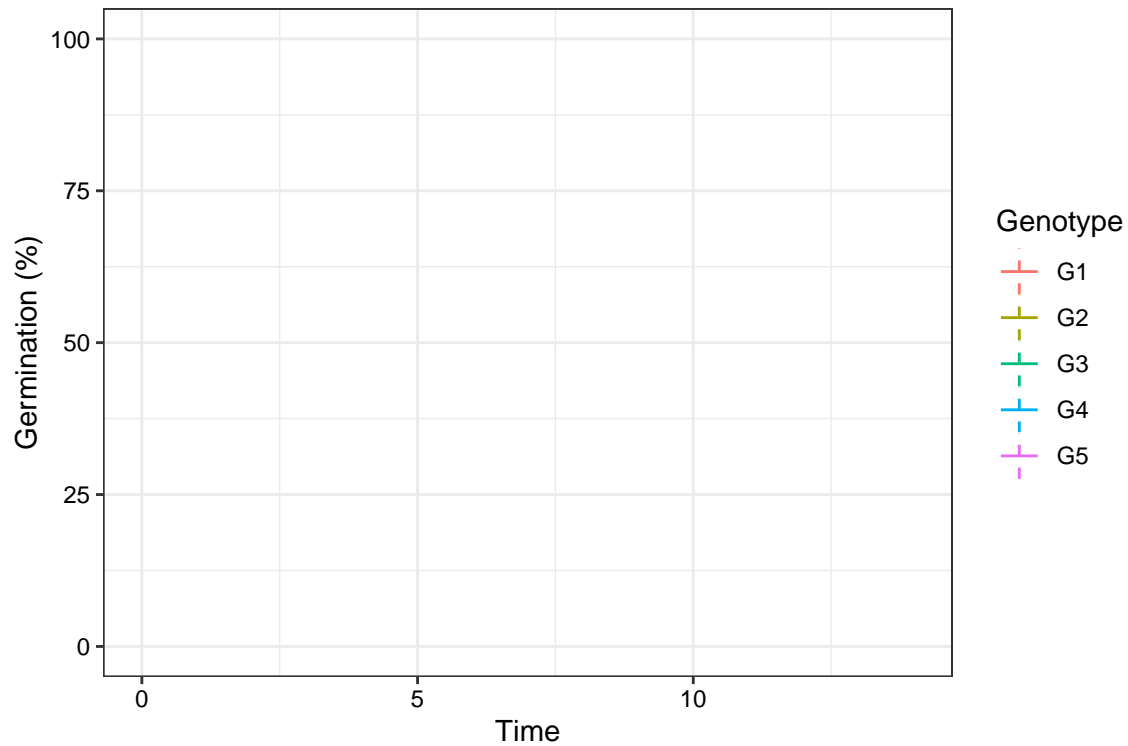
```
plot(fits, group.col = "Genotype", annotate = "tmgr")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).



```
plot(fits, group.col = "Genotype", annotate = "mgt")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).

