

# The `germinationmetrics` Package: A Brief Introduction

*Aravind, J., Vimala Devi, S., Radhamani, J., Jacob, S. R., and Kalyani Srinivasan*

*2019-01-20*

ICAR-National Bureau of Plant Genetic Resources, New Delhi.

---

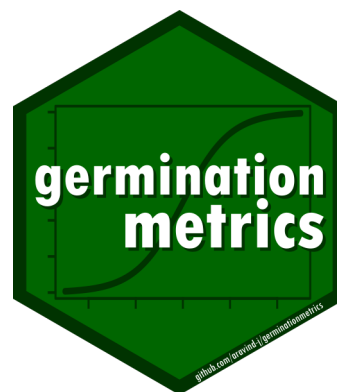
## Contents

Overview	1
Installation	1
Version History	2
Germination count data	2
Single-value germination indices	3
Curve fitting	28
Four-parameter hill function	28
Wrapper function	38
Citing <code>germinationmetrics</code>	41
Session Info	42
References	43

## 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 0.1.3. 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

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.

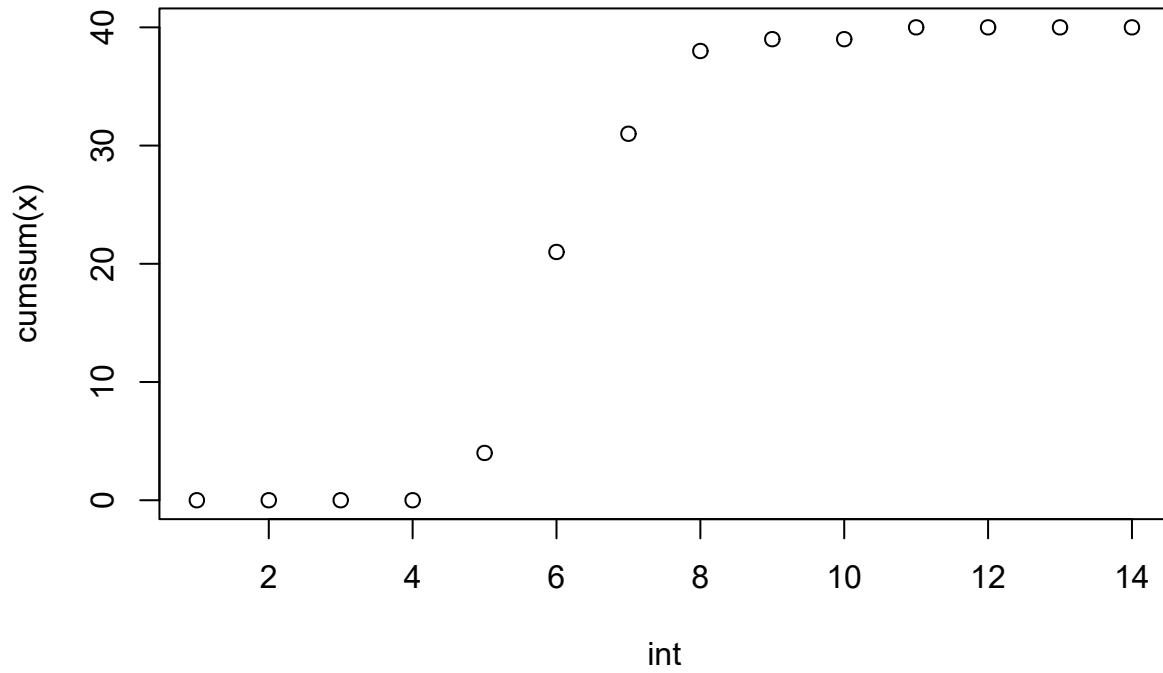
intervals	counts	cumulative.counts
1	0	0
2	0	0
3	0	0
4	0	0
5	4	4
6	17	21
7	10	31
8	7	38
9	1	39
10	0	39
11	1	40
12	0	40
13	0	40
14	0	40

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 Germinability ( <i>GP</i> )	<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)
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)	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)	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-Mudaris (1998); Schrader and Graves (2000); Kader (2005)
Peak period of germination or Modal time of germination	<b>PeakGermTime</b>	It is the time in which highest frequency of germinated seeds are observed and need not be unique.	time	Germination time	Ranal and Santana (2006)
Median germination time ( $t_{50}$ ) (Coolbear)	<b>t50</b>	It is the time to reach 50% of final/maximum germination. With argument method specified as " <code>coolbear</code> ", it is computed according to the formula by (Coolbear et al., 1984) as follows: $t_{50} = T_i + \frac{(\frac{N+1}{2} - N_i)(T_j - T_i)}{N_j - N_i}$ Where, $t_{50}$ is the median germination time, $N$ is the final number of germinated seeds and $N_i$ and $N_j$ are the total number of seeds germinated in adjacent counts at time $T_i$ and $T_j$ respectively, when $N_i < \frac{N+1}{2} < N_j$ .	time	Germination time	Coolbear et al. (1984)

Germination index	function	Details	Unit	Measures	Reference
Median germination time ( $t_{50}$ ) (Farooq)	<b>t50</b>	<p>With argument method specified as "<b>farooq</b>", it is computed according to the formula by (Coolbear et al., 1984) 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 ( $SI$ )	<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 observation, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination.</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); Ellis and Roberts (1980) Labouriau (1983a); Ranal and Santana (2006)
Variance of germination time ( $s_T^2$ )	<b>VarGermTime</b>	<p>It is computed according to the following formula.</p> $s_T^2 = \frac{\sum_{i=1}^k N_i (T_i - \bar{T})^2}{\sum_{i=1}^k N_i - 1}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th observation, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination.</p>	time	Germination time	Labouriau (1983a); Ranal and Santana (2006)

Germination index	function	Details	Unit	Measures	Reference
Standard error of germination time ( $s_{\bar{T}}$ )	<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> $s_{\bar{T}} = \sqrt{\frac{s_T^2}{\sum_{i=1}^k N_i}}$ <p>Where, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination.</p>	time	Germination time	Labouriau (1983a); Ranal and Santana (2006)
Mean germination rate ( $\bar{V}$ )	<b>MeanGermRate</b>	<p>It is computed according to the following formula:</p> $\bar{V} = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k N_i T_i}$ <p>Where, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th observation, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination. It is the inverse of mean germination time (<math>\bar{T}</math>).</p> $\bar{V} = \frac{1}{\bar{T}}$	time <sup>-1</sup>	Germination rate	Labouriau and Valadares (1976); Labouriau (1983b); Ranal and Santana (2006)
Coefficient of velocity of germination ( $CVG$ ) or Coefficient of rate of germination ( $CRG$ ) 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 observation, <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination.</p>	% day <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)

Germination index	function	Details	Unit	Measures	Reference
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 (not the accumulated number, but the number correspondent to the <math>i</math>th observation) and <math>k</math> is the last time of germination.</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 (Germination index according to 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> $S = \frac{N_1}{T_1} + \frac{N_2}{T_2} + \frac{N_3}{T_3} + \dots + \frac{N_n}{T_n}$ <p>Where, <math>N_1, N_2, N_3, \dots, N_n</math> are the number of germinated seeds observed at time (days or hours) <math>T_1, T_2, T_3, \dots, T_n</math> after sowing. (Not accumulated/cumulative number, but the number of seeds that germinated at the specific time). Instead of germination counts, germination percentages may also be used for computation of speed of germination.</p>	% time <sup>-1</sup>	Mixed	Throneberry and Smith (1955); Maguire (1962); Allan et al. (1962); Kendrick and Frankland (1969); Bouton et al. (1976); AOSA (1983); Khandakar and Bradbeer (1983); Bradbeer (1988); Wardle et al. (1991)
Speed of accumulated germination	<b>GermSpeedAccumulated</b>	<p>It is estimated as follows:</p> $S_{accumulated} = \frac{N_1}{T_1} + \frac{N_1 + N_2}{T_2} + \frac{N_1 + N_2 + N_3}{T_3} + \dots + \frac{N_1 + N_2}{T_n}$ <p>Where, <math>N_1, N_2, N_3, \dots, N_n</math> are the number of germinated seeds observed at time (days or hours) <math>T_1, T_2, T_3, \dots, T_n</math> after sowing. (Not accumulated/cumulative number, but the number of seeds that germinated at the specific time). Instead of germination counts, germination percentages may also be used for computation of speed of germination.</p>	% 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>FGP</math>: the final germination percentage or germinability.</p>	time <sup>-1</sup>	Mixed	Evetts and Burnside (1972)

