Supplementary information for

Ecotypic variation in multiple traits of European beech – selection of suitable provenances based on performance and stability

Katharina J. Liepe, Ernst van der Maaten, Marieke van der Maaten-Theunissen, Jonathan M. Kormann, Heino Wolf, Mirko Liesebach

Correspondence: Katharina J. Liepe (katharina.liepe@thuenen.de)

This file includes:

Supplementary Figures S1-S8

Supplementary Tables S1-S5

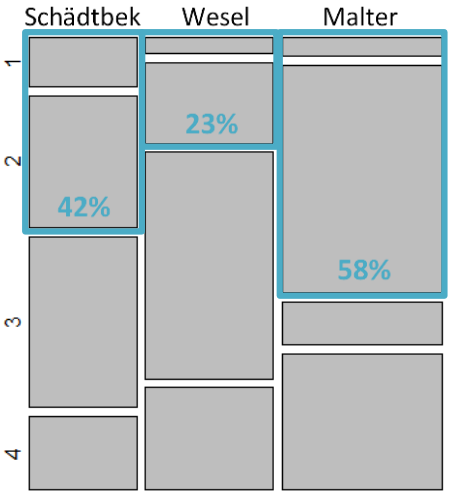

Fig. S1: Mosaic plot indicating the relative frequencies of each stem form quality class per trial site. Class 1 and 2 were summarized as 'acceptable stem form'

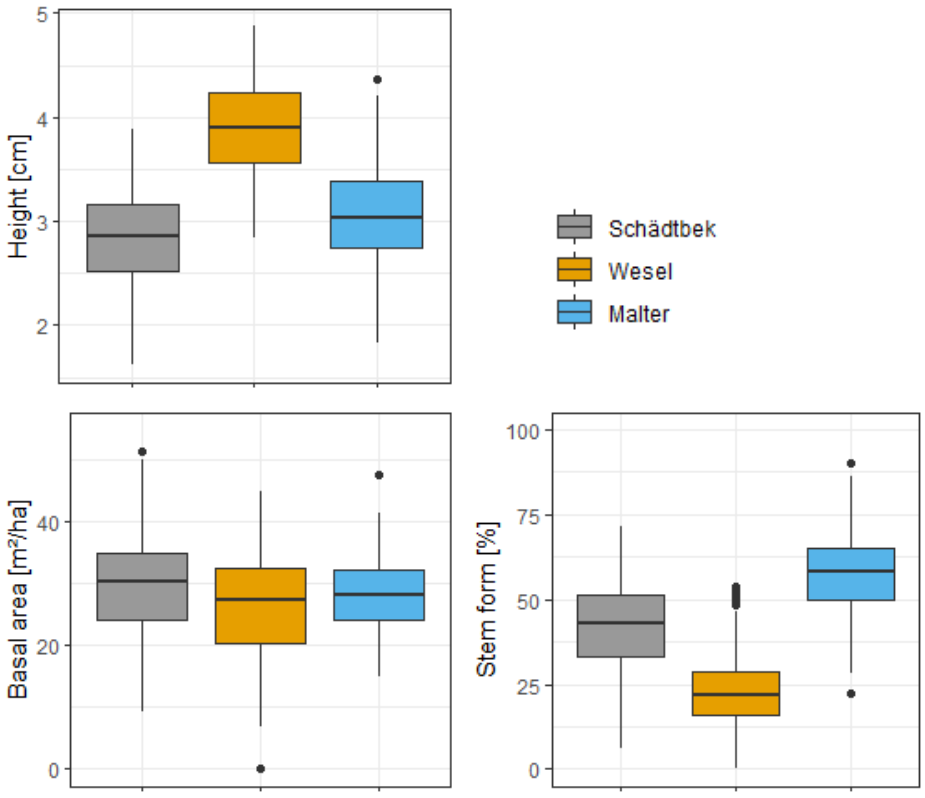

Fig. S2: Distribution of trait expression summarized at plot level by sites used as response variables in the analysis