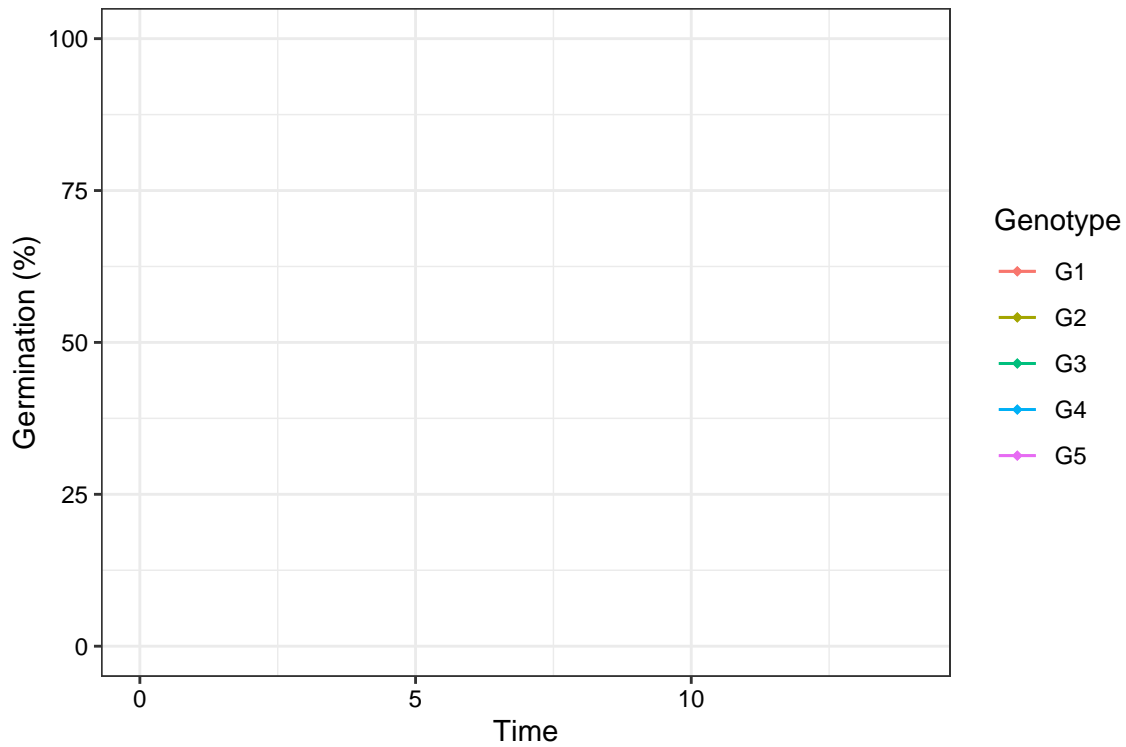


```
plot(fits, group.col = "Genotype", annotate = "uniformity")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).

Warning: Removed 15 rows containing missing values (``geom_point()``).  
Removed 15 rows containing missing values (``geom_point()``).

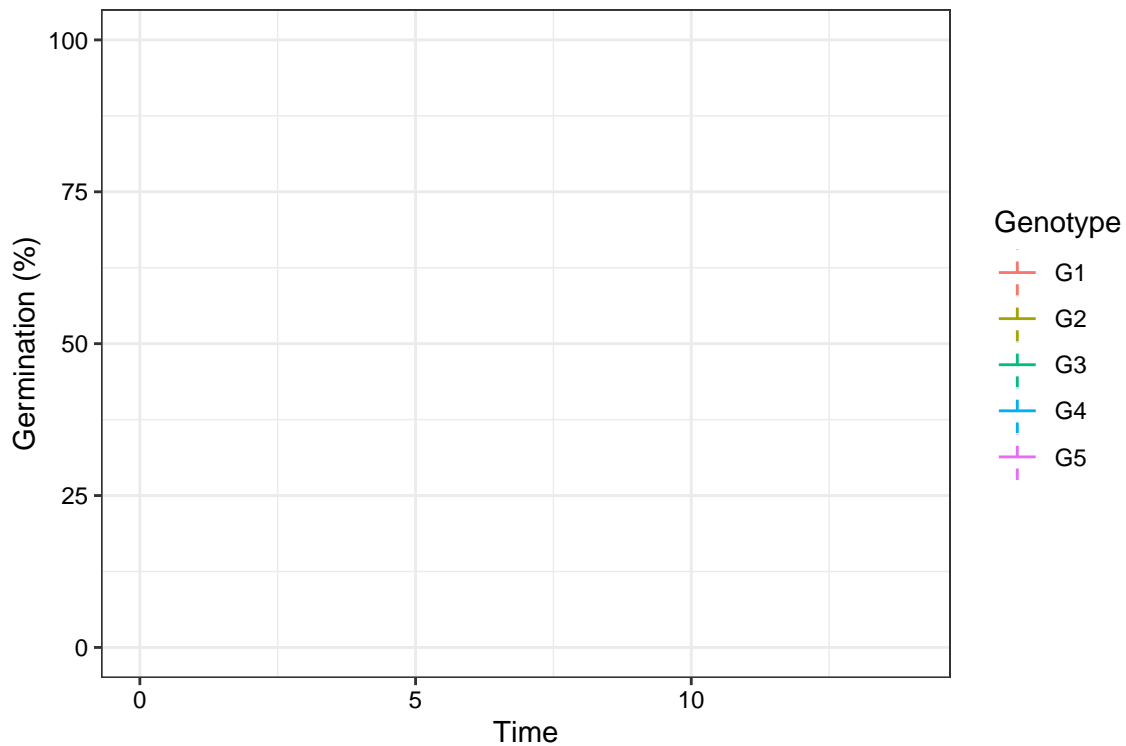
Warning: Removed 15 rows containing missing values (``geom_segment()``).