Germination index	function	Details	Unit	Measures	Reference
Weighted germination percentage (WGP)	<b>WeightGermPercent</b>	<p>It is estimated as follows:</p> $WGP = \frac{\sum_{i=1}^t (t-i+1)N_i}{t \times N} \times 100$ <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>t</math> is the total number of time intervals.</p>		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> $\overline{G} = \frac{GP}{T_n}$ <p>Where, <math>GP</math> is the final germination percentage and <math>T_n</math> is the total number of intervals( e.g. days) required for final germination.</p>		Mixed	Czabator (1962)
Number of seeds germinated per unit time $\overline{N}$	<b>MeanGermNumber</b>	<p>It is estimated as follows:</p> $\overline{N} = \frac{N_g}{T_n}$ <p>Where, <math>N_g</math> is the number of germinated seeds and <math>T_n</math> is the total number of intervals ( e.g. days) required for final germination.</p>		Mixed	Khamassi et al. (2013)
Timson's index [ $\sum 10$ (Ten summation), $\sum 5$ or $\sum 20$ ] or Germination energy index ( $GEI$ )	<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> $\sum n = \sum_{i=1}^t G_i$ <p>Where, <math>G_i</math> is the cumulative germination percentage in time interval <math>i</math> and <math>t</math> is the total number of time intervals. It also estimated in terms of partial germination percentage as follows:</p> $\sum n = \sum_{i=1}^t g_i(t-j)$ <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>t</math>) and <math>t</math> is the total number of time intervals and <math>j = i - 1</math>.</p>		Mixed	Grose and Zimmer (1958); Timson (1965); Brown and Mayer (1988); Baskin and Baskin (1998); Goodchild and Walker (1971)



Germination index	function	Details	Unit	Measures	Reference
Modified Timson's index (Labouriau)	TimsonsIndex	It is estimated as Timson's index $T$ divided by the sum of partial germination percentages. $T_{mod} = \frac{T}{\sum_{i=1}^t g_i}$		Mixed	Ranal and Santana (2006)
Modified Timson's index (Khan and Unger)	TimsonsIndex	It is estimated as Timson's index ( $T$ ) divided by the number of intervals ( $t$ ). $T_{mod} = \frac{T}{t}$		Mixed	Khan and Ungar (1984)
George's index	GermRateGeorge	It is estimated as follows: $GR = \sum_{i=1}^t N_i K_i$ Where $N_i$ is the number of seeds germinated by $i$ th interval and $K_i$ is the number of intervals(eg. days) until the end of the test.		Mixed	George (1961); Tucker and Wright (1965); Nichols and Heydecker (1968)
Peak value( $PV$ ) (Czabator) or Emergence Energy ( $EE$ )	PeakValue	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.		Mixed	Czabator (1962); Bonner (1967)
Germination value ( $GV$ ) (Czabator)	GermValue	It is computed as follows: $GV = PV \times MDG$ Where, $PV$ is the peak value and $MDG$ 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 $MDG$ with the mean germination percentage per unit time ( $\overline{GP}$ ).		Mixed	Czabator (1962)

Germination index	function	Details	Unit	Measures	Reference
Germination value ( $GV$ ) (Diavanshir and Pourbiek)	<b>GermValue</b>	<p>It is computed as follows:</p> $GV = \frac{\sum DGS}{N} \times GP \times k$ <p>Where, <math>DGS</math> is the daily germination speed computed by dividing cumulative germination percentage by the number of days since the onset of germination, <math>N</math> is the frequency or number of DGS calculated during the test, <math>GP</math> is the germination percentage expressed over 100 and <math>k</math> is a constant. The value of <math>k</math> is decided on the basis of average daily speed of germination (<math>\frac{\sum DGS}{N}</math>). If it is less than 10, then <math>k</math> value of 10 can be used and if it is more than 10, then value of 7 or 8 can be used for <math>k</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>		Mixed	Djavanshir and Pourbeik (1976); Brown and Mayer (1988)
Coefficient of uniformity of germination ( $CUG$ )	<b>CUGerm</b>	<p>It is computed as follows:</p> $CV_T = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k (\bar{T} - T_i)^2 N_i}$ <p>Where, <math>\bar{T}</math> is the the mean germination time, <math>T_i</math> is the time from the start of the experiment to the <math>i</math>th observation (day for the example); <math>N_i</math> is the number of seeds germinated in the <math>i</math>th time (not the accumulated number, but the number correspondent to the <math>i</math>th observation), and <math>k</math> is the last time of germination.</p>		Germination uniformity	Heydecker (1972); Bewley and Black (1994)
Coefficient of variation of the germination time ( $CV_T$ )	<b>CVGermTime</b>	<p>It is estimated as follows:</p> $CV_T = \sqrt{\frac{s_T^2}{\bar{T}}}$ <p>Where, <math>s_T^2</math> is the variance of germination time and <math>\bar{T}</math> is the mean germination time.</p>		Germination uniformity	Ranal and Santana (2006)
Synchronization index ( $\bar{E}$ ) or Uncertainty of the germination process ( $U$ ) or informational entropy ( $H$ )	<b>GermUncertainty</b>	<p>It is estimated as follows:</p> $\bar{E} = - \sum_{i=1}^k f_i \log_2 f_i$ <p>Where, <math>f_i</math> is the relative frequency of germination (<math>f_i = \frac{N_i}{\sum_{i=1}^k N_i}</math>), <math>N_i</math> is the number of seeds germinated on the <math>i</math>th time and <math>k</math> is the last day of observation.</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>	<p>It is computed as follows:</p> $Z = \frac{\sum_{i=1}^k C_{N_i,2}}{C_{\Sigma N_i,2}}$ <p>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 (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.</p>		Germination synchrony	Primack (1985); Ranal and Santana (2006)

## Examples

`GermPercent()`

```
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)
```

```
# From partial germination counts
GermPercent(germ.counts = x, total.seeds = 50)
```

```
[1] 80
```

```
# From cumulative germination counts
GermPercent(germ.counts = y, total.seeds = 50, partial = FALSE)
```

```
[1] 80
```

```
# From number of germinated seeds
GermPercent(germinated.seeds = 40, total.seeds = 50)
```

```
[1] 80
```

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

```
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)
```

```
[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
```

```
t50()
```

```
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")
```

```
[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
```

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

```
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)
```

```
[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

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

[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

GermSpeed(), GermSpeedAccumulated(), GermSpeedCorrected()
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)

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

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

[1] 0.07673656
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                  method = "accumulated")

[1] 0.4326958

# 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] 0.07673656
GermSpeedCorrected(germ.counts = y, intervals = int,
                    partial = FALSE, total.seeds = 50, method = "accumulated")

[1] 0.4326958
# 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

GermSpeed(), GermSpeedAccumulated(), GermSpeedCorrected()
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)

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

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

[1] 0.07673656
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                    method = "accumulated")

[1] 0.4326958
# 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] 0.07673656
```

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

```
[1] 0.4326958
```

```
# 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
```

```
WeightGermPercent()
```

```
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)
```

```
[1] 47.42857
```

```
# From cumulative germination counts
```

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

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

```
[1] 47.42857
```

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

```
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)
```

```
[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
```

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

```
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)
```

```
[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
```

```
# 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
```

```
# Wihout max specified
GermRateGeorge(germ.counts = x, intervals = int)
```

```
[1] 332
```

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

```
[1] 172
```

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

```
[1] 332
```

```
# From cumulative germination counts
#-----
```

```
# Wihout max specified
GermRateGeorge(germ.counts = x, intervals = int, partial = TRUE)
```

```
[1] 332
```

```
# With max specified
GermRateGeorge(germ.counts = x, intervals = int, partial = TRUE, max = 10)
```

```
[1] 172
```

