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Supplement of

Implementing spatially explicit wind-driven seed and pollen dispersal in the individual-based larch simulation model: LAVESI-WIND 1.0

Stefan Kruse et al.

Correspondence to: Stefan Kruse (stefan.kruse@awi.de)

1. Supplement

1.1. Verification of wind-dependency

1.1.1. Simulation setup

The simulation experiments were conducted on a 200 x 200 m plot using the model with the new processes for verification. Populations were initiated on empty areas by randomly distributing a fixed number of seeds during the first 100 years of a 1,000 year long stabilisation period. The simulation model randomly drew weather conditions for each year from the complete available period 1934–2013 during the stabilisation period. In the final 80 simulation years, the actual weather data were used.

First, we performed simulation experiments with constant wind conditions to verify the implemented dispersal processes. Wind forcing was from the north or from the south, both with a constant wind speed of 10 km h^{-1}. Simulations were repeated 50 times with an input of 250 seeds per year during initialisation.

Second, we evaluated the functionality of the seed dispersal function by forcing the model with wind data from the reanalysis data set ERA-Interim (Balsamo et al., 2015). Simulations were repeated 10 times and population growth initiated by introducing 100 seeds per year during initialisation.

The dispersal distance and direction as well as the release height of every 100^{th} seed dispersal event were recorded during each year of the complete simulation run. Pollination was assessed by recording the distance and direction from the selected pollen sources to the seed positions prior to seed release of all tree individuals present at the final year of the simulation.

1.1.2. Evaluation of dispersal processes

The seed dispersal and pollination distances were evaluated by calculating the mean dispersal distances for both processes in bins of 30° cardinal directions over the complete simulation run for years with available wind data (1979–2012). In addition, we selected two years with contrasting wind patterns, the year 1990 with predominant winds from the east, and 1998 from the west. The results were qualitatively compared to observed values from the literature.

During the simulations, we recorded only one pollination event per tree per year reaching the central area of 20 x 20 m of the plot and every 100^{th} seed dispersal event.

1.1.3. Analyses

We verified the wind-dependent seed dispersal by comparing the simulation results with the simulated results from the implemented dispersal function and refer to these values as ‘expected’. Therefore, we estimated the dispersal distances with the implemented dispersal functions (seeds Eq.4 and pollen Eq.3) under the same conditions as used for driving the model, namely winds from north or south with a constant speed of 10 km h^{-1}. The observed mean log-transformed (to achieve normal distribution) dispersal distances were compared to each other with a Welch two-sample t-test. We compared simulated to expected dispersal distances in each wind direction in height classes of trees in 10% steps of the sorted values, excluding the minimum and maximum values where only few observations could be recorded. The simulated data values in the range of ±5% at the determined height classes were first tested for an interaction between the release height and the dispersal distance with a Spearman's rank-based measure of association (rho) and a t-test. Then we compared the simulated distances for each height class to the expected distances, both log-transformed prior to analysis, with a t-test. Furthermore, we compared the dispersal in both directions to each other using the same procedure.

The simulated pollination distances were compared to estimates from the implemented function under the same conditions, namely the adult tree's position and constant north or south winds with a speed of 10 km h^{-1}. The resulting three-dimensional pollination distribution probabilities at simulation year 2011 (first year of fieldwork) were binned to cardinal directions in steps of 30°, starting with north between 345° and 15°. The simulated and directly estimated log-transformed pollination distances were tested for differences in each individual direction with a Welch two-sample t-test for cases with >10 observations. We tested whether the mean of the p-values is significantly greater than 0.01 with a Student t-test.

1.1.4. Results

All simulated values were highly correlated to the directly estimated distances (p>0.05, Table S2; Fig. 2). The mean log-transformed simulated distances in a north or south direction were not different when comparing releasing trees of the same height (p>0.05, Table S3).

The distances, simulated and expected from direct calculation, are more similar for those pollination directions with more samples, and only 4-6% of tests show significant differences (Table S4). The higher distance values for these directions may be based on the uniform sampling of fathers and the associated smaller sample sizes in these directions. In all comparisons, we find no evidence that the differences are significant (Table S5).

Table S1. Model structures and memory consumption as the estimated mean over a typical dense forest plot of one hectare, with 80 years climate forcing data and an additional 1,000 years initialising phase.