```
# Plot ROG curves with annotations  
plot(fits, rog = TRUE, group.col = "Genotype", annotate = "t50.total")
```

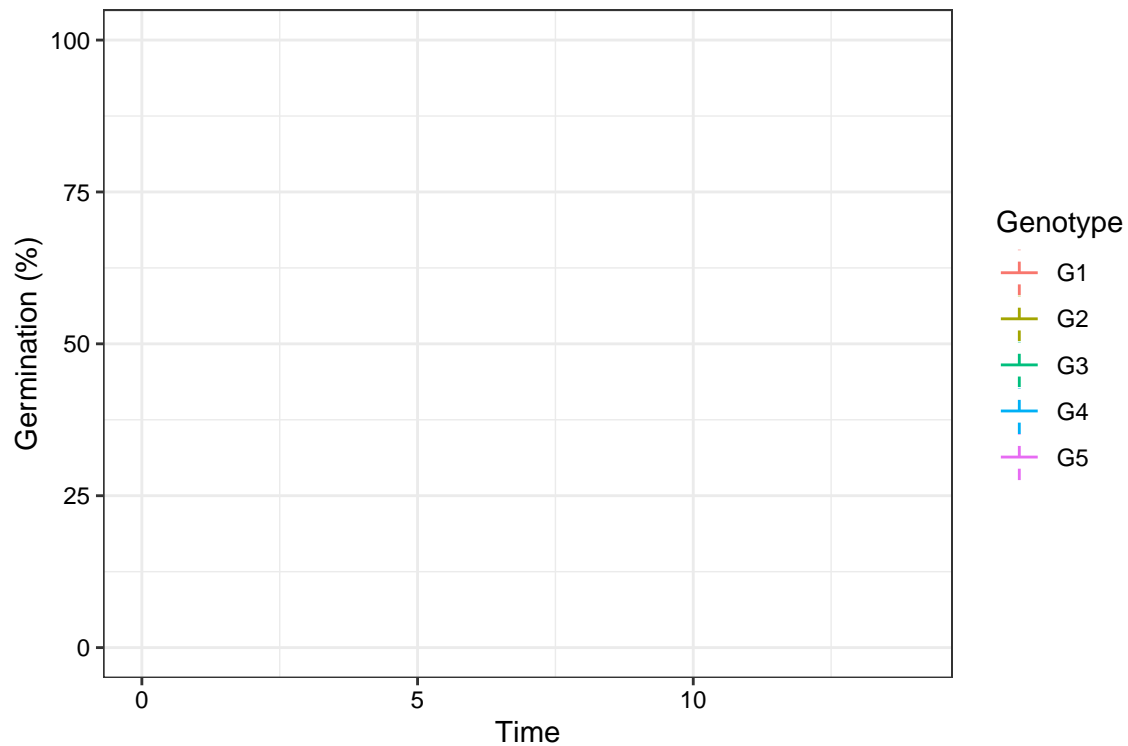
Warning: Removed 1965 rows containing missing values (``geom_line()``).

Warning: Removed 15 rows containing missing values (``geom_vline()``).



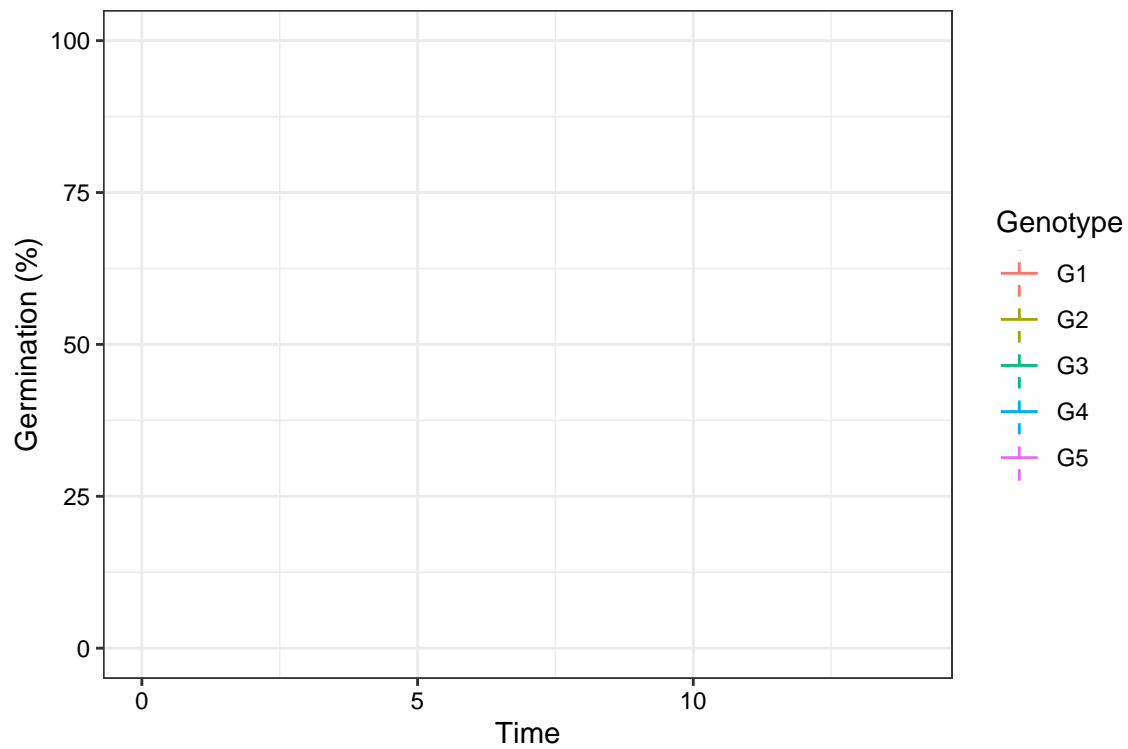
```
plot(fits, rog = TRUE, group.col = "Genotype", annotate = "t50.germ")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).



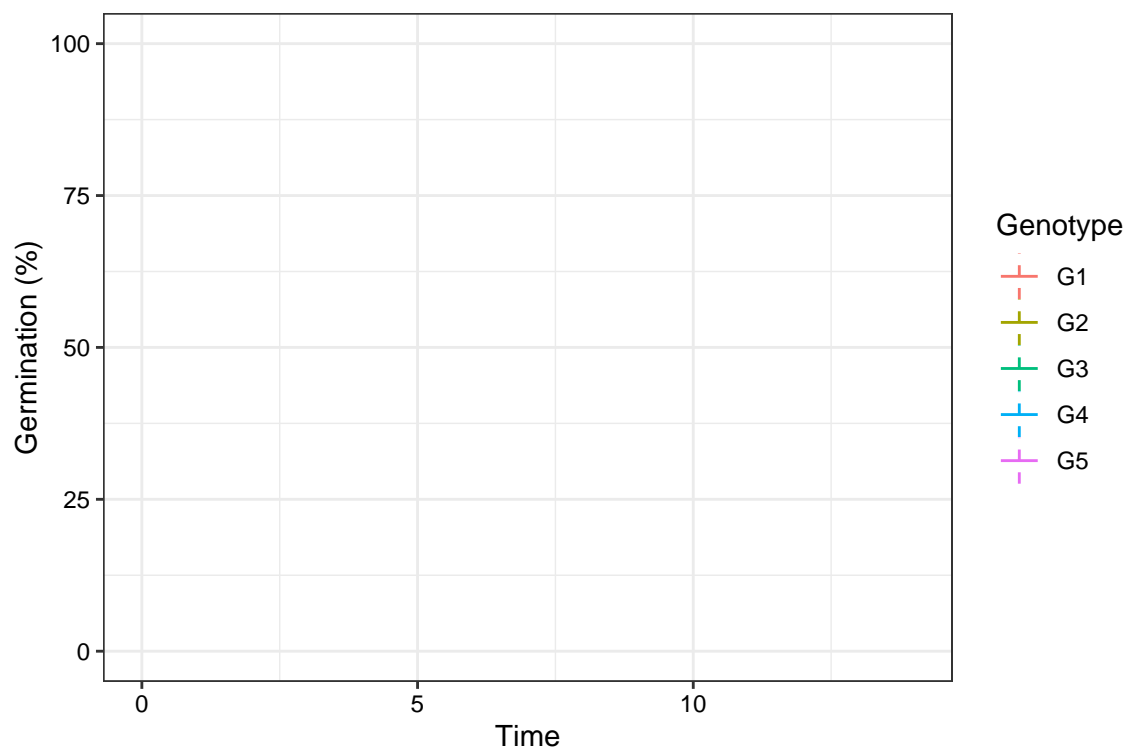
```
plot(fits, rog = TRUE, group.col = "Genotype", annotate = "tmgr")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).