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

```
[1] 332
```

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

```
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)
```

```
[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
3	34	3	34	17.0
4	40	4	74	37.0
5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5
8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0
14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0
18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

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

	DGS	SumDGSbyN	GV
3	5.666667	5.666667	9.633333
4	9.250000	7.458333	27.595833
5	9.500000	8.138889	38.659722
6	8.750000	8.291667	43.531250
7	7.785714	8.190476	44.638095
8	7.125000	8.012897	45.673512
9	6.500000	7.796769	45.611097
10	6.100000	7.584673	46.266503
11	5.909091	7.398497	48.090230
12	5.708333	7.229481	49.521942
13	5.538462	7.075752	50.945411
14	5.357143	6.932534	51.994006
15	5.200000	6.799262	53.034246
16	5.000000	6.670744	53.365948
17	4.705882	6.539753	52.318022
18	4.500000	6.412268	51.939373
19	4.263158	6.285850	50.915385
20	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
1	0	1	0	0.0
2	0	2	0	0.0

3	34	3	34	17.0
4	40	4	74	37.0
5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5
8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0
14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0
18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

DGS

1	0.000000
2	0.000000
3	5.666667
4	9.250000
5	9.500000
6	8.750000
7	7.785714
8	7.125000
9	6.500000
10	6.100000
11	5.909091
12	5.708333
13	5.538462
14	5.357143
15	5.200000
16	5.000000
17	4.705882
18	4.500000
19	4.263158
20	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
1	0	1	0	0.0
2	0	2	0	0.0
3	34	3	34	17.0
4	40	4	74	37.0
5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5

8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0
14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0
18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

	DGS	SumDGSbyN	GV
1	0.000000	0.000000	0.000000
2	0.000000	0.000000	0.000000
3	5.666667	1.888889	3.211111
4	9.250000	3.729167	13.797917
5	9.500000	4.883333	23.195833
6	8.750000	5.527778	29.020833
7	7.785714	5.850340	31.884354
8	7.125000	6.009673	34.255134
9	6.500000	6.064153	35.475298
10	6.100000	6.067738	37.013202
11	5.909091	6.053316	39.346552
12	5.708333	6.024567	41.268285
13	5.538462	5.987174	43.107655
14	5.357143	5.942172	44.566291
15	5.200000	5.892694	45.963013
16	5.000000	5.836901	46.695205
17	4.705882	5.770370	46.162961
18	4.500000	5.699794	46.168331
19	4.263158	5.624182	45.555871
20	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
3	34	3	34	17.0
4	40	4	74	37.0

5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5
8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0
14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0
18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

DGS

3	5.666667
4	9.250000
5	9.500000
6	8.750000
7	7.785714
8	7.125000
9	6.500000
10	6.100000
11	5.909091
12	5.708333
13	5.538462
14	5.357143
15	5.200000
16	5.000000
17	4.705882
18	4.500000
19	4.263158
20	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
3	34	3	34	17.0
4	40	4	74	37.0
5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5
8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0



14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0
18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

	DGS	SumDGSbyN	GV
3	5.666667	5.666667	9.633333
4	9.250000	7.458333	27.595833
5	9.500000	8.138889	38.659722
6	8.750000	8.291667	43.531250
7	7.785714	8.190476	44.638095
8	7.125000	8.012897	45.673512
9	6.500000	7.796769	45.611097
10	6.100000	7.584673	46.266503
11	5.909091	7.398497	48.090230
12	5.708333	7.229481	49.521942
13	5.538462	7.075752	50.945411
14	5.357143	6.932534	51.994006
15	5.200000	6.799262	53.034246
16	5.000000	6.670744	53.365948
17	4.705882	6.539753	52.318022
18	4.500000	6.412268	51.939373
19	4.263158	6.285850	50.915385
20	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
1	0	1	0	0.0
2	0	2	0	0.0
3	34	3	34	17.0
4	40	4	74	37.0
5	21	5	95	47.5
6	10	6	105	52.5
7	4	7	109	54.5
8	5	8	114	57.0
9	3	9	117	58.5
10	5	10	122	61.0
11	8	11	130	65.0
12	7	12	137	68.5
13	7	13	144	72.0
14	6	14	150	75.0
15	6	15	156	78.0
16	4	16	160	80.0
17	0	17	160	80.0

18	2	18	162	81.0
19	0	19	162	81.0
20	2	20	164	82.0

DGS

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

	DGS	SumDGSbyN	GV
1	0.000000	0.000000	0.000000

```

2  0.000000  0.000000  0.000000
3  5.666667  1.888889  3.211111
4  9.250000  3.729167 13.797917
5  9.500000  4.883333 23.195833
6  8.750000  5.527778 29.020833
7  7.785714  5.850340 31.884354
8  7.125000  6.009673 34.255134
9  6.500000  6.064153 35.475298
10 6.100000  6.067738 37.013202
11 5.909091  6.053316 39.346552
12 5.708333  6.024567 41.268285
13 5.538462  5.987174 43.107655
14 5.357143  5.942172 44.566291
15 5.200000  5.892694 45.963013
16 5.000000  5.836901 46.695205
17 4.705882  5.770370 46.162961
18 4.500000  5.699794 46.168331
19 4.263158  5.624182 45.555871
20 4.100000  5.547972 45.493374

```

```
$testend
```

```
[1] 16
```

```
CUGerm()
```

```

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)
```

```
[1] 0.7092199
```

```
# From cumulative germination counts
```

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

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

```
[1] 0.05267935
```

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

```

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)
```

```
[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
```

## Curve fitting

Several mathematical functions have been used to fit the cumulative germination count data and describe the germination process 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”.

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
$lag$	It is the time at germination onset and is computed by solving four-parameter hill function after setting $y$ to 0 as follows:	time	Germination time
$lag = b \sqrt{\frac{-y_0 c^b}{a + y_0}}$			
$D_{lag-50}$	The duration between the time at germination onset ( $lag$ ) and that at 50% germination ( $c$ ).	time	Germination time

Germination parameters	Details	Unit	Measures
$t_{50_{total}}$	Time required for 50% of total seeds to germinate.	time	Germination time
$t_{50_{germinated}}$	Time required for 50% of viable/germinated seeds to germinate	time	Germination time
$t_{x_{total}}$	Time required for $x\%$ of total seeds to germinate.	time	Germination time
$t_{x_{germinated}}$	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 <code>umin</code> and <code>umax</code> to germinate.	time	Germination time
Time at maximum germination rate ( $TMGR$ )	<p>The partial derivative of the four-parameter hill function gives the instantaneous rate of germination (<math>s</math>) as follows:</p> $s = \frac{\partial y}{\partial x} = \frac{abc^b x^{b-1}}{(c^b + x^b)^2}$ <p>From this function for instantaneous rate of germination, <math>TMGR</math> can be estimated as follows:</p> $TMGR = b \sqrt{\frac{c^b(b-1)}{b+1}}$ <p>It represents the point in time when the instantaneous rate of germination starts to decline.</p>	time	Germination time
Area under the curve ( $AUC$ )	It is obtained by integration of the fitted curve between time 0 and time specified in the argument <code>tmax</code> .		Mixed
$MGT$	Calculated by integration of the fitted curve and proper normalisation.	time	Germination time
$Skewness$	It is computed as follows:		
	$\frac{MGT}{t_{50_{germinated}}}$		

## Examples

### FourPHFfit()

```
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)
```

```
$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 80.000000 1.24158595  64.43372 1.973240e-14
2    b  9.881947 0.70779379  13.96162 6.952322e-08
3    c  6.034954 0.04952654 121.85294 3.399385e-17
4   y0  0.000000 0.91607007   0.00000 1.000000e+00

$Fit
      sigma isConv      finTol    logLik      AIC      BIC deviance
1 1.769385  TRUE 1.490116e-08 -25.49868 60.99736 64.19265 31.30723
  df.residual
1           10

$a
[1] 80

$b
[1] 9.881947

$c
[1] 6.034954

$y0
[1] 0

$lag
[1] 0

$Dlag50
[1] 6.034954

$t50.total
[1] 6.355122

$txp.total
[1] 4.956266 6.744598

$t50.Germinated

```

```

[1] 6.034954

$txp.Germinated
[1] 4.831809 6.287724

$Uniformity
      90      10 uniformity
7.537688 4.831809 2.705880

$TMGR
[1] 5.912195

$AUC
[1] 1108.975

$MGT
[1] 6.632252

$Skewness
[1] 1.098973

$msg
[1] "#1. Relative error in the sum of squares is at most `ftol'. "

$isConv
[1] TRUE

attr("class")
[1] "FourPHFfit"

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

$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 80.000000 1.2415867  64.43368 1.973252e-14

```

