Supplementary Information

Source-sink relationships during grain filling in wheat in response to various temperature, water deficit and nitrogen deficit regimes

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Table S1. Metainformation of the experiments used in this study.								
Experiment code	**Treatment code**	**Factor**	**Environmental regimes [a]**			**Cultivar**	**Sowing date**	**Anthesis date**
			Temperature	**Drought**	**Nitrogen**			
EXP1991[b]	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between 6 DAA and maturity	Well-watered [d]	Non-limiting N supply (33 g N m^{-2})	Thésée	1990-11-28	1991-05-31
	28/20°C	HT	High constant day/night temperature (28/20°C) between 6 DAA and maturity	Well-watered [d]	Non-limiting N supply (33 g N m^{-2})	Thésée	1990-11-28	1991-05-31
EXP1993	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between 0 DAA and maturity	Well-watered (267.5 mm from anthesis to maturity)	Non-limiting N supply (30.5 g N m^{-2})	Thésée	1992-11-09	1993-05-26
	34/10°C	HT	High constant day temperature (34/10°C) between 0 DAA and maturity	Well-watered (287.25 mm from anthesis to maturity)	Non-limiting N supply (30.5 g N m^{-2})	Thésée	1992-11-09	1993-05-26
	28/20°C	HT	High constant day and night temperature (28/20°C) between 0 DAA and maturity	Well-watered (303.95 mm from anthesis to maturity)	Non-limiting N supply (30.5 g N m^{-2})	Thésée	1992-11-09	1993-05-26
	28/20°C eCO_2	HT	High constant day and night temperature (28/20°C) and elevated CO_2 (~700 ppm; ambient was ~380 ppm) between 0 DAA and maturity	Well-watered (262.65 mm from anthesis to maturity)	Non-limiting N supply (30.5 g N m^{-2})	Thésée	1992-11-09	1993-05-26
EXP1994[b,c]	Out°C (CK)	CK	Fluctuating outside ambient temperature during grain filing (average temperature 17.66°C)	Well-watered (135 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1993-11-26	1994-05-23
	Out+5°C	HT	Fluctuating outside ambient temperature plus 5°C (average temperature 21.94°C) between 4 DAA and maturity	Well-watered (145 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1993-11-26	1994-05-23
	Out +5C→Out+10°C	HT	Fluctuating outside ambient temperature plus 5°C (average temperature 21.59°C) between 4 and 18 DAA, and then plus	Well-watered (120 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1993-11-26	1994-05-23

			10°C (average temperature 28.71°C) until maturity					
	Out+10°C→Out+5°C	HT	Fluctuating outside ambient temperature plus 10°C (average temperature 26.17 °C) between 4 and 16 DAA, and then plus 5°C (average temperature 22.12°C) until maturity	Well-watered (145 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1993-11-26	1994-05-23
	Out–5°C	LT	Fluctuating outside ambient temperature minus 5°C (average temperature 14.60°C) between 4 DAA and maturity	Well-watered (150 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1993-11-26	1994-05-23
EXP1995[b]	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between 9 DAA and maturity	Well-watered (179.25 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1994-10-13	1995-05-23
	28/20°C–>34/10°C	HT	High constant night temperature (28/20°C day/night) between 9 and 14 DAA, and then high constant day temperature (34/10°C day/night) until maturity[#]	Well-watered (136.5 mm from anthesis to maturity)	Non-limiting N supply (33 g N m^{-2})	Thésée	1994-10-13	1995-05-23
EXP1996[b]	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between 4 DAA and maturity	Well-watered (188.5 mm from anthesis to maturity)	Non-limiting N supply (28 g N m^{-2})	Thésée	1995-11-14	1996-05-29
	34/10°C	HT	High constant day temperature (34/10°C day/night) between 4 DAA and maturity	Well-watered (160.5 mm from anthesis to maturity)	Non-limiting N supply (28 g N m^{-2})	Thésée	1995-11-13	1996-05-29
	28/20°C	HT	High constant night temperature (28/20°C day/night) between 4 DAA and maturity	Well-watered (165.5 mm from anthesis to maturity)	Non-limiting N supply (28 g N m^{-2})	Thésée	1995-11-15	1996-05-29
EXP1997[b,c]	Out+10°C→34/20°C	HT	Fluctuating outside ambient temperature plus 10°C (average temperature 28.13°C) between 6 and 22 DAA with mid-grain filling (2 days with 4 h at 40°C	Well-watered (252 mm from anthesis to maturity)	Non-limiting N supply (23 g N m^{-2})	Thésée	1996-11-14	1997-05-23