```
plot(fits, rog = TRUE, group.col = "Genotype", annotate = "mgt")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).  
Removed 15 rows containing missing values (``geom_vline()``).

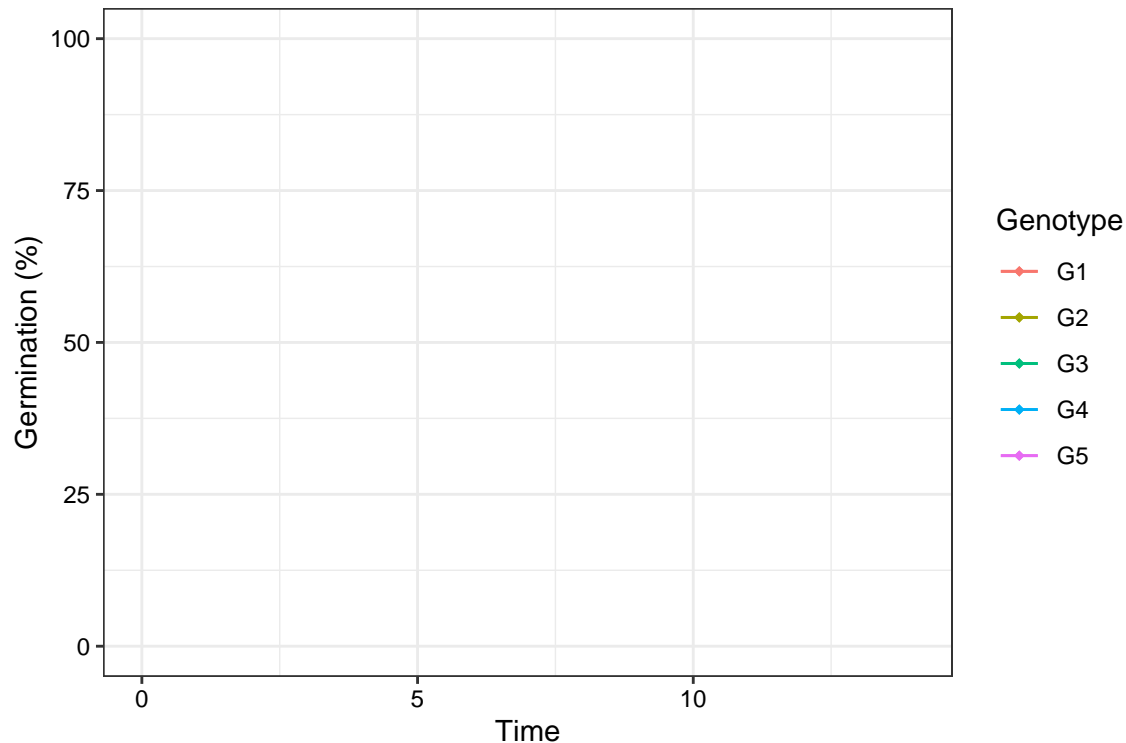


```
plot(fits, rog = TRUE, group.col = "Genotype", annotate = "uniformity")
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).

Warning: Removed 15 rows containing missing values (``geom_point()``).  
 Removed 15 rows containing missing values (``geom_point()``).

Warning: Removed 15 rows containing missing values (``geom_segment()``).

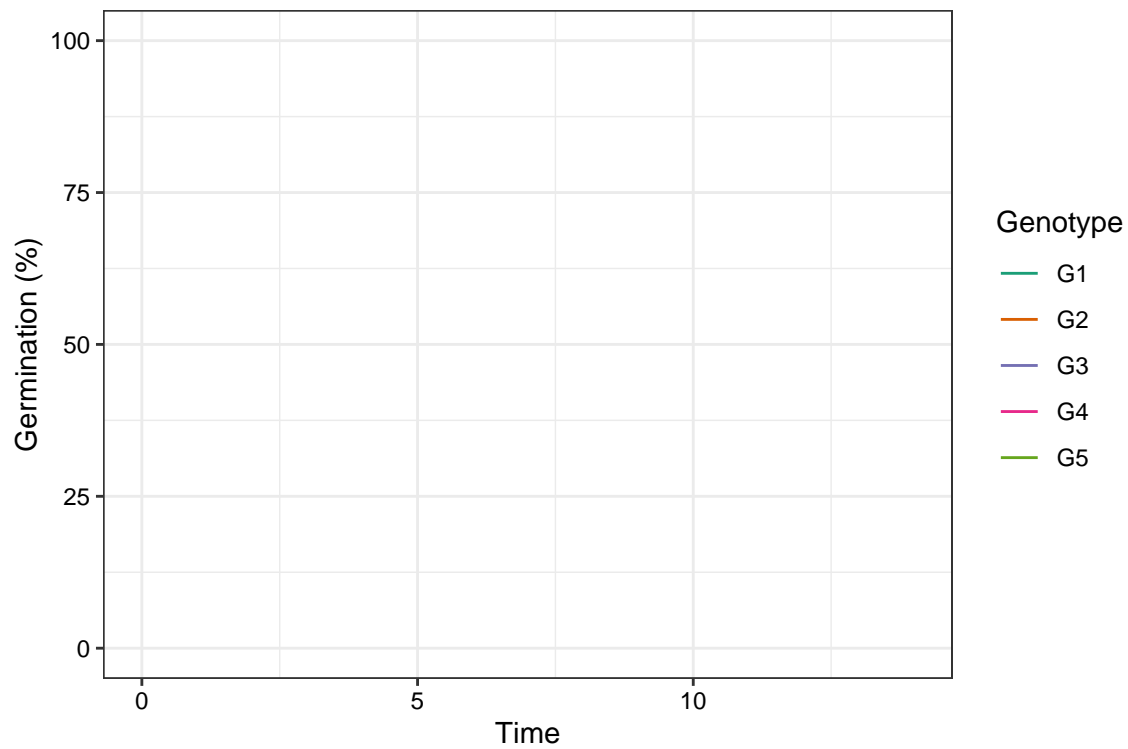