```

2   b  9.881927 0.7077918 13.96163 6.952270e-08
3   c  6.034953 0.0495266 121.85275 3.399437e-17
4  y0  0.000000 0.9160705  0.00000 1.000000e+00

```

```

$Fit
      sigma isConv      finTol    logLik      AIC      BIC deviance
1 1.769385  TRUE 1.490116e-08 -25.49868 60.99736 64.19265 31.30723
  df.residual
1           10

```

```

$a
[1] 80

```

```

$b
[1] 9.881927

```

```

$c
[1] 6.034953

```

```

$y0
[1] 0

```

```

$lag
[1] 0

```

```

$Dlag50
[1] 6.034953

```

```

$t50.total
[1] 6.355121

```

```

$txp.total
[1] 4.956263 6.744599

```

```

$t50.Germinated
[1] 6.034953

```

```

$txp.Germinated
[1] 4.831806 6.287723

```

```

$Uniformity
      90      10 uniformity
7.537691 4.831806 2.705885

```

```

$TMGR
[1] 5.912194

```

```

$AUC
[1] 1108.976

```

```

$MGT
[1] 6.632252

```

```

$Skewness

```



```
[1] 1.098973

$msg
[1] "#1. Relative error in the sum of squares is at most `ftol'. "
```

```
$isConv
[1] TRUE
```

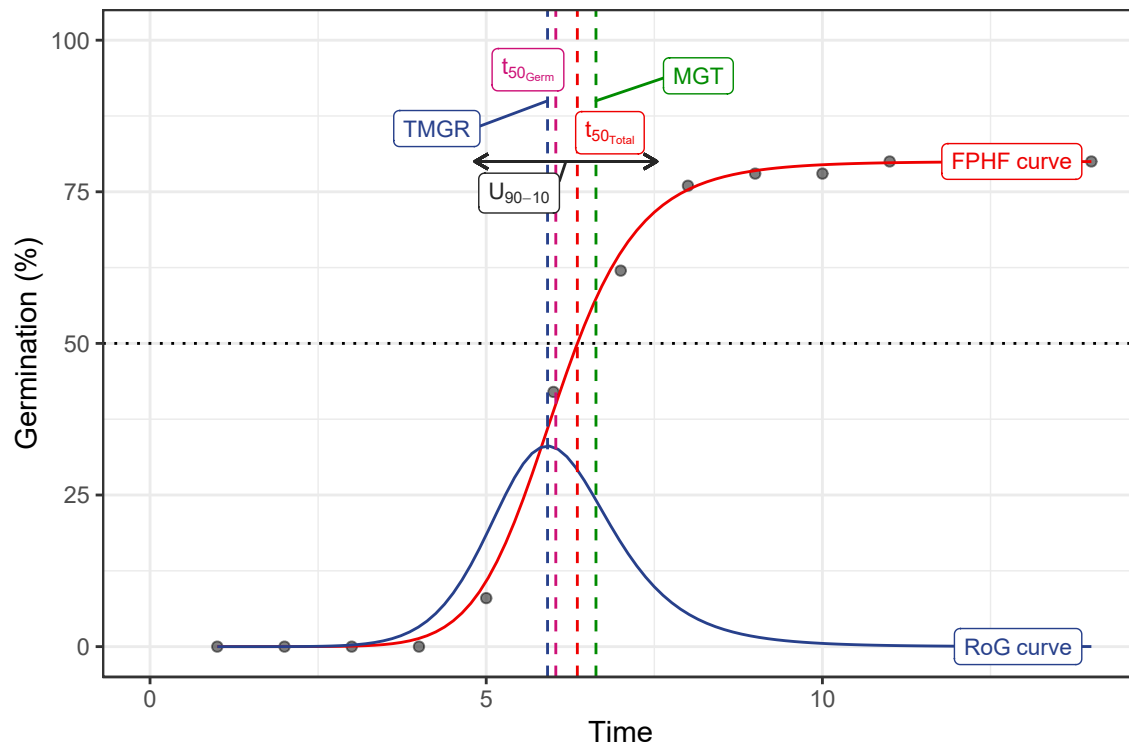
```
attr("class")
[1] "FourPHFfit"
```

```
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

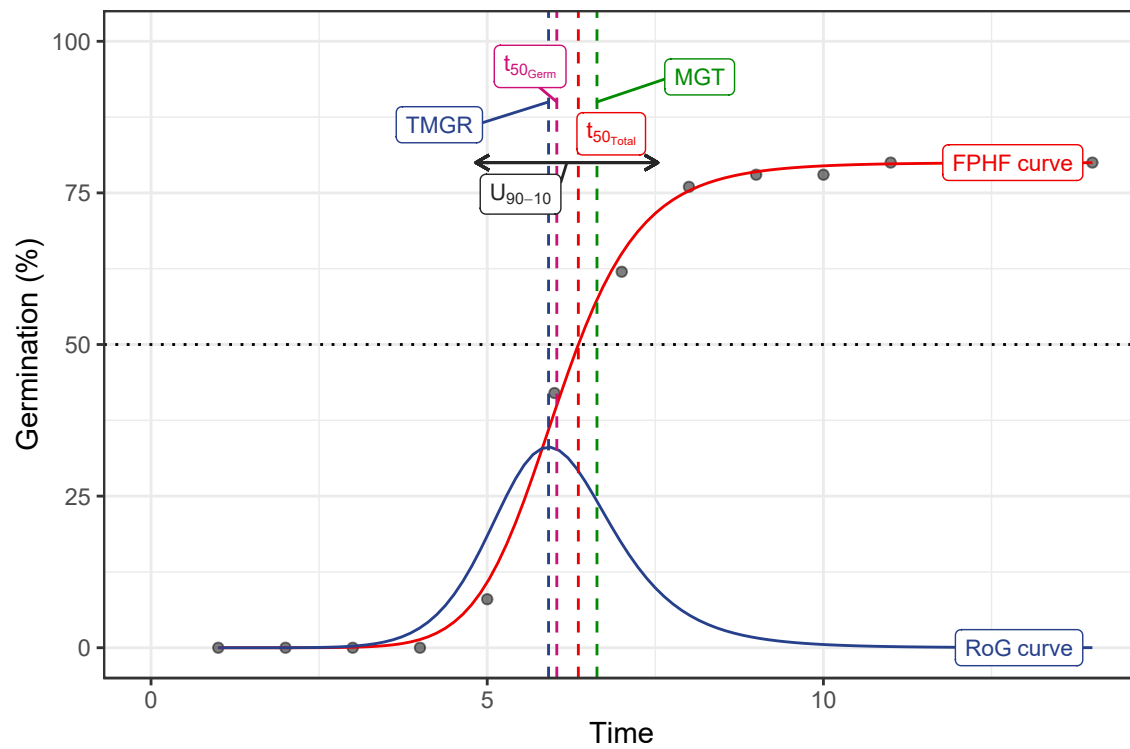
# From partial germination counts
#-----
fit1 <- FourPHFfit(germ.counts = x, intervals = int,
                  total.seeds = 50, tmax = 20)