			starting 13 DAA), and then constant high day and night temperature (34/20°C day/night) until maturity					
	Out+10°C→34/20°C	HT	Fluctuating outside ambient temperature plus 10°C (average temperature 28.16°C) between 6 and 22 DAA with mid-grain filling (2 days with 4 h at 40°C starting 13 DAA), and then constant high day and night temperature (34/20°C day/night) until maturity	Well-watered (245 mm from anthesis to maturity)	Non-limiting N supply (23 g N m^{-2})	Thésée	1996-11-14	1997-05-23
	Out–5°C→18/10°C	LT	Fluctuating outside ambient temperature minus 5°C (average temperature 12.57°C) between 4 and 37 DAA, and then moderate constant temperature (18/10°C day/night) until maturity	Well-watered (183 mm from anthesis to maturity)	Non-limiting N supply (23 g N m^{-2})	Thésée	1996-11-14	1997-05-23
	Out–5°C→34/10°C	LT	Fluctuating outside ambient temperature minus 5°C (average temperature 12.57°C) between 4 and 37 DAA, and then moderate constant day/night temperature (34/10°C) until maturity	Well-watered (199 mm from anthesis to maturity)	Non-limiting N supply (23 g N m^{-2})	Thésée	1996-11-14	1997-05-23
EXP1998	Out°C WW (CK)	CK	Fluctuating outside ambient temperature during grain filing (average temperature 16.67°C)	Well-watered (125 mm from 28 days before anthesis to anthesis; 205.5 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out°C WD1	WD	Fluctuating outside ambient temperature during grain filling (average temperature 16.66°C)	Pre-anthesis water deficit (water withheld from 28 days before anthesis to anthesis) (55 mm from 28 days before anthesis to	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18

				anthesis; 225.5 mm from anthesis to maturity)				
	Out°C WD2	WD	Fluctuating outside ambient temperature during grain filling (average temperature 16.06°C)	Post-anthesis water deficit (water withheld from 0 DAA to maturity) (187.5 mm from 28 days before anthesis to anthesis; 35 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out°C WD12	WD	Fluctuating outside ambient temperature during grain filling (average temperature 15.61°C)	Pre- and post-anthesis water deficit (water withheld from 28 days before anthesis to maturity) (10 mm from 28 days before anthesis to anthesis; 35 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out°C WD3	WD	Fluctuating outside ambient temperature during grain filling (average temperature 15.58°C)	Late water deficit (water withheld from 11 DAA to maturity) (182 mm from 28 days before anthesis to anthesis; 90 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out+5°C WW[b]	HT	Moderate constant day/night temperature (18/10°C) from 2 to 8 DAA; and fluctuating outside ambient temperature plus 5°C (average temperature 21.15°C) between 9 DAA and maturity	Well-watered (250 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18