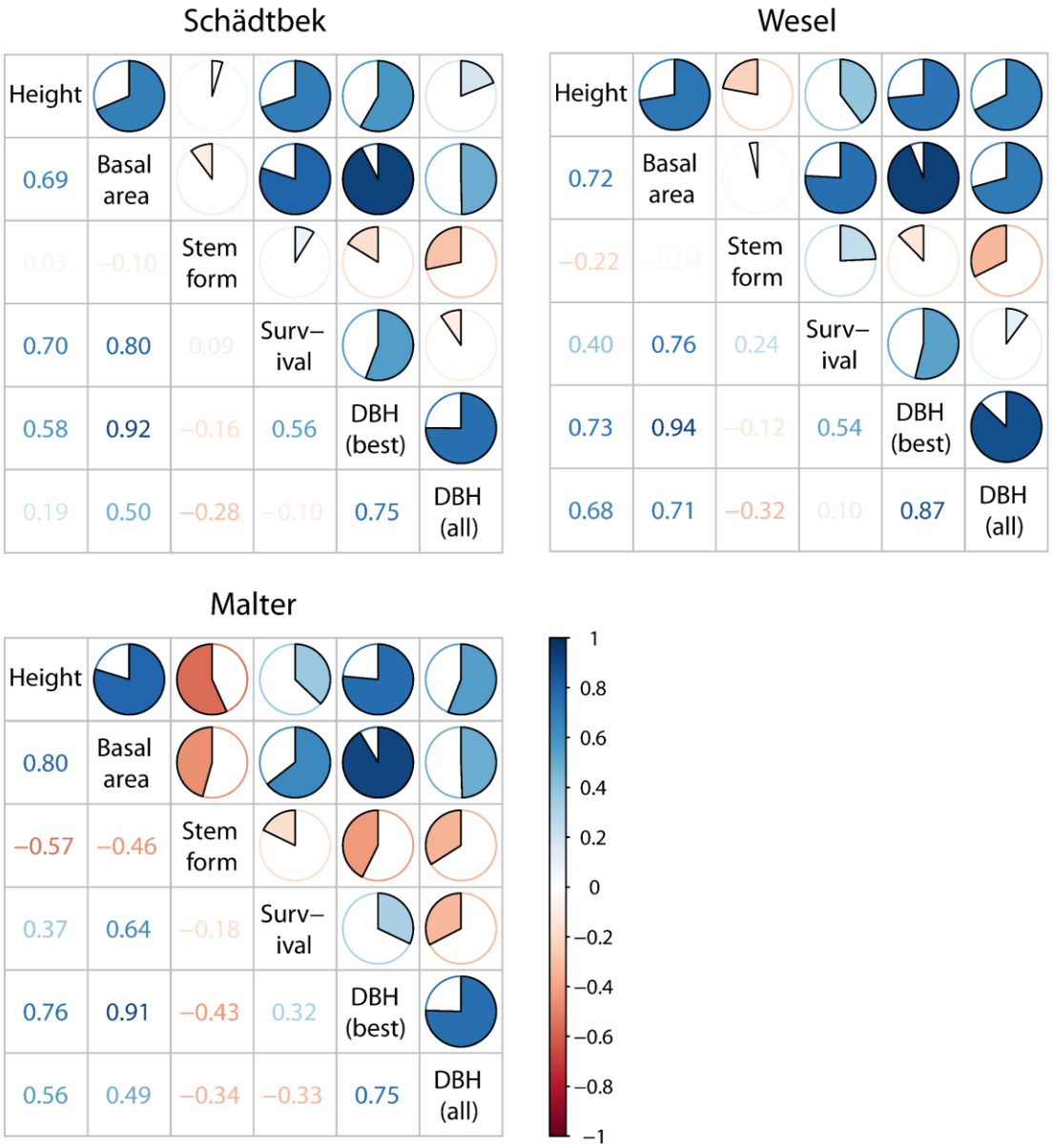

Fig. S3: Correlations among phenotypic traits at each individual trial site. Size and color of the pie charts in the upper half indicate the strength and direction of the correlation coefficients displayed in the lower half

In addition to the three main traits of interest, we further investigated survival [%] and DBH [cm], which were likewise summarized at plot level. Since, there was no silvicultural thinning prior to the measurement at age 25, survival was estimated as the proportion of living trees to the total number of trees planted. Plot mean values for DBH were derived in two ways: DBH (all) including all remaining individuals, and DBH (best) including only the 15 strongest, most competitive trees per plot, in order to minimize bias caused by suppressed or damaged trees that will likely drop out by natural selection (Liesebach et al. 2011; Horváth and Mátyás 2016). Due to the high shade tolerance of beech, these have remained alive so far, but in several cases no growth was recorded between 2012 and 2017. Results of the mixed models for these additional traits are presented in Table S2 and S3.