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

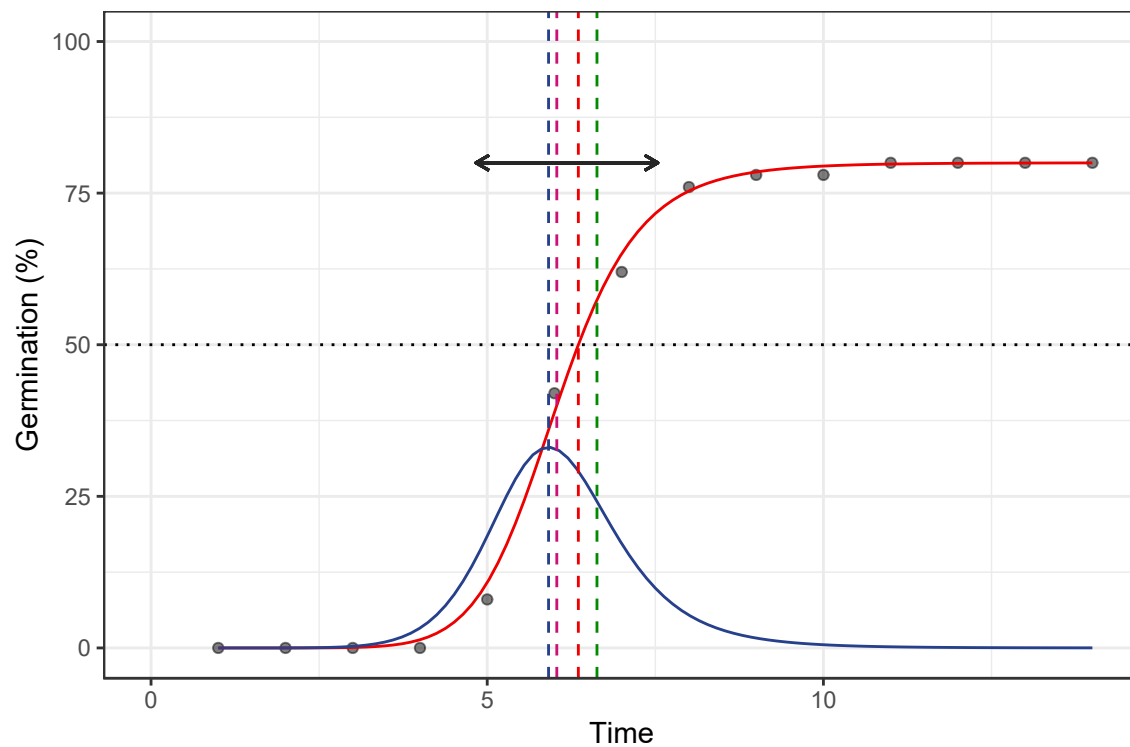
# Default plots
plot(fit1)
```



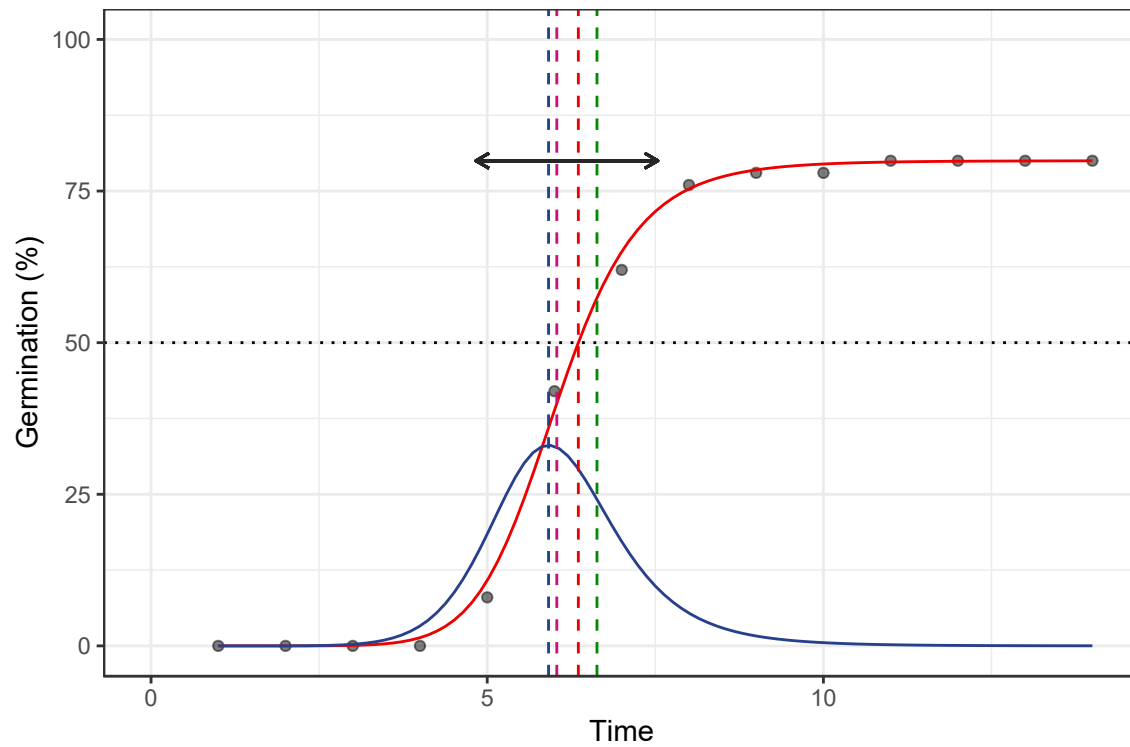
```
plot(fit2)
```



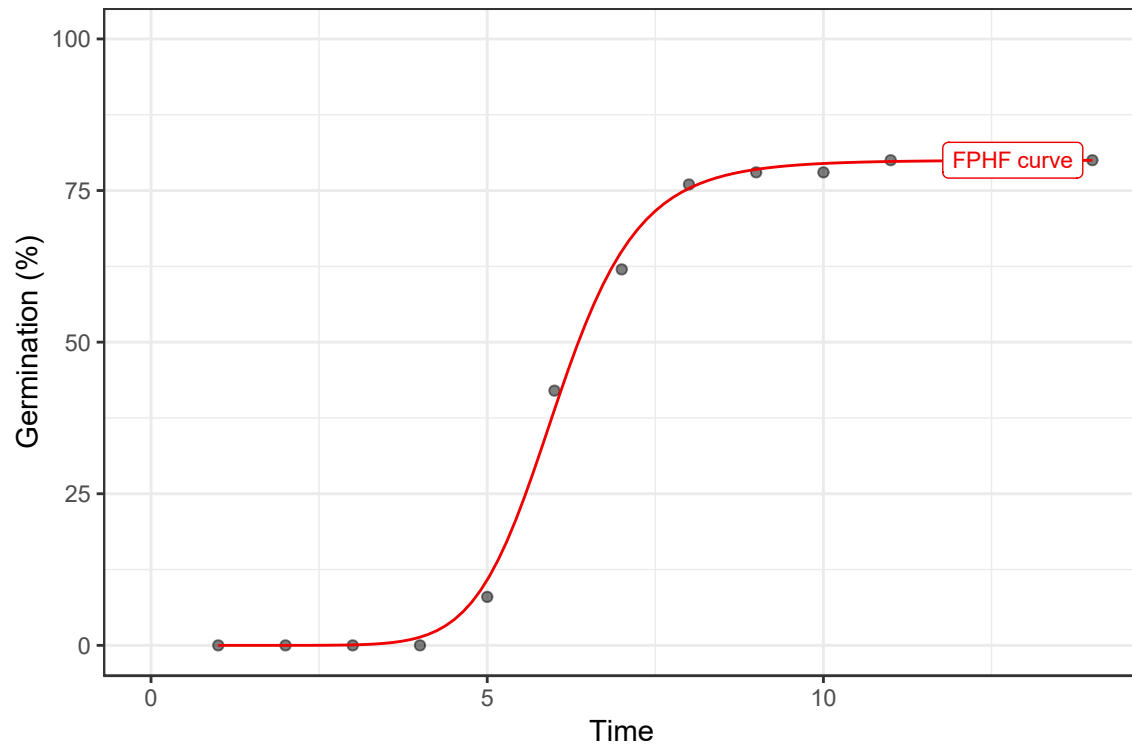
```
# No labels
plot(fit1, plotlabels = FALSE)
```



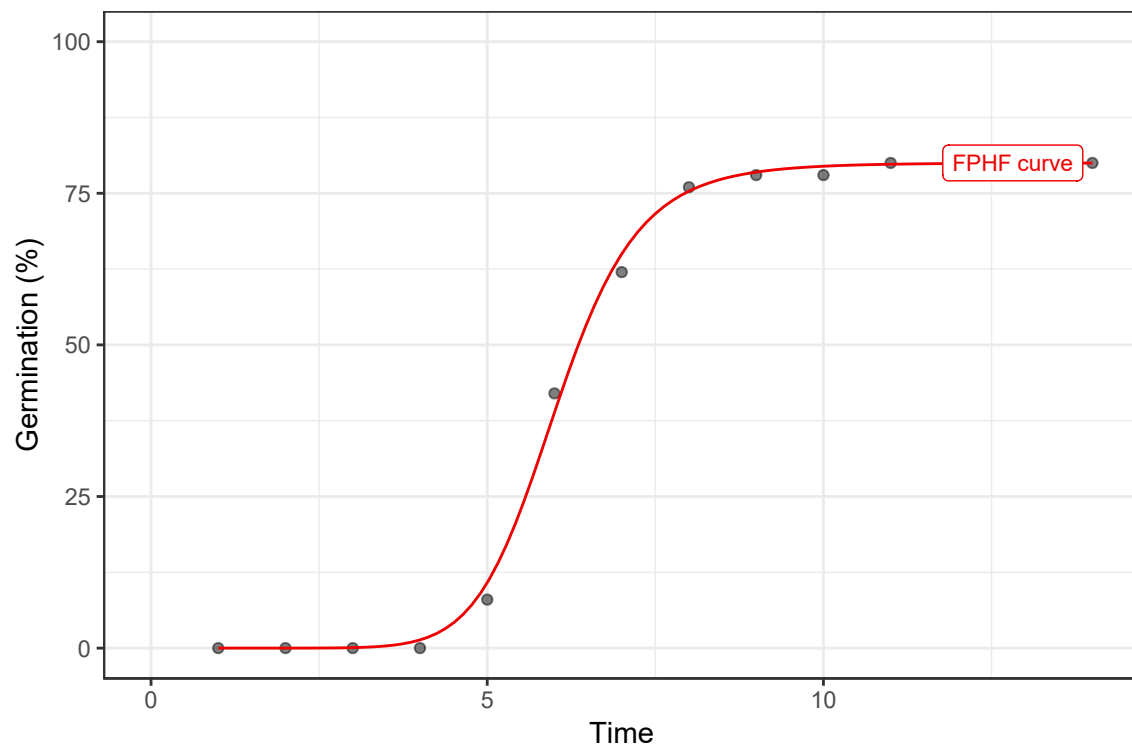
```
plot(fit2, plotlabels = FALSE)
```



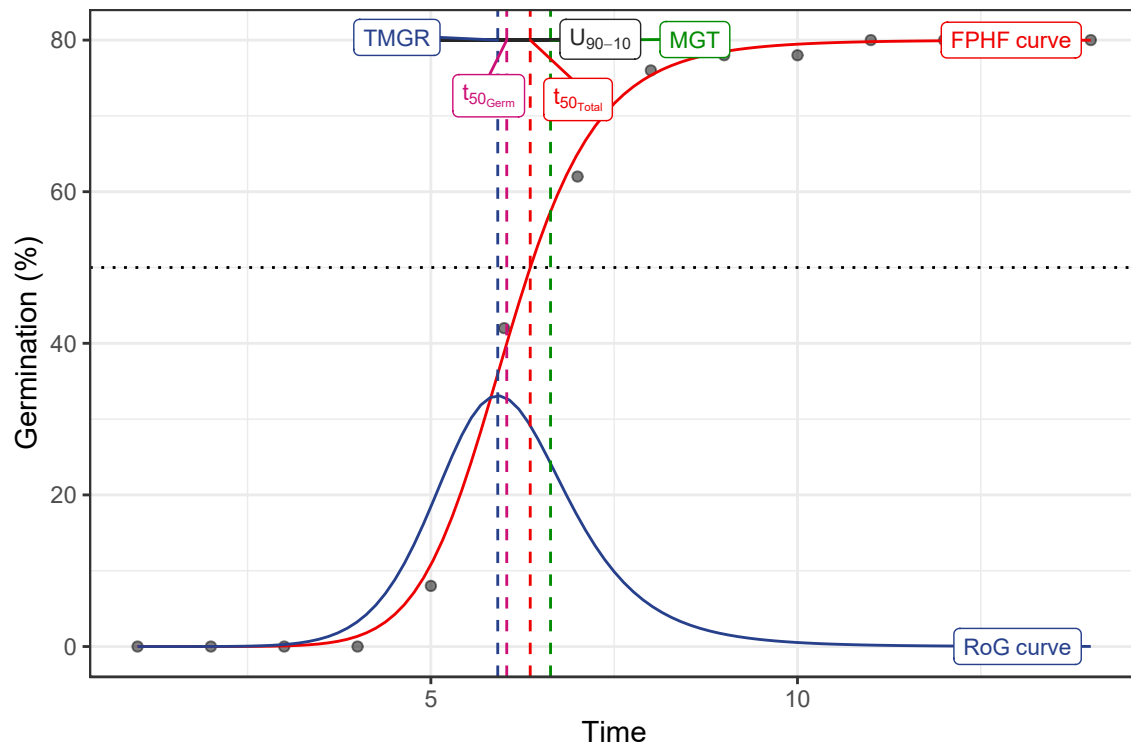
```
# Only the FPHF curve
plot(fit1, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
     tmgr = FALSE, mgt = FALSE, uniformity = FALSE)
```



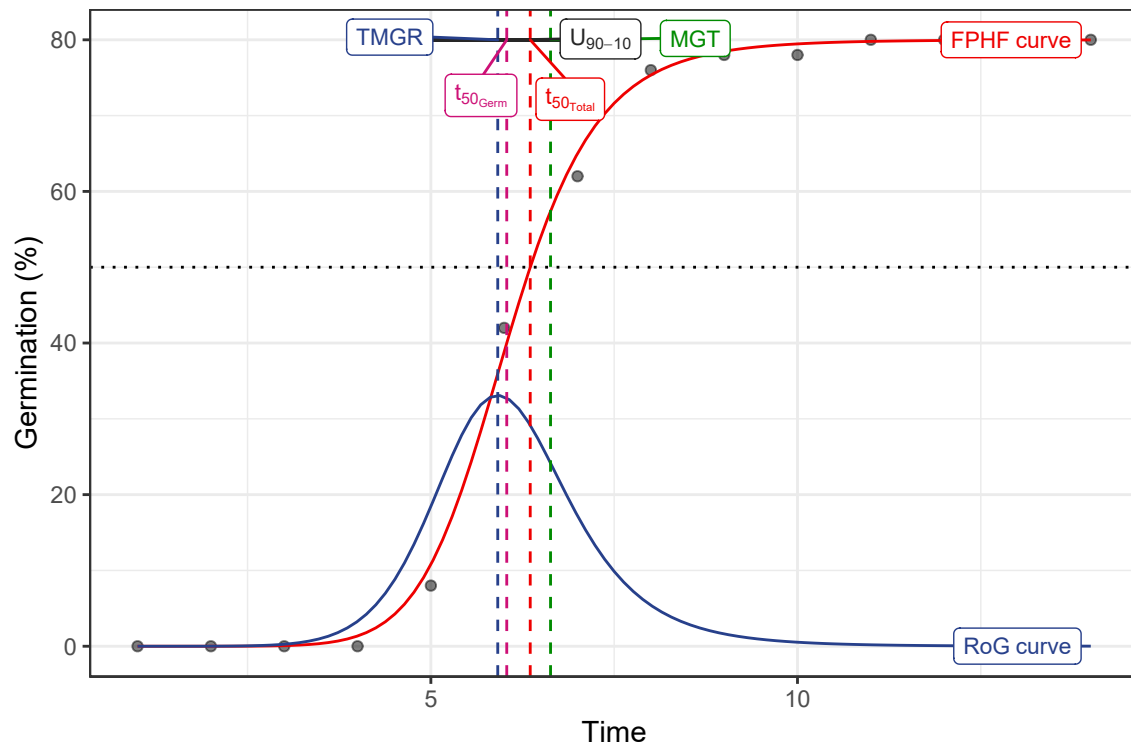
```
plot(fit2, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
     tmgr = FALSE, mgt = FALSE, uniformity = FALSE)
```



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



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



## Wrapper function

The wrapper function `germination.indices()` can be used to compute multiple germination indices from a data frame of germination counts recorded at specific time intervals for multiple samples in batch.