	Out+5°C WD[b]	HT/WD	Moderate constant day/night temperature (18/10°C) from 2 to 8 DAA; and fluctuating outside ambient temperature plus 5°C (average temperature 20.95°C) between 9 DAA and maturity	Post-anthesis water deficit (water withheld from 0 DAA to maturity; 72.5 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out–5°C WW[b]	LT	Fluctuating outside ambient temperature minus 5°C (average temperature 12.75°C) between 2 DAA and maturity	Well-watered (260 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
	Out–5°C WD[b]	LT	Fluctuating outside ambient temperature minus 5°C (average temperature 11.66°C) between 2 DAA and maturity	Post-anthesis water deficit (water withheld from 0 DAA to maturity; 42.5 mm from anthesis to maturity)	Non-limiting N supply (23.8 g N m^{-2})	Thésée	1997-11-04	1998-05-18
EXP1999[b]	18/10°C WW (CK)	CK	Moderate constant day/night temperature (18/10°C) between 9 DAA and maturity	Well-watered (242.5 mm from anthesis to maturity)	Non-limiting N supply (32.2 g N m^{-2})	Renan	1998-11-17	1999-05-22
	18/10°C WD	WD	Moderate constant day/night temperature (18/10°C) between 9 DAA and maturity	Post-anthesis water deficit (water withheld from 3 DAA to maturity; 104.5 mm from anthesis to maturity)	Non-limiting N supply (32.2 g N m^{-2})	Renan	1998-11-17	1999-05-22
	28/15°C WW	HT/WD	High night temperature (28/20°C day/night) between 9 DAA and maturity	Well-watered (201.5 mm from anthesis to maturity)	Non-limiting N supply (32.2 g N m^{-2})	Renan	1998-11-17	1999-05-22
	28/15°C WD	HT	High night temperature (28/20°C day/night) between 9 DAA to maturity	Post-anthesis water deficit (water withheld from 3 DAA to maturity; 90 mm from anthesis to	Non-limiting N supply (32.2 g N m^{-2})	Renan	1998-11-17	1999-05-22

				maturity)				
EXP2000	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between –1 DAA and maturity	Well-watered (224 mm from anthesis to maturity)	Non-limiting N supply (23.6 g N m^{-2})	Récital	1999-11-10	2000-05-15
	28/15°C[c]	HT	High constant day/night temperature (28/15°C) between 5 DAA and maturity	Well-watered (259 mm from anthesis to maturity)	Non-limiting N supply (23.6 g N m^{-2})	Récital	1999-11-10	2000-05-15
	18/10°C HS3[c]	HS	Fluctuating outside ambient temperature minus 5°C from 2 to 21 DAA (average temperature 10.10°C); and then moderate constant day/night temperature (18/10°C) until maturity with late-grain filling HS (2 days with 4 h at 38°C starting 30 DAA)	Well-watered (246 mm from anthesis to maturity)	Non-limiting N supply (23.6 g N m^{-2})	Récital	1999-11-10	2000-05-15
EXP2001[b]	18/10°C (CK)	CK	Moderate constant day/night temperature (18/10°C) between 1 DAA and maturity	Well-watered (211 mm from anthesis to maturity)	Non-limiting N supply (18.5 g N m^{-2})	Récital	2000-11-08	2001-05-14
	18/10°C HS1	HS	Moderate constant day/night temperature (18/10°C) between 1 DAA and maturity with early-grain filling HS (4 days with 4 h at 38°C and 20 °C for the rest of the day, starting 7 DAA)	Well-watered (210.5 mm from anthesis to maturity)	Non-limiting N supply (18.5 g N m^{-2})	Récital	2000-11-08	2001-05-14
	18/10°C HS2	HS	Moderate constant day/night temperature (18/10°C) between 1 DAA and maturity with mid-grain filling HS (4 days with 4 h at 38°C and 20 °C for the rest of the day, starting 18 DAA)	Well-watered (226 mm from anthesis to maturity)	Non-limiting N supply (18.5 g N m^{-2})	Récital	2000-11-06	2001-05-14
	18/10°C WD	WD	Moderate constant day/night temperature (18/10°C) between 1 DAA and maturity	Mid-grain filing water deficit (water withheld from 7 to 21 DAA; 137 mm from	Non-limiting N supply (15.5 g N m^{-2})	Récital	2000-11-08	2001-05-14