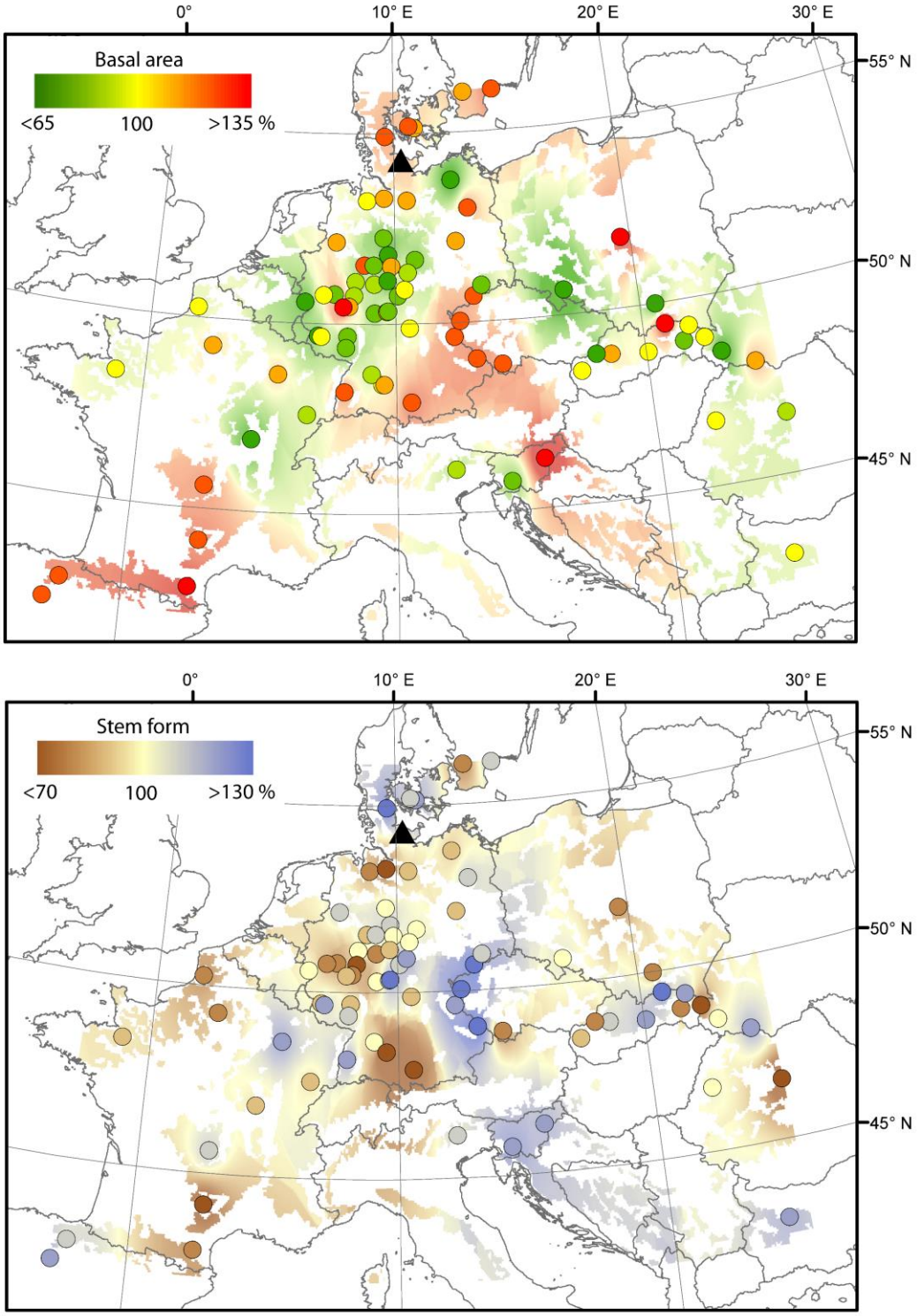

Fig. S4: Differentiation among provenances at the trial site Schädtbek visualized at their corresponding location of origin (points) for basal area and stem form. They are represented as % deviation from the overall mean (100 %). That means a performance < 100 % represents a trait being poorer than average, while > 100 % represents a trait being higher than average. The species range in the background represents an interpolated surface created by IDW interpolation between provenances and is colored by the same scales