```
germination.indices()
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
1	G1	1	0	0	0	0	4	17	10	7	1
2	G2	1	0	0	0	1	3	15	13	6	2
3	G3	1	0	0	0	2	3	18	9	8	2
4	G4	1	0	0	0	0	4	19	12	6	2
5	G5	1	0	0	0	0	5	20	12	8	1
6	G1	2	0	0	0	0	3	21	11	7	1
7	G2	2	0	0	0	0	4	18	11	7	1
8	G3	2	0	0	0	1	3	14	12	6	2
9	G4	2	0	0	0	1	3	19	10	8	1
10	G5	2	0	0	0	0	4	18	13	6	2
11	G1	3	0	0	0	0	5	21	11	8	1
12	G2	3	0	0	0	0	3	20	10	7	1
13	G3	3	0	0	0	0	4	19	12	8	1
14	G4	3	0	0	0	0	3	21	11	6	1
15	G5	3	0	0	0	0	4	17	10	8	1
	Day10	Day11	Day12	Day13	Day14	Total	Seeds	GermPercent	FirstGermTime		
1	0	1	0	0	0		50	80.00000		5	
2	1	0	1	0	0		51	82.35294		4	
3	1	1	1	0	0		48	93.75000		4	
4	1	1	1	0	0		51	90.19608		5	
5	0	0	1	1	0		50	96.00000		5	
6	1	1	1	0	0		49	93.87755		5	
7	0	1	0	0	0		48	87.50000		5	
8	1	0	1	0	0		47	85.10638		4	
9	1	1	1	0	0		52	86.53846		4	
10	1	0	1	0	0		50	90.00000		5	
11	0	0	1	1	0		51	94.11765		5	
12	1	1	1	0	0		51	86.27451		5	
13	1	0	1	1	0		49	95.91837		5	
14	0	1	1	0	0		48	91.66667		5	
15	1	1	0	0	0		48	87.50000		5	
	LastGermTime	PeakGermTime	TimeSpreadGerm	t50_Coolbear	t50_Farooq						
1	11		6	6	5.970588	5.941176					
2	12		6	8	6.192308	6.153846					
3	12		6	8	6.000000	5.972222					
4	12		6	7	6.041667	6.000000					
5	13		6	8	5.975000	5.950000					
6	12		6	7	5.976190	5.952381					