```
# Change colour of curves using ggplot2 options
library(ggplot2)
curvesplot <- plot(fits, group.col = "Genotype")

# 'Dark2' palette from RColorBrewer
curvesplot + scale_colour_brewer(palette = "Dark2")
```

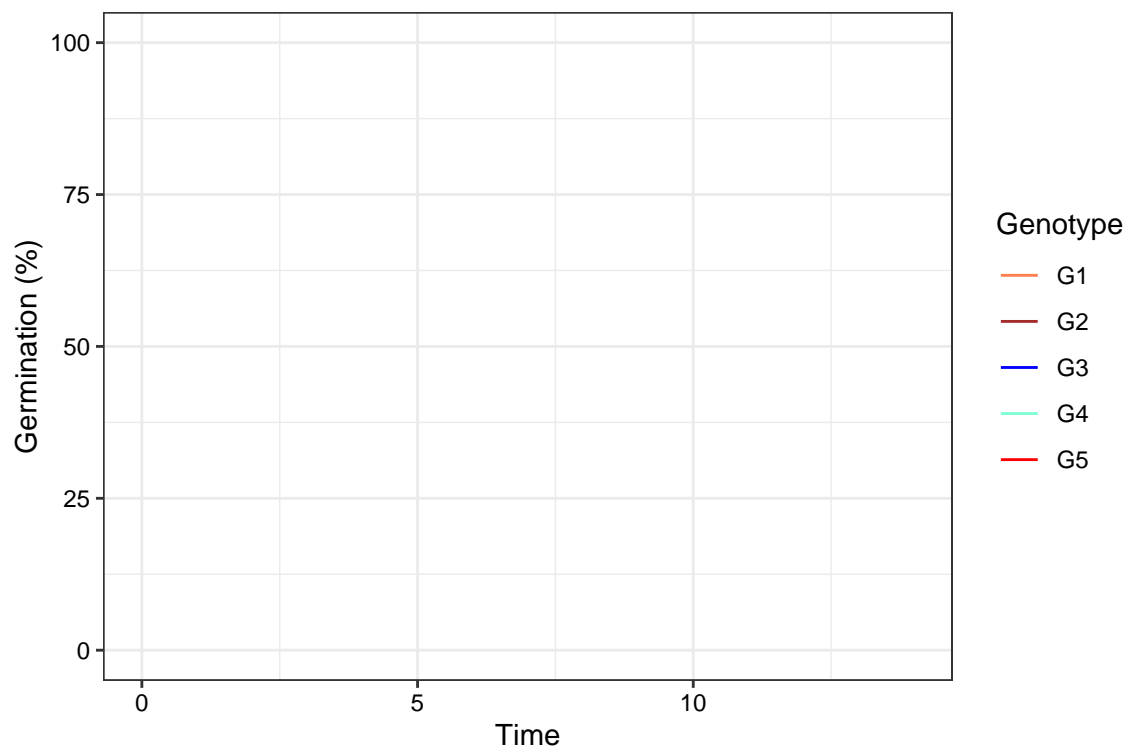
Warning: Removed 1965 rows containing missing values (``geom_line()``).





```
# Manual colours
curvesplot +
  scale_colour_manual(values = c("Coral", "Brown", "Blue",
                                "Aquamarine", "Red"))
```

Warning: Removed 1965 rows containing missing values (``geom_line()``).



## Citing *germinationmetrics*

To cite the R package '*germinationmetrics*' in publications use:

Aravind, J., Vimala Devi, S., Radhamani, J., Jacob, S. R., and Kalyani Srinivasan ().  
*germinationmetrics*: Seed Germination Indices and Curve Fitting. R package version 0.1.7.9000,  
<https://github.com/aravind-j/germinationmetrics><https://cran.r-project.org/package=germinationmetrics>.

A BibTeX entry for LaTeX users is

```
@Manual{,
  title = {germinationmetrics: Seed Germination Indices and Curve Fitting},
  author = {J. Aravind and S. {Vimala Devi} and J. Radhamani and Sherry Rachel Jacob and {Kalyani Srinivasan}},
  note = {R package version 0.1.7.9000 https://aravind-j.github.io/germinationmetrics/ https://CRAN.R-project.org/package=germinationmetrics}
}
```

This free and open-source software implements academic research by the authors and co-workers. If you use it, please support the project by citing the package.

## Session Info

```
sessionInfo()
```

R Under development (unstable) (2023-08-09 r84924 ucrt)

Platform: x86\_64-w64-mingw32/x64

Running under: Windows 11 x64 (build 22621)

Matrix products: default

locale:

```
[1] LC_COLLATE=English_India.utf8  LC_CTYPE=English_India.utf8    LC_MONETARY=English_India.utf8
[4] LC_NUMERIC=C                  LC_TIME=English_India.utf8
```

time zone: Asia/Calcutta

tzcode source: internal

attached base packages:

```
[1] stats      graphics  grDevices  utils      datasets  methods    base
```

other attached packages:

```
[1] germinationmetrics_0.1.7.9000 ggplot2_3.4.2                testthat_3.1.10
```

loaded via a namespace (and not attached):

```
[1] utf8_1.2.3      generics_0.1.3  tidyr_1.3.0     bitops_1.0-7    stringi_1.7.12  lat
[7] digest_0.6.33   magrittr_2.0.3  RColorBrewer_1.1-3 evaluate_0.21    grid_4.4.0      pkg
[13] fastmap_1.1.1   plyr_1.8.8      Matrix_1.6-0    ggrepel_0.9.3   backports_1.4.1  bri
[19] tinytex_0.46    httr_1.4.6      pander_0.6.5    purrr_1.0.1     fansi_1.0.4      sca
[25] XML_3.99-0.14   Rdpack_2.4      cli_3.6.1       rlang_1.1.1     rbibutils_2.2.14  mun
[31] withr_2.5.0     yaml_2.3.7      tools_4.4.0     parallel_4.4.0  reshape2_1.4.4   dpl
[37] colorspace_2.1-0 mathjaxr_1.6-0   curl_5.0.1      broom_1.0.5     vctr_0.6.3       R6_
[43] lifecycle_1.0.3 gslns_1.1.2     stringr_1.5.0   pkgconfig_2.0.3 rJava_1.0-6      pil
[49] gtable_0.3.3    data.table_1.14.8 glue_1.6.2      Rcpp_1.0.11     highr_0.10       xfu
[55] tibble_3.2.1    tidyselect_1.2.0 rstudioapi_0.15.0 knitr_1.43      farver_2.1.1     htm
```

[61] `labeling_0.4.2`      `rmarkdown_2.23`      `compiler_4.4.0`      `RCurl_1.98-1.12`

## References

- Allan, R. E., Vogel, O. A., and Peterson, C. J. (1962). Seedling emergence rate of fall-sown wheat and its association with plant height and coleoptile length. *Agronomy Journal* 54, 347. doi:10.2134/agronj1962.00021962005400040022x.
- Al-Mudaris, M. A. (1998). Notes on various parameters recording the speed of seed germination. *Der Tropenlandwirt - Journal of Agriculture in the Tropics and Subtropics* 99, 147–154. Available at: <https://www.jarts.info/index.php/tropenlandwirt/article/download/1495/671>.
- AOSA (1983). *Seed Vigor Testing Handbook*. Ithaca, NY, USA: Association of Official Seed Analysts.
- Baskin, C. C., and Baskin, J. M. (1998). *Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination*. San Diego: Academic Press.
- Bewley, J. D., and Black, M. (1994). *Physiology of Development and Germination*. New York, USA: Plenum Publishing Corporation Available at: <https://www.cabdirect.org/cabdirect/abstract/19950315483>.
- Bilbro, J. D., and Wanjura, D. F. (1982). Soil crusts and cotton emergence relationships. *Transactions of the ASAE* 25, 1484–1487. doi:10.13031/2013.33750.
- Bonner, F. T. (1967). Ideal sowing depth for sweetgum seed. *Tree Planters' Notes* 18, 1–1. Available at: <https://www.fs.usda.gov/treearch/pubs/download/42583.pdf>.
- Bouton, J. H., Dudeck, A. E., and Smith, R. L. (1976). Germination in freshly harvested seed of centipedegrass. *Agronomy Journal* 68, 991. doi:10.2134/agronj1976.00021962006800060040x.
- Bradbeer, J. W. (1988). *Seed Dormancy and Germination*. Glasgow; London: Blackie Available at: [www.springer.com/in/book/9780216916364](http://www.springer.com/in/book/9780216916364) [Accessed January 15, 2018].
- Brown, R. F., and Mayer, D. G. (1988). Representing cumulative germination. 1. A critical analysis of single-value germination indices. *Annals of Botany* 61, 117–125. doi:10.1093/oxfordjournals.aob.a087534.
- Chaudhary, T. N., and Ghildyal, B. P. (1970). Effect of temperature associated with levels of bulk density on rice seedling emergence. *Plant and Soil* 33, 87–90. doi:10.1007/bf01378199.
- Chopra, U. K., and Chaudhary, T. N. (1980). Effect of soil temperature alteration by soil covers on seedling emergence of wheat (*Triticum aestivum* L.) sown on two dates. *Plant and Soil* 57, 125–129. doi:10.1007/bf02139648.
- Coolbear, P., Francis, A., and Grierson, D. (1984). The effect of low temperature pre-sowing treatment on the germination performance and membrane integrity of artificially aged tomato seeds. *Journal of Experimental Botany* 35, 1609–1617. doi:10.1093/jxb/35.11.1609.
- Czabator, F. J. (1962). Germination value: An index combining speed and completeness of pine seed germination. *Forest Science* 8, 386–396. doi:10.1093/forestscience/8.4.386.
- Djavanshir, K., and Pourbeik, H. (1976). Germination value-A new formula. *Silvae Genetica* 25, 79–83. Available at: [https://www.thuenen.de/media/institute/fg/PDF/Silvae\\_Genetica/1976/Vol.\\_25\\_Heft\\_2/25\\_2\\_79.pdf](https://www.thuenen.de/media/institute/fg/PDF/Silvae_Genetica/1976/Vol._25_Heft_2/25_2_79.pdf).
- Edmond, J. B., and Drapala, W. J. (1958). The effects of temperature, sand and soil, and acetone on germination of okra seed. *Proceedings of the American Society for Horticultural Science* 71, 428–434.
- Edwards, T. I. (1932). Temperature relations of seed germination. *The Quarterly Review of Biology* 7, 428–443. doi:10.1086/394417.
- El-Kassaby, Y. A., Moss, I., Kolotelo, D., and Stoehr, M. (2008). Seed germination: Mathematical representation and parameters extraction. *Forest Science* 54, 220–227. doi:10.1093/forestscience/54.2.220.