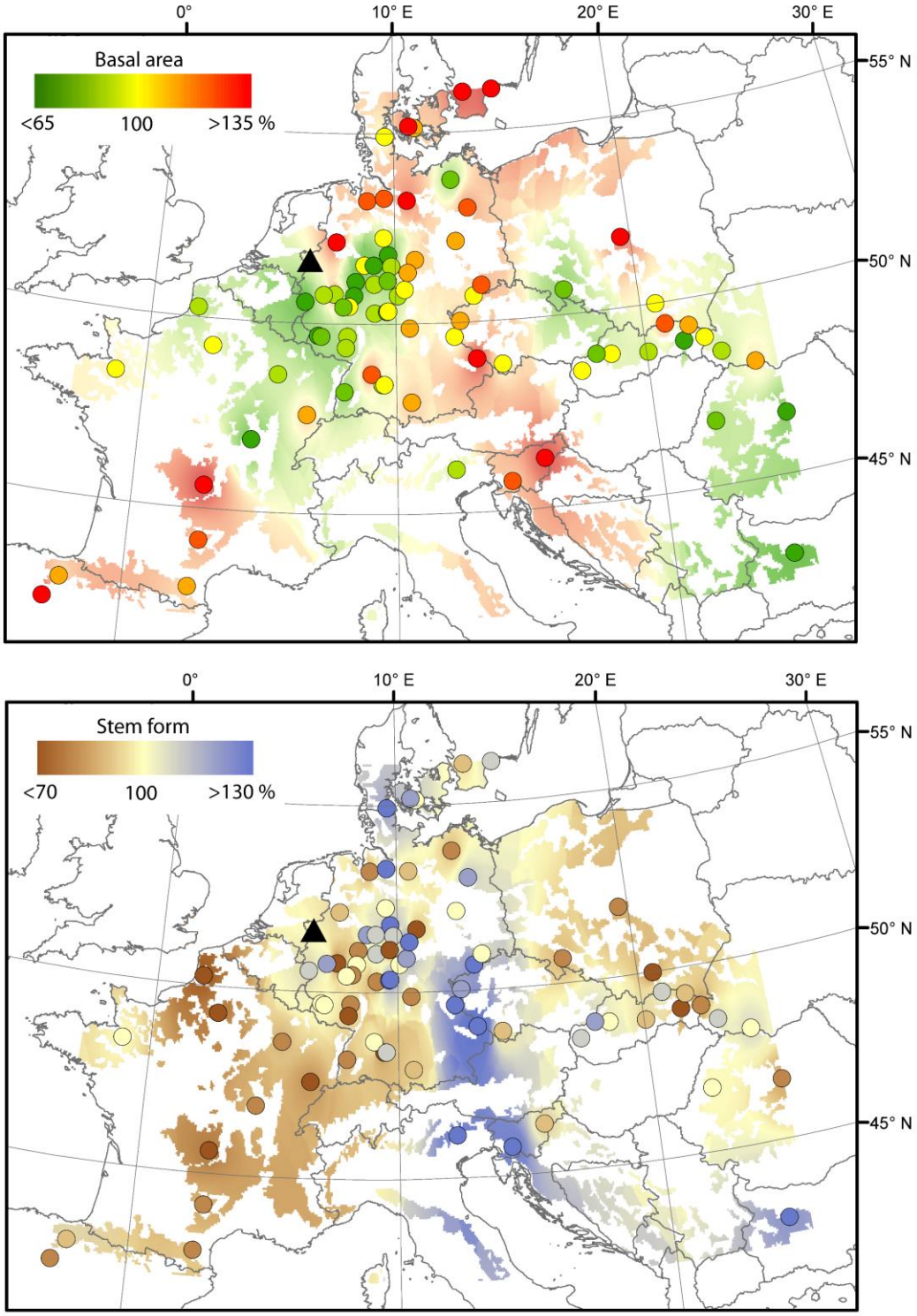

Fig. S5: Differentiation among provenances at the trial site Wesel visualized at their corresponding location of origin (points) for basal area and stem form. For further description see Figure S4