Structure	Substructure	Total for each element in structure [b]	Total in each simulation [kb]
Parameter	-	642	0.64
Weather[1]	Year(i)	390	31.2
Environment[2]	Grid(i)	54	2,700
Trees[3]	Tree(i)	120	3,000
Seeds[4]	Seed(i)	98	9,016
Evaluation[5]	Evaluation(i)	117	105.86
TOTAL			**14,853.7**

1: with 80 years of weather input data on a monthly basis;

2: 50,000 grid tiles at a resolution of 20 x 20 cm tiles on a hectare;

3: ~25,000 larch individuals appear per hectare in simulations of a typical dense forest plot;

4: ~92,000 larch seeds are present on a hectare of a typical dense forest plot simulation;

5: the length of the simulation is calculated with 1,000 years stabilization and 80 years simulation phase

Table S2. Comparison of simulated to directly estimated seed dispersal from the implemented functions of north and south winds at the same observed release heights calculated for each direction separately.

Wind direction	Tree height [cm]	Significance value (p)	Degrees of freedom	Statistic value (t)	Distances percentile 0%	[m] 1%	25%	50%	75%	99%	100%
North	215	0.405	1067	0.832	0.1	0.8	4.0	6.2	9.1	60.8	214,580.7
	274	0.272	1049	1.100	0.1	0.9	5.1	7.9	11.4	58.5	839,991.5
	337	0.317	1048	-1.001	0.1	1.2	6.2	9.7	13.9	65.4	106,316.3
	406	0.356	1034	-0.924	0.1	1.5	7.6	11.7	16.7	70.7	7,540,295.2
	486	0.119	1027	-1.561	0.2	1.7	9.0	13.8	19.9	75.6	1,800,875.2
	580	0.971	1038	-0.036	0.2	2.0	10.8	16.6	23.7	79.8	295,290.7
	698	0.815	1047	0.234	0.2	2.4	12.8	20.0	28.3	90.7	366,330.3
	860	0.393	1056	0.855	0.1	3.0	15.8	24.5	35.0	99.6	22,430,488.9
South	214	0.328	1081	0.979	0.1	0.8	4.0	6.3	9.1	54.8	142,464.5
	270	0.049	1054	1.969	0.1	0.9	5.0	7.8	11.3	56.0	1,386,968.5
	330	0.721	1054	-0.358	0.1	1.2	6.2	9.5	13.7	65.2	316,950.6
	397	0.796	1045	0.258	0.1	1.4	7.4	11.4	16.3	67.7	3,506,206.1
	476	0.440	1040	-0.772	0.1	1.7	8.8	13.6	19.4	69.2	15,711,413.0
	570	0.794	1036	0.262	0.1	2.0	10.6	16.4	23.3	78.3	160,559.1
	685	0.361	1033	-0.914	0.2	2.5	12.6	19.7	27.9	89.0	1,290,583.5
	851	0.306	1058	-1.025	0.2	2.9	15.7	24.3	34.6	104.8	1,459,702.6

Table S3. Comparison of seed dispersal distances in simulations forced with winds from north and south directions.

Wind direction	Tree height [cm]	Distances percentile 0%	[m] 1%	25%	50%	75%	99%	100%	Significance value (p)	Degrees of freedom	Statistic value (t)
North	215	0.1	0.7	4.0	6.2	9.0	60.2	214,580.7	0.336	58,956	-0.961
South		0.1	0.8	4.0	6.3	9.1	55.9	142,464.5			
North	272	0.1	0.9	5.1	7.8	11.3	58.8	94,025.3	0.235	88,336	-1.189
South		0.1	0.9	5.1	7.9	11.3	58.3	1,386,968.5			
North	333	0.1	1.2	6.1	9.6	13.8	65.0	106,316.3	0.047	91,926	-1.985
South		0.1	1.2	6.2	9.6	13.9	67.1	316,950.6			
North	402	0.1	1.4	7.5	11.6	16.5	71.2	7,540,295.2	0.164	100,519	1.393
South		0.1	1.4	7.4	11.5	16.4	68.6	2,260,443.8			
North	481	0.2	1.7	8.9	13.7	19.7	73.8	1,800,875.2	0.388	101,366	0.864
South		0.1	1.7	8.9	13.7	19.6	70.3	322,285.9			
North	575	0.1	2.0	10.7	16.5	23.5	80.5	295,290.7	0.565	101,072	0.576
South		0.1	2.0	10.7	16.6	23.6	79.8	160,559.1			
North	692	0.2	2.4	12.7	19.8	28.1	91.8	366,330.3	0.230	92,599	-1.201
South		0.2	2.5	12.8	19.9	28.2	89.8	1,290,583.5			
North	856	0.1	3.0	15.7	24.4	34.8	99.3	22,430,488.9	0.921	74,922	0.100
South		0.2	2.9	15.7	24.5	34.7	105.8	1,459,702.7			

Table S4. Pollination event comparison between simulated and expected values. The statistics are based on 50 simulation repeats. Significant differences between expected and simulated distances tested with a Welch two-sample t-test.