- Ellis, R. H., and Roberts, E. H. (1980). Improved equations for the prediction of seed longevity. *Annals of Botany* 45, 13–30. doi:10.1093/oxfordjournals.aob.a085797.
- Erbach, D. C. (1982). Tillage for continuous corn and corn-soybean rotation. *Transactions of the ASAE* 25, 906–911. doi:10.13031/2013.33638.
- Evetts, L. L., and Burnside, O. C. (1972). Germination and seedling development of common milkweed and other species. *Weed Science* 20, 371–378. doi:10.1017/S004317450003589x.
- Fakorede, M. A. B., and Agbana, S. B. (1983). Heterotic effects and association of seedling vigour with mature characteristics and grain yield in some tropical maize cultivars. *Maydica* 28, 327–338.
- Fakorede, M. A. B., and Ayoola, A. O. (1980). Relation between seedling vigor and selection for yield improvement in maize. *Maydica* 25, 135–147.
- Fakorede, M. A. B., and Ojo, D. K. (1981). Variability for seedling vigour in maize. *Experimental Agriculture*

- 17, 195–201. doi:10.1017/s0014479700011455.
- Farooq, M., Basra, S. M. A., Ahmad, N., and Hafeez, K. (2005). Thermal hardening: A new seed vigor enhancement tool in rice. *Journal of Integrative Plant Biology* 47, 187–193. doi:10.1111/J.1744-7909.2005.00031.x.
- George, D. W. (1961). Influence of germination temperature on the expression of post-harvest dormancy in wheat. in *Crop Science Abstracts; Western Society of Crop Science Annual Meeting, 1961* (Western Society of Crop Science), 15.
- Goloff, A. A., and Bazzaz, F. A. (1975). A germination model for natural seed populations. *Journal of Theoretical Biology* 52, 259–283. doi:10.1016/0022-5193(75)90001-6.
- Gomes, F. P. (1960). *Curso De Estatística Experimental*. Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo Available at: <https://books.google.de/books?id=ZckqGwAACAAJ>.
- Goodchild, N. A., and Walker, M. G. (1971). A method of measuring seed germination in physiological studies. *Annals of Botany* 35, 615–621. doi:10.1093/oxfordjournals.aob.a084504.
- Gordon, A. G. (1969). Some observations on the germination energy tests for cereals. *Proceedings of the Association of Official Seed Analysts* 59, 58–72. Available at: <https://www.jstor.org/stable/23432357> [Accessed December 11, 2018].
- Gordon, A. G. (1971). The germination resistance test - A new test for measuring germination quality of cereals. *Canadian Journal of Plant Science* 51, 181–183. doi:10.4141/cjps71-036.
- Grose, R. J., and Zimmer, W. J. (1958). Some laboratory germination responses of the seeds of river red gum, *Eucalyptus camaldulensis* Dehn. Syn. *Eucalyptus rostrata* Schlecht. *Australian Journal of Botany* 6, 129. doi:10.1071/bt9580129.
- Haugland, E., and Brandsaeter, L. O. (1996). Experiments on bioassay sensitivity in the study of allelopathy. *Journal of Chemical Ecology* 22, 1845–1859. doi:10.1007/BF02028508.
- Heydecker, W. (1972). *Seed Ecology. Proceedings of the Nineteenth Easter School in Agricultural Science, University of Nottingham, 1972*. University Park, USA: Pennsylvania State University Press.
- Hsu, F. H., and Nelson, C. J. (1986). Planting date effects on seedling development of perennial warm-season forage grasses. I. Field emergence. *Agronomy Journal* 78, 33–38. doi:10.2134/agronj1986.00021962007800010008x.
- ISTA (2015). “Chapter 5: The germination test,” in *International Rules for Seed Testing. International Seed Testing Association, Zurich, Switzerland*. (International Seed Testing Association), i-5-56. Available at: <https://doi.org/10.15258/istarules.2015.05>.
- Kader, M. A. (2005). A comparison of seed germination calculation formulae and the associated interpretation of resulting data. *Journal and Proceedings of the Royal Society of New South Wales* 138, 65–75. Available at: [https://royalsoc.org.au/images/pdf/journal/138\\_Kader.pdf](https://royalsoc.org.au/images/pdf/journal/138_Kader.pdf).
- Kendrick, R. E., and Frankland, B. (1969). Photocontrol of germination in *Amaranthus caudatus*. *Planta* 85, 326–339. doi:10.1007/bf00381281.
- Khamassi, K., Harbaoui, K., Jaime, A. T. da S., and Jeddi, F. B. (2013). Optimal germination temperature assessed by indices and models in field bean (*Vicia faba* L. Var. *Minor*). *Agriculturae Conspectus Scientificus* 78, 131–136. Available at: <https://hrcak.srce.hr/104663>.
- Khan, M. A., and Ungar, I. A. (1984). The effect of salinity and temperature on the germination of polymorphic seeds and growth of *Atriplex triangularis* Willd. *American Journal of Botany* 71, 481–489. doi:10.2307/2443323.
- Khandakar, A. L., and Bradbeer, J. W. (1983). *Jute seed quality*. Bangladesh Agricultural Research Council, Dhaka.
- Kotowski, F. (1926). Temperature relations to germination of vegetable seeds. *Proceedings of the American Society for Horticultural Science* 23, 176–184.
- Labouriau, L. G. (1983a). *A Germinação Das Sementes*. Organização dos Estados Americanos. Programa Regional de Desenvolvimento Científico e Tecnológico. Série de Biologia. Monografia 24.