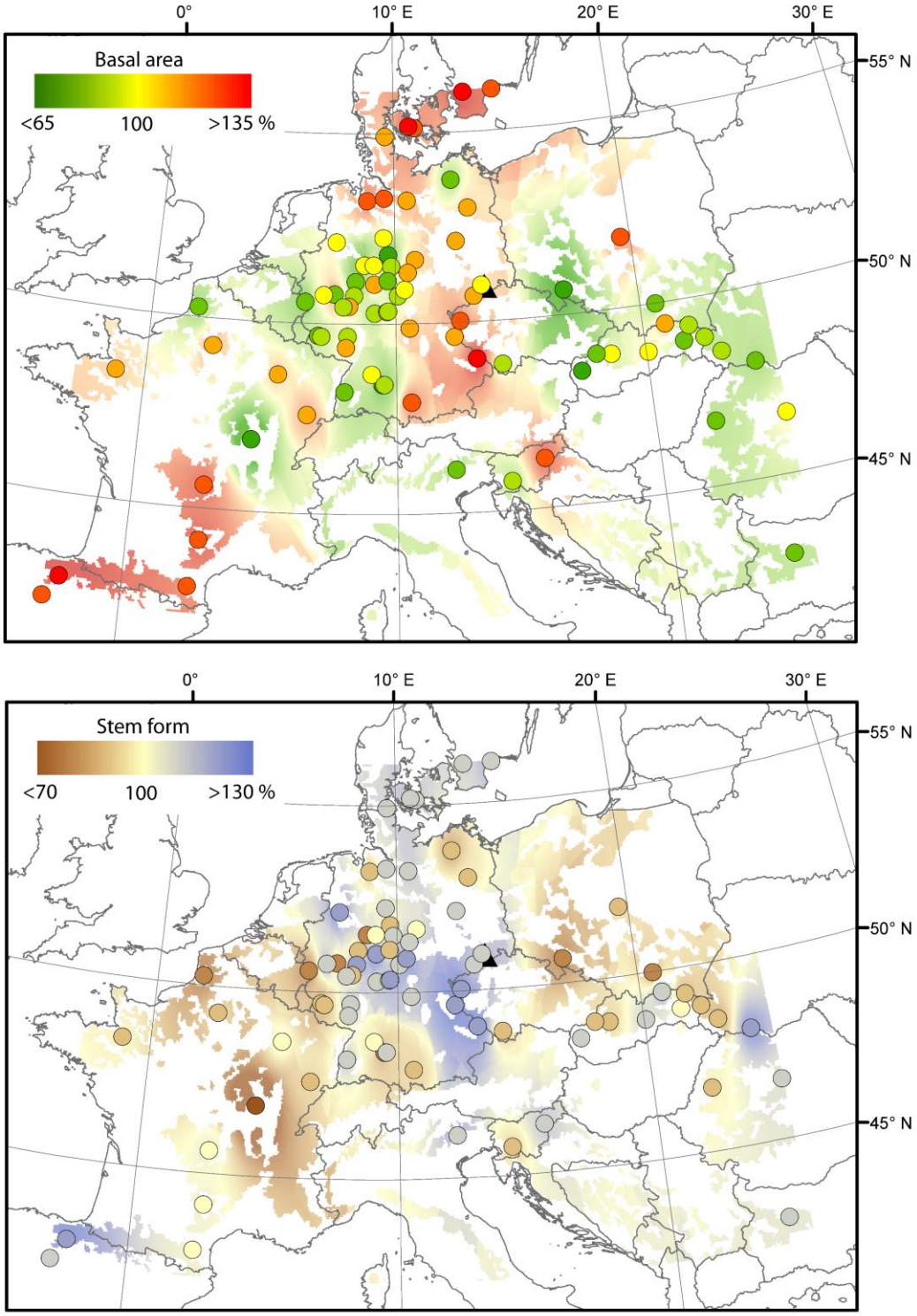

Fig. S6: Differentiation among provenances at the trial site Malter visualized at their corresponding location of origin (points) for basal area and stem form. For further description see Figure S4