7	11	6	6	5.972222	5.944444
8	12	6	8	6.208333	6.166667
9	12	6	8	6.000000	5.973684
10	12	6	7	6.076923	6.038462
11	13	6	8	5.928571	5.904762
12	12	6	7	5.975000	5.950000
13	13	6	8	6.083333	6.041667
14	12	6	7	5.928571	5.904762
15	11	6	6	6.050000	6.000000
	MeanGermTime	VarGermTime	SEGermTime	CVGermTime	MeanGermRate
1	6.700000	1.446154	0.1901416	0.1794868	0.1492537
2	6.857143	2.027875	0.2197333	0.2076717	0.1458333
3	6.866667	2.572727	0.2391061	0.2335882	0.1456311
4	6.891304	2.187923	0.2180907	0.2146419	0.1451104
5	6.812500	2.368351	0.2221275	0.2259002	0.1467890
6	6.869565	2.071498	0.2122088	0.2095140	0.1455696
7	6.690476	1.389663	0.1818989	0.1761967	0.1494662
8	6.875000	2.112179	0.2297923	0.2113940	0.1454545
9	6.866667	2.300000	0.2260777	0.2208604	0.1456311
10	6.822222	1.831313	0.2017321	0.1983606	0.1465798
11	6.791667	2.381206	0.2227295	0.2272072	0.1472393
12	6.886364	2.149577	0.2210295	0.2129053	0.1452145
13	6.936170	2.539315	0.2324392	0.2297410	0.1441718
14	6.772727	1.900634	0.2078370	0.2035568	0.1476510
15	6.809524	1.670151	0.1994129	0.1897847	0.1468531
	VarGermRate	SEGermRate	CVG	GermRateRecip_Coolbear	
1	0.0007176543	0.004235724	14.92537	0.1674877	
2	0.0009172090	0.004673148	14.58333	0.1614907	
3	0.0011572039	0.005071059	14.56311	0.1666667	
4	0.0009701218	0.004592342	14.51104	0.1655172	
5	0.0010995627	0.004786184	14.67890	0.1673640	
6	0.0009301809	0.004496813	14.55696	0.1673307	
7	0.0006935558	0.004063648	14.94662	0.1674419	
8	0.0009454531	0.004861721	14.54545	0.1610738	
9	0.0010345321	0.004794747	14.56311	0.1666667	
10	0.0008453940	0.004334343	14.65798	0.1645570	
11	0.0011191581	0.004828643	14.72393	0.1686747	
12	0.0009558577	0.004660905	14.52145	0.1673640	
13	0.0010970785	0.004831366	14.41718	0.1643836	
14	0.0009033254	0.004531018	14.76510	0.1686747	
15	0.0007767634	0.004300508	14.68531	0.1652893	
	GermRateRecip_Farooq	GermSpeed_Count	GermSpeed_Percent		
1	0.1683168	6.138925	12.27785		
2	0.1625000	6.362698	12.47588		
3	0.1674419	6.882179	14.33787		
4	0.1666667	6.927417	13.58317		
5	0.1680672	7.318987	14.63797		
6	0.1680000	6.931782	14.14649		
7	0.1682243	6.448449	13.43427		
8	0.1621622	6.053175	12.87909		
9	0.1674009	6.830592	13.13575		
10	0.1656051	6.812698	13.62540		
11	0.1693548	7.342796	14.39764		
12	0.1680672	6.622258	12.98482		

13	0.1655172	7.052320	14.39249	
14	0.1693548	6.706782	13.97246	
15	0.1666667	6.363925	13.25818	
	GermSpeedAccumulated_Count	GermSpeedAccumulated_Percent		
1	34.61567	69.23134		
2	35.54058	69.68741		
3	38.29725	79.78594		
4	38.68453	75.85202		
5	41.00786	82.01571		
6	38.77620	79.13509		
7	36.38546	75.80304		
8	33.77079	71.85275		
9	38.11511	73.29829		
10	38.19527	76.39054		
11	41.17452	80.73436		
12	37.00640	72.56158		
13	39.29399	80.19182		
14	37.69490	78.53103		
15	35.69697	74.36868		
	GermSpeedCorrected_Normal	GermSpeedCorrected_Accumulated		
1	0.07673656	0.4326958		
2	0.07726134	0.4315642		
3	0.07340991	0.4085040		
4	0.07680397	0.4288937		
5	0.07623944	0.4271652		
6	0.07383855	0.4130508		
7	0.07369656	0.4158338		
8	0.07112480	0.3968068		
9	0.07893128	0.4404413		
10	0.07569665	0.4243919		
11	0.07801721	0.4374793		
12	0.07675799	0.4289379		
13	0.07352419	0.4096608		
14	0.07316490	0.4112171		
15	0.07273057	0.4079653		
	WeightGermPercent	MeanGermPercent	MeanGermNumber	TimsonsIndex
1	47.42857	5.714286	2.857143	8.000000
2	47.89916	5.882353	3.000000	9.803922
3	54.46429	6.696429	3.214286	14.583333
4	52.24090	6.442577	3.285714	7.843137
5	56.14286	6.857143	3.428571	10.000000
6	54.51895	6.705539	3.285714	6.122449
7	51.93452	6.250000	3.000000	8.333333
8	49.39210	6.079027	2.857143	10.638298
9	50.27473	6.181319	3.214286	9.615385
10	52.57143	6.428571	3.214286	8.000000
11	55.18207	6.722689	3.428571	9.803922
12	50.00000	6.162465	3.142857	5.882353
13	55.24781	6.851312	3.357143	8.163265
14	53.86905	6.547619	3.142857	6.250000
15	51.19048	6.250000	3.000000	8.333333
	TimsonsIndex_Labouriau	TimsonsIndex_KhanUngar	GermRateGeorge	PeakValue
1	1.00	0.5714286	4	9.500000
2	1.25	0.7002801	5	9.313725



3	1.40	1.0416667	7	10.416667
4	1.00	0.5602241	4	10.049020
5	1.00	0.7142857	5	11.250000
6	1.00	0.4373178	3	10.714286
7	1.00	0.5952381	4	10.416667
8	1.25	0.7598784	5	9.574468
9	1.25	0.6868132	5	9.855769
10	1.00	0.5714286	4	10.250000
11	1.00	0.7002801	5	11.029412
12	1.00	0.4201681	3	9.803922
13	1.00	0.5830904	4	10.969388
14	1.00	0.4464286	3	10.677083
15	1.00	0.5952381	4	10.156250
GermValue_Czabator GermValue_DP GermValue_Czabator_mod GermValue_DP_mod				
1	54.28571	57.93890	54.28571	39.56076
2	54.78662	52.58713	54.78662	40.99260
3	69.75446	68.62289	69.75446	53.42809
4	64.74158	70.43331	64.74158	48.86825
5	77.14286	80.16914	77.14286	56.23935
6	71.84506	76.51983	71.84506	53.06435
7	65.10417	69.41325	65.10417	47.37690
8	58.20345	56.00669	58.20345	43.67948
9	60.92165	58.13477	60.92165	45.30801
10	65.89286	70.91875	65.89286	49.10820
11	74.14731	77.39782	74.14731	54.27520
12	60.41632	64.44988	60.41632	44.71582
13	75.15470	78.16335	75.15470	54.94192
14	69.90947	74.40140	69.90947	51.41913
15	63.47656	67.62031	63.47656	46.48043
CUGerm GermSynchrony GermUncertainty				
1	0.7092199	0.2666667	2.062987	
2	0.5051546	0.2346109	2.321514	
3	0.3975265	0.2242424	2.462012	
4	0.4672113	0.2502415	2.279215	
5	0.4312184	0.2606383	2.146051	
6	0.4934701	0.2792271	2.160545	
7	0.7371500	0.2729384	2.040796	
8	0.4855842	0.2256410	2.357249	
9	0.4446640	0.2494949	2.321080	
10	0.5584666	0.2555556	2.187983	
11	0.4288905	0.2686170	2.128670	
12	0.4760266	0.2737844	2.185245	
13	0.4023679	0.2506938	2.241181	
14	0.5383760	0.2991543	2.037680	
15	0.6133519	0.2497096	2.185028	