- Labouriau, L. G. (1983b). Uma nova linha de pesquisa na fisiologia da germinação das sementes. in *Anais do XXXIV Congresso Nacional de Botânica. SBB, Porto Alegre* (Sociedade Botânica do Brasil), 11–50.
- Labouriau, L. G., and Valadares, M. E. B. (1976). On the germination of seeds of *Calotropis procera* (Ait.) Ait. f. *Anais da Academia Brasileira de Ciências* 48.
- Maguire, J. D. (1962). Speed of germination - Aid in selection and evaluation for seedling emergence and vigor. *Crop Science* 2, 176–177. doi:10.2135/cropsci1962.0011183x000200020033x.
- Melville, A. H., Galletta, G. J., Draper, A. D., and Ng, T. J. (1980). Seed germination and early seedling

- vigor in progenies of inbred strawberry selections. *HortScience* 15, 749–750.
- Mock, J. J., and Eberhart, S. A. (1972). Cold tolerance in adapted maize populations. *Crop Science* 12, 466–469. doi:10.2135/cropsci1972.0011183x001200040021x.
- Negm, F. B., and Smith, O. E. (1978). Effects of ethylene and carbon dioxide on the germination of osmotically inhibited lettuce seed. *Plant Physiology* 62, 473–476. doi:10.1104/pp.62.4.473.
- Nichols, M. A., and Heydecker, W. (1968). Two approaches to the study of germination data. *Proceedings of the International Seed Testing Association* 33, 531–540.
- Primack, R. B. (1985). Longevity of individual flowers. *Annual Review of Ecology and Systematics* 16, 15–37. doi:10.1146/annurev.es.16.110185.000311.
- Quintanilla, L. G., Pajarón, S., Pangua, E., and Amigo, J. (2000). Effect of temperature on germination in northernmost populations of *Culcita macrocarpa* and *Woodwardia radicans*. *Plant Biology* 2, 612–617. doi:10.1055/s-2000-16638.
- Ranal, M. A. (1999). Effects of temperature on spore germination in some fern species from semideciduous mesophytic forest. *American Fern Journal* 89, 149. doi:10.2307/1547349.
- Ranal, M. A., and Santana, D. G. de (2006). How and why to measure the germination process? *Brazilian Journal of Botany* 29, 1–11. doi:10.1590/s0100-84042006000100002.
- Reddy, L. V. (1978). Effect of temperature on seed dormancy and alpha-amylase activity during kernel maturation and germination in wheat (*Triticum aestivum* L.) cultivars. Available at: [https://ir.library.oregonstate.edu/concern/graduate\\_thesis\\_or\\_dissertations/1j92gb854](https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/1j92gb854).
- Reddy, L. V., Metzger, R. J., and Ching, T. M. (1985). Effect of temperature on seed dormancy of wheat. *Crop Science* 25, 455. doi:10.2135/cropsci1985.0011183X002500030007x.
- Roh, M., Bentz, J.-A., Wang, P., Li, E., and Koshioka, M. (2004). Maturity and temperature stratification affect the germination of *Styrax japonicus* seeds. *The Journal of Horticultural Science and Biotechnology* 79, 645–651. doi:10.1080/14620316.2004.11511820.
- Santana, D. G. de, and Ranal, M. A. (2004). *Análise Da Germinação: Um Enfoque Estatístico*. Brasília: Universidade de Brasília.
- Schrader, J. A., and Graves, W. R. (2000). Seed germination and seedling growth of *Alnus maritima* from its three disjunct populations. *Journal of the American Society for Horticultural Science* 125, 128–134. doi:10.21273/JASHS.125.1.128.
- Scott, S. J., Jones, R. A., and Williams, W. A. (1984). Review of data analysis methods for seed germination. *Crop Science* 24, 1192–1199. doi:10.2135/cropsci1984.0011183x002400060043x.
- Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal* 27, 379–423. doi:10.1002/j.1538-7305.1948.tb01338.x.
- Shmueli, M., and Goldberg, D. (1971). Emergence, early growth, and salinity of five vegetable crops germinated by sprinkle and trickle irrigation in an arid zone. *HortScience* 6, 563–565.
- Smith, P. G., and Millet, A. H. (1964). Germinating and sprouting responses of the tomato at low temperatures. *Proceedings of the American Society for Horticultural Science* 84, 480–484.
- Throneberry, G. O., and Smith, F. G. (1955). Relation of respiratory and enzymatic activity to corn seed viability. *Plant Physiology* 30, 337–343. doi:10.1104/pp.30.4.337.
- Timson, J. (1965). New method of recording germination data. *Nature* 207, 216. doi:10.1038/207216a0.
- Tucker, H., and Wright, L. N. (1965). Estimating rapidity of germination. *Crop Science* 5, 398–399. doi:10.2135/cropsci1965.0011183X000500050006x.
- Vallance, K. (1950). Studies on the germination of the seeds of *Striga hermonthica* I. The influence of moisture-treatment, stimulant-dilution, and after-ripening on germination. *Annals of Botany* 14, 347–363. doi:10.1093/oxfordjournals.aob.a083251.
- Wardle, D. A., Ahmed, M., and Nicholson, K. S. (1991). Allelopathic influence of nodding thistle (*Carduus nutans* L.) seeds on germination and radicle growth of pasture plants. *New Zealand Journal of Agricultural Research* 34, 185–191. doi:10.1080/00288233.1991.10423358.
- Went, F. W. (1957). *The experimental control of plant growth*. Chronica Botanica Co., Waltham, Mass., USA; The Ronald Press Co., New York, USA.