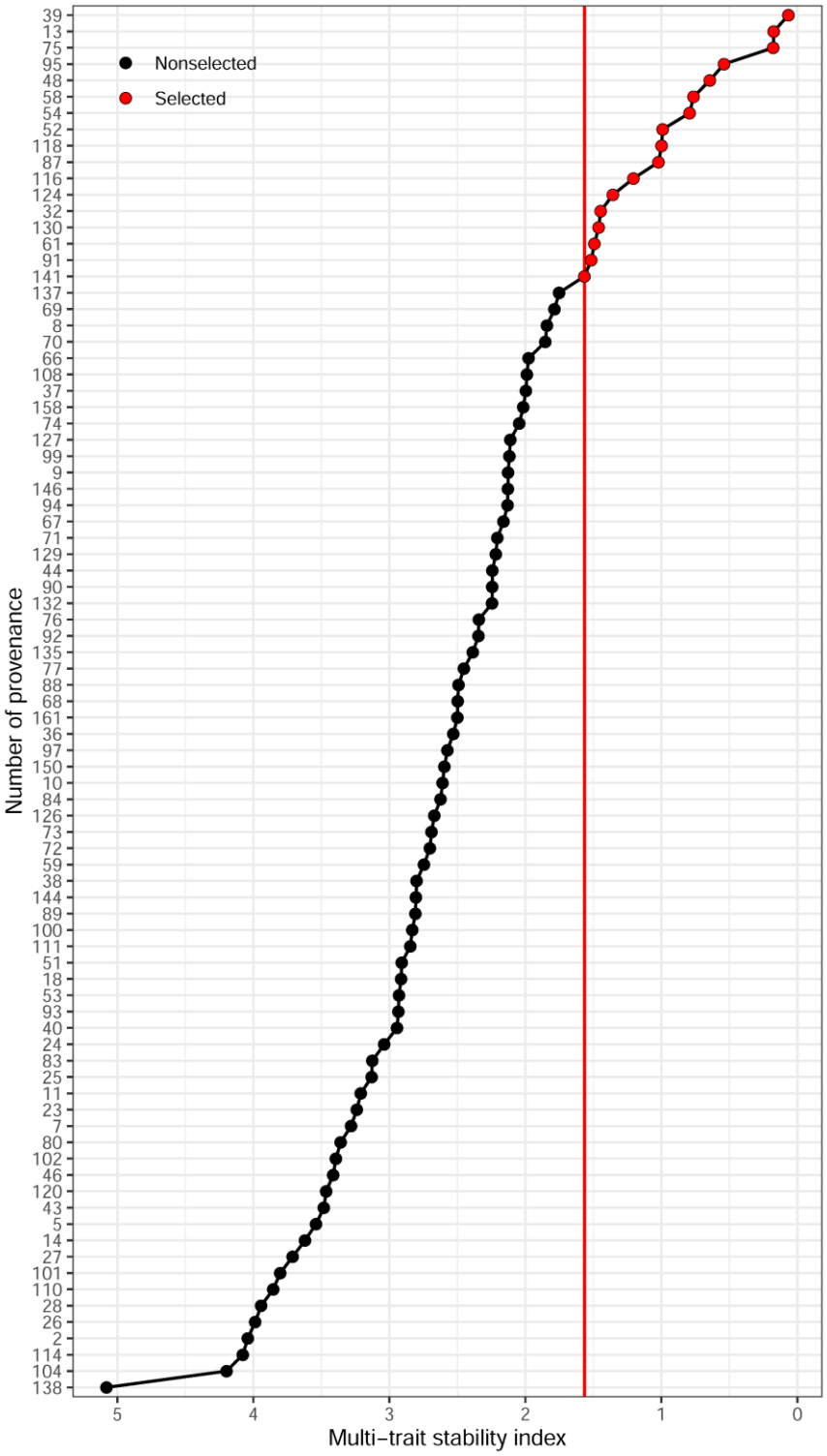

Fig. S7: Ranking of provenances according to their Multi-trait stability index (MTSI). The red line indicates the selection intensity of 20 %. Provenances to the right of this line marked in red are selected. Provenance names corresponding to the numbers are given in Table S1

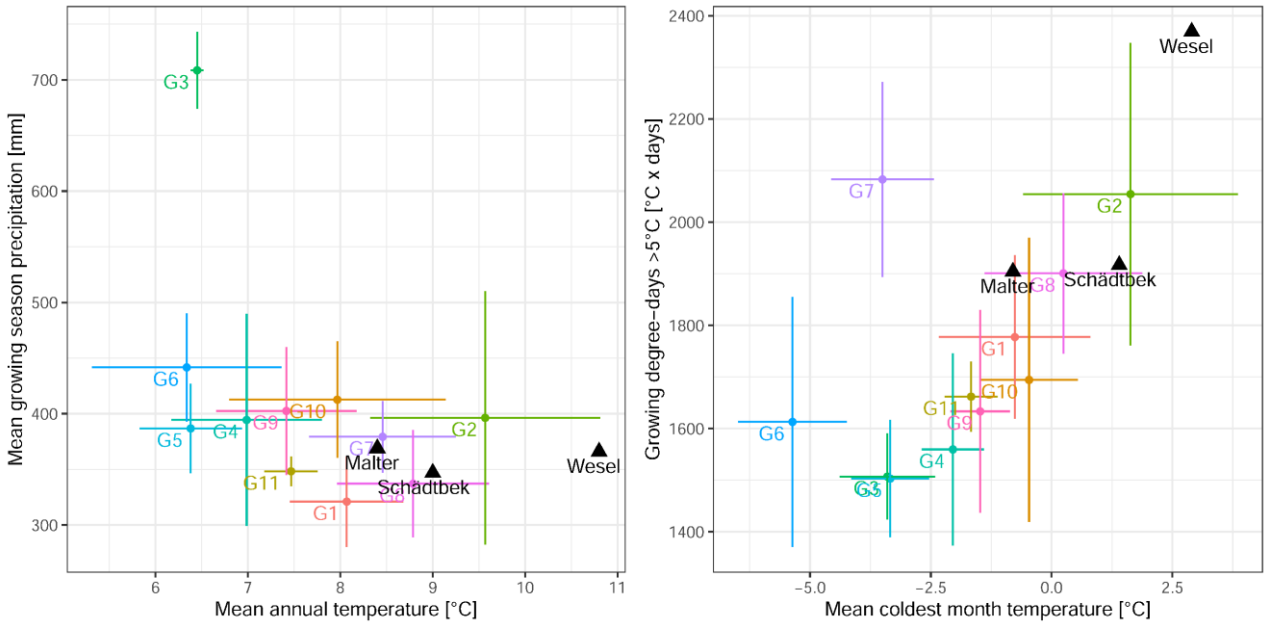

Fig. S8: Mean climate space of the 11 groups derived by multivariate regression tree analysis (G1 to G11). Corresponding standard deviations are indicated by error bars. Climate variables for provenance origin were extracted for the normal period 1961-1990 (using *ClimateEU* by Marchi et al., 2020), representing the climatic conditions prior to seed collection to which the sourced populations likely have adapted. Climate variables for the three trial sites were extracted for the normal period 1991-2020

Table S1: List of 85 beech provenances planted at each of the three German sites of the 4th international trial series of *Fagus sylvatica*

No gives the provenance number used for identification, *SBNr* the seed book number assigned with receival of each seed lot in 1992. *Provenance* gives a short name, while *Provenance Long Name* reports further details reported at time of seed collection. *Countries* are abbreviated according to ISO 3166-1 Alpha 2 code. The large set of provenances originating from Germany is further characterized by the *federal state* (BB = Brandenburg, BW = Baden-Württemberg, BY = Bavaria, HE = Hesse, MV = Mecklenburg-Vorpommern, NI= Lower Saxony, NW = North Rhine-Westphalia, RP = Rhineland-Palatine, SN = Saxony, ST = Saxony-Anhalt, TH = Thuringia) and *region of provenance* according to the current delineation (Anonymous 1994). Note that the registry numbers given with the provenance long name may be outdated, e.g. for provenances from Germany, due to revisions of national regulations on forest resource material. Geographic coordinates are given in decimal degrees. In a few cases, elevation of the location of origin was not provided by seed collectors, these were approximated with a digital elevation model based on the available geographic coordinates and marked by '*est.*' in the table.