## Citing *germinationmetrics*

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

Aravind, J., Vimala Devi, S., Radhamani, J., Jacob, S. R., and Kalyani Srinivasan (2019). *germinationmetrics*: Seed Germination Indices and Curve Fitting. R package version 0.1.3.9000,

<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 Sri},
  year = {2019},
  note = {R package version 0.1.3.9000},
  note = {https://github.com/aravind-j/germinationmetrics},
  note = {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) (2018-10-27 r75507)
```

```
Platform: x86_64-w64-mingw32/x64 (64-bit)
```

```
Running under: Windows >= 8 x64 (build 9200)
```

```
Matrix products: default
```

```
locale:
```

```
[1] LC_COLLATE=English_India.1252 LC_CTYPE=English_India.1252
```

```
[3] LC_MONETARY=English_India.1252 LC_NUMERIC=C
```

```
[5] LC_TIME=English_India.1252
```

```
attached base packages:
```

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

```
other attached packages:
```

```
[1] germinationmetrics_0.1.3.9000 readxl_1.2.0
```

```
loaded via a namespace (and not attached):
```

```
[1] ggrepel_0.8.0      Rcpp_1.0.0          lattice_0.20-38
[4] tidyr_0.8.2        prettyunits_1.0.2   ps_1.3.0
[7] assertthat_0.2.0    rprojroot_1.3-2     digest_0.6.18
[10] R6_2.3.0            cellranger_1.1.0    plyr_1.8.4
[13] backports_1.1.3     evaluate_0.12        httr_1.4.0
[16] ggplot2_3.1.0       highr_0.7            pillar_1.3.1
[19] Rdpack_0.10-3       rlang_0.3.1          lazyeval_0.2.1
[22] curl_3.3            rstudioapi_0.9.0     data.table_1.12.0
[25] callr_3.1.1         rmarkdown_1.11      labeling_0.3
[28] desc_1.2.0          devtools_2.0.1.9000 pander_0.6.3
[31] stringr_1.3.1       RCurl_1.95-4.11     munsell_0.5.0
[34] broom_0.5.1         compiler_3.6.0       xfun_0.4
[37] pkgconfig_2.0.2     pkgbuild_1.0.2       htmltools_0.3.6
[40] tidyselect_0.2.5    tibble_2.0.1         roxygen2_6.1.1
[43] XML_3.98-1.16       crayon_1.3.4         dplyr_0.7.8
```

[46] <code>withr_2.1.2</code>	<code>bitops_1.0-6</code>	<code>commonmark_1.7</code>
[49] <code>grid_3.6.0</code>	<code>nlme_3.1-137</code>	<code>gtable_0.2.0</code>
[52] <code>magrittr_1.5</code>	<code>scales_1.0.0</code>	<code>bibtex_0.4.2</code>
[55] <code>cli_1.0.1</code>	<code>stringi_1.2.4</code>	<code>fs_1.2.6</code>
[58] <code>remotes_2.0.2</code>	<code>bindrcpp_0.2.2</code>	<code>testthat_2.0.1</code>
[61] <code>xml2_1.2.0</code>	<code>generics_0.0.2</code>	<code>tools_3.6.0</code>
[64] <code>glue_1.3.0</code>	<code>purrr_0.2.5</code>	<code>processx_3.2.1</code>
[67] <code>pkgload_1.0.2</code>	<code>yaml_2.2.0</code>	<code>colorspace_1.4-0</code>
[70] <code>sessioninfo_1.1.1</code>	<code>gbRd_0.4-11</code>	<code>memoise_1.1.0</code>
[73] <code>minpack.lm_1.2-1</code>	<code>knitr_1.21</code>	<code>bindr_0.1.1</code>
[76] <code>usethis_1.4.0</code>		

## 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/cm7jct](https://doi.org/10.1093/oxfordjournals.aob.a087534).
- 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.
- 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). *Seeds: Physiology of Development and Germination*. New York, USA: Plenum Publishing Corporation Available at: <https://www.cabdirect.org/cabdirect/abstract/19950315483>.
- Bonner, F. T. (1967). Ideal sowing depth for sweetgum seed. *Tree Planters' Notes* 18, 1–1. Available at: <https://www.fs.usda.gov/treesearch/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/cskpqh](https://doi.org/10.1093/oxfordjournals.aob.a087534).
- Bradbeer, J. W. (1988). *Seed Dormancy and Germination*. Glasgow; London: Blackie Available at: [www.springer.com/in/book/9780216916364](https://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](https://doi.org/10.1093/oxfordjournals.aob.a087534).
- 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](https://doi.org/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](https://doi.org/10.1093/forestscience/8.4.386).
- Djavanshir, K., and Pourbeik, H. (1976). Germination value-A new formula. *Silvae genetica* 25, 79–83.
- 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.
- 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](https://doi.org/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](https://doi.org/10.1093/oxfordjournals.aob.a085797).

- 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](https://doi.org/10.1017/S004317450003589x).
- 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](https://doi.org/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. *Crop Science Abstracts; Western Society of Crop Science Annual Meeting, 1961*, 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](https://doi.org/10.1016/0022-5193(75)90001-6).
- Goodchild, N. A., and Walker, M. G. (1971). A method of measuring seed germination in physiological studies. *Annals of Botany* 35, 615–621. Available at: <https://www.jstor.org/stable/42908843> [Accessed January 15, 2018].
- 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/fh6586](https://doi.org/10/fh6586).
- 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/bkp42t](https://doi.org/10/bkp42t).
- Haugland, E., and Brandsaeter, L. O. (1996). Experiments on bioassay sensitivity in the study of allelopathy. *Journal of Chemical Ecology* 22, 1845–1859.
- 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.
- ISTA (2015). Chapter 5: The germination test. *International Rules for Seed Testing. International Seed Testing Association, Zurich, Switzerland*. 2015, 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.
- Kendrick, R. E., and Frankland, B. (1969). Photocontrol of germination in *Amaranthus caudatus*. *Planta* 85, 326–339. doi:[10.1007/bf00381281](https://doi.org/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](https://doi.org/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. *Anais do XXXIV Congresso Nacional de Botânica. SBB, Porto Alegre*, 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](https://doi.org/10.2135/cropsci1962.0011183x000200020033x).
- 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](https://doi.org/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](https://doi.org/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](https://doi.org/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](https://doi.org/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](https://doi.org/10.2135/cropsci1985.0011183X002500030007x).
- 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. Available at: <http://journal.ashspublications.org/content/125/1/128> [Accessed December 12, 2018].
- 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](https://doi.org/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](https://doi.org/10.1002/j.1538-7305.1948.tb01338.x).
- Smith, P. G., and Millet, A. H. (1964). Germinating and sprouting responses of the tomato at low temperatures. *Journal 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.
- Timson, J. (1965). New Method of Recording Germination Data. *Nature* 207, 216. doi:[10.1038/207216a0](https://doi.org/10.1038/207216a0).
- Tucker, H., and Wright, L. N. (1965). Estimating rapidity of germination. *Crop Science* 5, 398–399. doi:[10.2135/cropsci1965.0011183X000500050006x](https://doi.org/10.2135/cropsci1965.0011183X000500050006x).
- 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](https://doi.org/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.