				anthesis to maturity)				
EXP2002	Récital (CK)	CK	Fluctuating outside ambient temperature during grain filling (average temperature 17.78°C)	Well-watered (185 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Récital	2001-11-08	2002-05-14
	Récital 28/15°C[b]	HT	High constant day and night temperature (28/15°C) between 3 DAA and maturity	Well-watered (218 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Récital	2001-11-08	2002-05-14
	Récital WD	WD	Fluctuating outside ambient temperature during grain filling (average temperature 16.96°C)	Post-anthesis water deficit (water withheld from 2 DAA to maturity; 91 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Récital	2001-11-08	2002-05-14
	Récital N0	LN	Fluctuating outside ambient temperature during grain filling (average temperature 17.92°C)	Well-watered (135 mm from anthesis to maturity)	Low N (no N fertilizer application after 19 February) (5 g N m^{-2})	Récital	2001-11-08	2002-05-14
	Arche (CK)	CK	Fluctuating outside ambient temperature during grain filling (average temperature 18.80°C)	Well-watered (165 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Arche	2001-11-08	2002-05-27
	Arche 28/15°C[b]	HT	High constant day and night temperature (28/15°C) between 4 DAA and maturity	Well-watered (197 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Arche	2001-11-08	2002-05-27
	Arche WD	WD	Fluctuating outside ambient temperature during grain filling (average temperature 18.45°C)	Post-anthesis water deficit (water withheld from –4 DAA to maturity; 56 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Arche	2001-11-08	2002-05-27
	Arche N0	LN	Fluctuating outside ambient	Well-watered	Low N (no N	Arche	2001-11-08	2002-05-27

			temperature during grain filling (average temperature 18.80°C)	(110 mm from anthesis to maturity)	fertilizer application after 19 February) (5 g N m^{-2})			
	Renan (CK)	CK	Fluctuating outside ambient temperature during grain filling (average temperature 18.03°C)	Well-watered (165 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Renan	2001-11-08	2002-05-21
	Renan 28/15°C[b]	HT	High constant day and night temperature (28/15°C) between 6 DAA and maturity	Well-watered (194 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Renan	2001-11-08	2002-05-21
	Renan WD	WD	Fluctuating outside ambient temperature during grain filling (average temperature 18.08°C)	Post-anthesis water deficit (water withheld from –5 DAA to maturity; 56 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Renan	2001-11-08	2002-05-21
	Renan N0	LN	Fluctuating outside ambient temperature during grain filling (average temperature 18.02°C)	Well-watered (110 mm from anthesis to maturity)	Low N (no N fertilizer application after 19 February) (5 g N m^{-2})	Renan	2001-11-08	2002-05-21
	Tamaro (CK)	CK	Fluctuating outside ambient temperature during grain filling (average temperature 19.50°C)	Well-watered (140 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Tamaro	2001-11-08	2002-05-30
	Tamaro 28/15°C[b]	HT	High constant day and night temperature (28/15°C) between 1 DAA and maturity	Well-watered (197 mm from anthesis to maturity)	Non-limiting N supply (30 g N m^{-2})	Tamaro	2001-11-08	2002-05-30
	Tamaro WD	WD	Fluctuating outside ambient temperature during grain filling (average temperature 18.85°C)	Post-anthesis water deficit (water withheld from –7 DAA to maturity; 46 mm from	Non-limiting N supply (30 g N m^{-2})	Tamaro	2001-11-08	2002-05-30