Cardinal direction of winds	Direction of pollination [°]	Distance (simulated/expected) [m]	Fraction of observations (simulated/expected) [%]	Fraction of significant differences
North	135-165	44.32/43.79	9.00/8.39	20%
	165-195	39.03/38.90	81.53/82.68	4%
	195-225	40.03/40.19	9.47/8.93	14%
South	315-345	40.94/40.47	7.55/7.92	12%
	345-15	36.98/37.90	82.92/82.8	6%
	15-45	42.76/40.84	9.51/9.28	22%
	45-75	*53.80/-*	0.01/0.00	*

* only one observation, thus excluded from further analyses.

Table S5. Comparison of pollination dispersal distances with Student's t-test of the mean p-values at a significance level of 0.01. Only cases with >10 pollination events of the five trees producing most seeds were considered.

Cardinal direction of winds	Wind direction [°]	Mean p-value	Significance value (p)	Degrees of freedom	Statistic value (t)
North	165-195	0.449	<0.001	49	10.133
	135-165	0.277	<0.001	38	5.629
	195-225	0.406	<0.001	37	6.704
South	345-15	0.415	<0.001	49	10.171
	15-45	0.302	<0.001	40	5.734
	315-345	0.408	<0.001	39	8.315

Table S6. Test statistics for generalised nonparametric regression analyses (significance level: *** p<0.001).

Simulation version	Model formula	Aikaike's Information Criterion (AIC)	Dispersion parameter for Gaussian family	Model term	Degrees of freedom	Sum of squares	F-test statistic value	Significance
+POLLEN_PAR A	*t~Nt*	964	0.17	*Nt*	1	10160.4	59340.3	***
				Residuals	1076	184.2		
	t~Ns	1042	0.29	*Ns*	1	9093.8	31780.8	***
				Residuals	1076	307.9		
	t~Nt+Ns	1167	0.15	*Nt*	1	9879.2	65019.1	***
				Ns	1	7.3	48.2	***
				Residuals	1072	162.9		
	t~Nt+Ns+Nt:Ns	1722	0.14	*Nt*	1	10688.2	75655.2	***
				Ns	1	705.7	4995.0	***
				Nt:Ns	1	1843.4	13048.4	***
				Residuals	1071	151.3		
+POLLEN	*t~Nt*	884	0.17	*Nt*	1	9730.8	56047.3	***
				Residuals	1077	187.0		
	t~Ns	975	0.29	*Ns*	1	8857.5	30113.9	***
				Residuals	1077	316.8		
	t~Nt+Ns	1183	0.14	*Nt*	1	9472.3	66387.8	***
				Ns	1	9.0	63.3	***
				Residuals	1073	153.1		
	t~Nt+Ns+Nt:Ns	1754	0.13	*Nt*	1	10215.8	77934.1	***
				Ns	1	582.7	4445.4	***
				Nt:Ns	1	1647.4	12567.5	***
				Residuals	1072	140.5		
+POLLEN_PAR B	*t~Nt*	734	0.15	*Nt*	1	9923.8	64828.7	***
				Residuals	1075	164.6		
	t~Ns	833	0.25	*Ns*	1	8939.3	35072.6	***
				Residuals	1075	274.0		
	t~Nt+Ns	1045	0.13	*Nt*	1	9583.7	76495.4	***
				Ns	1	20.8	166.2	***
				Residuals	1071	134.2		
	t~Nt+Ns+Nt:Ns	1596	0.11	*Nt*	1	10405.4	91086.0	***
				Ns	1	681.4	5964.8	***
				Nt:Ns	1	1705.2	14927.1	***
				Residuals	1070	122.2		
SEED	*t~Nt*	-403	0.05	*Nt*	1	1440.4	30730.1	***
				Residuals	1075	50.4		
	t~Ns	-375	0.06	*Ns*	1	1317.6	21817.7	***
				Residuals	1075	64.9		
	t~Nt+Ns	-233	0.04	*Nt*	1	1396.3	34099.6	***
				Ns	1	9.4	229.9	***
				Residuals	1071	43.9		
	t~Nt+Ns+Nt:Ns	40	0.04	*Nt*	1	1512.3	37915.5	***
				Ns	1	37.9	950.9	***
				Nt:Ns	1	288.9	7243.1	***
				Residuals	1070	42.7		