Table S1 is provided as separate file: Liepe et al_Table S1.xlsx

Table S2: Results of the random and fixed effects models for survival and DBH at each individual site

	Trait	LRT_P	V_P	V_R	MS B	Mean ± SD
Schädtbek	Survival	14.9 ***	27.4 (25%)	80.1 (75%)	202.0 n.s.	40.4 ± 3.73
	DBH (best)	28.7 ***	0.84 (35%)	1.53 (65%)	17.1 ***	14.6 ± 0.72
	DBH (all)	5.85 *	0.28 (16%)	1.5 (84%)	22.0 ***	13.0 ± 0.31
Wesel	Survival	15.2 ***	25.5 (26%)	73.0 (74%)	2515 ***	45.9 ± 3.60
	DBH (best)	32.2 ***	0.93 (38%)	1.54 (62%)	59.2 ***	13.2 ± 0.77
	DBH (all)	11.7 ***	0.34 (23%)	1.18 (77%)	16.6 ***	11.5 ± 0.40
Malter	Survival	7.08 ***	25.4 (17%)	120.0 (83%)	229 n.s.	55.7 ± 3.14
	DBH (best)	21.7 ***	0.41 (31%)	0.92 (69%)	3.08 *	13.3 ± 0.49
	DBH (all)	3.02 n.s.	0.14 (11%)	1.14 (89%)	3.34 n.s.	10.9 ± 0.20

LRT_P – likelihood ratio test for provenance effect; V_P – variance of the provenance random effect, V_R – residual variance, values in brackets report the proportion of variance accounted for by each effect; MS – mean squares for block (B); Mean – site mean ± standard deviation (SD); *, **, ***: significant at 5%, 1%, 0.1% respectively, n.s.: not significant.

Table S3: Results of the random and fixed effects models across sites for survival and DBH

Trait	LRT_P	$LRT_{P\times E}$	V_P	$V_{P\times E}$	V_R	MS E	MS B(E)	Mean ± SD
Survival	30.2 ***	1.80 n.s.	20.60 (18%)	5.51 (5%)	91.10 (78%)	5518 ***	982 ***	47.4 ± 12.78
DBH (best)	91.8 ***	0.04 n.s.	0.72 (35%)	0.01 (0%)	1.33 (65%)	83.4 ***	26.6 ***	13.7 ± 1.63
DBH (all)	18.3 ***	1.26 n.s.	0.19 (13%)	0.06 (4%)	1.27 (83%)	86.2 ***	14.0 ***	11.8 ± 1.56

LRT_P, $LRT_{P\times E}$ – likelihood ratio test for provenance and provenance by environment interaction effects; V_P, $V_{P\times E}$ – variance of random effects for provenance and provenance by environment interaction, V_R – residual variance, values in brackets report the proportion of variance accounted for by each effect; MS – mean squares for environments (E) and block within environment B(E); Mean – overall mean ± standard deviation (SD); *, **, ***: significant at 5%, 1%, 0.1% respectively, n.s.: not significant.

Table S4: Ranking of selected provenances by multi-trait selection at individual sites and across sites. These were selected using the multi-trait genotype–ideotype distance index (MGIDI) for individual sites and the multi-trait stability index (MTSI) across sites applying a selection intensity of 20 %

No	SBNr	Provenance	Country	DE - Fed. state	DE - Region of provenance	Provenances selected for individual sites (MGIDI)			Provenances selected across sites (MTSI)
						Schädtbek	Wesel	Malter	
8	9014	F.D. de Crecy	FR				14	7	
13	9021	F.D. de Planoise	FR			14	1		2
32	9098	Malchin I'92 / Teterow	DE	MV	81002	13	13	15	13
39	8786	Seelzerthurm	DE	NI	81009	1	10	10	1
48	8775	Monschau, Abt. 38 A	DE	NW	81008	6	3	8	5
52	8768	Eitorf 1502/209 a/b	DE	NW	81007		7	4	8
54	8782	Schmallenberg	DE	NW	81008	16	4	5	7
58	8771	Wünnenberg Glashütte, Abt. 15b	DE	NW	81007		5	2	6
61	8781	Neuenheerse, Abt. 175	DE	NW	81009	15	9		15
69	8970	Erl Abt. 762 (Standard)	DE	HE	81009		17		
70	8971	Büdingen Abt. 763 (Standard)	DE	HE	81009	11			
71	8967	Sinntal Abt. 410 (Standard)	DE	HE	81009			16	
74	8966	Schlüchtern	DE	HE	81009	3			
75	8766	Spangenberg, Rfö. Kaltenbach	DE	HE	81009	7	2	1	3
76	8994	Bad Salzungen	DE	TH	81010	17			
77	8995	Eisenach	DE	TH	81011	2			
87	8960	Osburg	DE	RP	81008		16	13	10
91	8765	Elmstein-Süd, Rfö.Wolfsgrube XIV 1a	DE	RP	81007	4	12		16
92	8959	Elmstein-Süd, Appenthal, XIVBuch.	DE	RP	81007	5			
94	8954	Ettenheim	DE	BW	81021		11		
95	8763	Münsingen Brente	DE	BW	81023		8		4
116	8979	Bnerko	PL					9	11
118	8978	Henrykow	PL			8		12	9
124	8946	Zamutov	SK				6		12
129	8948	Smolenice	SK					11	
130	8945	Trenc In	SK					14	14
135	8943	Medzilaborce-Koskovce	SK			10			
137	8883	Postojna	SI			9		3	
141	8987	Svaljava Polana	UA			12		6	17
146	8928	Beius-Bihor / Prisaca	RO					17	
150	8903	Sovata (25)	RO				15		

Table S5: Climatic characterization of ecotypes with similarly adapted provenances, derived by multivariate regression tree analysis.

Group		# of prov	Mean climate across provenances within MRT groups									
			MAT	MWMT	MCMT	TD	MAP	MSP	SHM	FFP	DD>5	CMD
G1	North European Plains	13	8.1	16.6	-0.8	17.4	678	321	52.5	195	1777	109
G2	Pyrenees, Massif Central, Eastern SL	6	9.6	18.1	1.6	16.5	972	396	49.4	195	2054	173
G3	Southern Alps > 1025 m	2	6.5	16.1	-3.4	19.5	1589	709	22.7	162	1507	0
G4	Transition zone, Harz down south to Bavaria	7	7.0	15.6	-2.0	17.6	818	394	41.0	164	1560	80
G5	Bavarian Forest, Ore mountains	5	6.4	15.5	-3.3	18.8	754	387	40.4	167	1503	57
G6	Sudets, Beskids, Carpathians > 325 m	8	6.3	16.0	-5.4	21.3	787	442	36.6	189	1613	63
G7	Sudets, Beskids, Carpathians < 325 m	7	8.5	18.3	-3.5	21.8	670	379	48.7	187	2083	165
G8	West / South-West DE, Northern FR < 425 m	16	8.8	17.0	0.2	16.7	761	337	51.4	199	1901	140
G9	West / South-West DE > 425 m	13	7.4	15.9	-1.5	17.4	877	403	40.1	175	1633	63
G10	Eifel, Hunsrück DE, Morvan FR, > 425 m	3	8.0	16.0	-0.5	16.5	1009	413	39.5	190	1694	61
G11	Outstanding provenances in central DE	3	7.5	15.9	-1.7	17.6	724	348	45.7	173	1662	110

Climate variables for provenances were extracted for the climate normal period 1961-90 characterizing the conditions to which the sourced provenances had adapted in the past. Definition of abbreviations and units according to Marchi et al. (2020): MAT = Mean annual temperature [°C], MWMT = Mean warmest month temperature [°C], MCMT = Mean coldest month temperature [°C], TD = Continentality, i.e., temperature difference between MWMT and MCMT, MAP = Mean annual precipitation [mm], MSP = Mai to September precipitation [mm], SHM = Summer heat moisture index [MWMT/(MSP/1000)], FFP = Frost-free period [days], DD>5 = Growing degree-days >5 °C [°C × days], CMD = Hargreaves climatic moisture deficit [mm].

References

Anonymous (1994) Forstvermehrungsgut-Herkunftsgebietsverordnung (FoVHgV) [Regulation on provenance regions for forest reproductive material]. Verordnung über Herkunftsgebiete für forstliches Vermehrungsgut vom 7.10.1994 (BGBl. I S. 3578), geändert durch die Verordnung vom 15.1.2003 (BGBl. I S. 238)

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Liesebach M, Schüler S, Wolf H (2011) Klima-Wachstums-Beziehungen von Rotbuchen-Herkünften (Fagus sylvatica L.) im Vergleich [Comparison of climate-growth relations among provenances of beech (Fagus sylvatica L.)]. Mitteilungen aus der Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz 79–91

Marchi M, Castellanos-Acuña D, Hamann A, et al (2020) ClimateEU, scale-free climate normals, historical time series, and future projections for Europe. Sci Data 7:1–10. https://doi.org/10.1038/s41597-020-00763-0