				anthesis to maturity)				
	Tamaro N0	LN	Fluctuating outside ambient temperature during grain filling (average temperature 18.20°C)	Well-watered (110 mm from anthesis to maturity)	Low N (no N fertilizer application after 19 February) (5 g N m^{-2})	Tamaro	2001-11-08	2002-05-30
EXP2007[b]	21/14°C (CK)	CK	Moderate constant day/night temperature (21/14°C) between 5 DAA and maturity	Well-watered (239 mm from anthesis to maturity)	Non-limiting N supply (20 g N m^{-2})	Récital	2006-11-07	2007-04-29
	21/14°C HS1	HS	Moderate constant day/night temperature (21/14°C) between 5 DAA and maturity with early-grain filling HS (4 days with 4 h at 38°C and 20 °C for the rest of the day, starting 8 DAA)	Well-watered (239 mm from anthesis to maturity)	Non-limiting N supply (20 g N m^{-2})	Récital	2006-11-07	2007-04-29
	21/14°C HS2	HS	Moderate constant day/night temperature (21/14°C) between 5 DAA and maturity with mid-grain filling HS (4 days with 4 h at 38°C and 20 °C for the rest of the day, starting 23 DAA)	Well-watered (239 mm from anthesis to maturity)	Non-limiting N supply (20 g N m^{-2})	Récital	2006-11-07	2007-04-29
	21/14°C HS12	HS	Moderate constant day/night temperature (21/14°C) between 5 DAA and maturity with early- and mid-grain filling HS (4 days with 4 h at 38°C and 20 °C for the rest of the day, starting 8 DAA and 23 DAA)	Well-watered (239 mm from anthesis to maturity)	Non-limiting N supply (20 g N m^{-2})	Récital	2006-11-07	2007-04-29
EXP2014[b]	21/15°C (CK)	CK	Moderate constant day/night temperature (21/15°C) between 3 DAA and maturity	Well-watered (264 mm from anthesis to maturity)	Non-limiting N supply (15 g N m^{-2})	SxB049	2014-03-06	2014-05-25
	22/20°C	HT	High constant night temperature (day/night 22/20°C) from 3 DAA to maturity	Well-watered (264 mm from anthesis to maturity)	Non-limiting N supply (15 g N m^{-2})	SxB049	2014-03-06	2014-05-25

	29/23°C→21/15°C	HT	High constant day/night temperature (29/23°C) from 3 to 12 DAA, and then moderate constant day/night temperature (21/15°C) until maturity	Well-watered (264 mm from anthesis to maturity)	Non-limiting N supply (15 g N m^{-2})	SxB049	2014-03-06	2014-05-25
	33/27°C→21/15°C	HT	Very high constant day/night temperature (33/27°C) from 3 to 12 DAA, and then moderate constant day/night temperature (21/15°C) until maturity	Well-watered (264 mm from anthesis to maturity)	Non-limiting N supply (15 g N m^{-2})	SxB049	2014-03-06	2014-05-25

[a] Maturity was defined as the end of the grain filling process, i.e., $t_{e.si}$ in Equation (1) for biomass.

[b] Before being transferred under the soil-plant-atmosphere-research facility (temperature control began), plants were grown under fluctuating outside ambient temperature after anthesis (Fig. 1).

[c] Plants were grown under 18/10°C for day/night temperature after being transferred under the soil-plant-atmosphere-research facility and before temperature targeted treatments began (Fig. 1).

[d] In this experiment, water was applied to maintain the soil moisture content near field capacity. Plants for '18/10°C' were watered twice weekly and received 22 L per week, and plants for '28/20°C' were watered three times per week and received 33 L per week

DAA, days after anthesis; CK, control; HT, elevated growth temperature; HS, Heat shock, LN, low N supply; LT, low temperature; WD, water deficit.

Protocol S1 SAS scripts for simultaneous estimation of post-anthesis source and sink parameters

```
TITLE 'The model for estimating source- and sink- parameters';

DATA A;
   INPUT Z1 Z2 T W;
   CARDS; * replace data below by your own data (here first two columns Z1=1 and
Z2=0 represents total mass while Z1=0 and Z2=1 represents grain mass, third
column is time while fourth column is either total or grain mass data)
1      0      3      1069.786667
1      0      8      1194.256667
1      0      14     1462.16
1      0      21     1729.326667
1      0      29     1943.263333
1      0      36     2025.856667
1      0      42     2110.513333
1      0      46     1978.386667
0      1      3      29.66333333
0      1      8      75.08666667
0      1      14     215.8733333
0      1      21     448.7566667
0      1      29     793.07
0      1      36     1009.666667
0      1      42     1078.48
0      1      46     1021.563333
;
PROC NLIN DATA=A METHOD=Gauss;
*PARMS line below is to set initial values of the parameters to be fitted;
PARMS WXO=2000 WBO=1000 TMO=20 TEO=40 WXI=1000 WBI=20 TMI=20 TEI=40;

TB = 0;
bounds TMO>0;
bounds TMI>0;

*The line below is to force source-sink balance (see eqn 12) if the * in front of
WXO is dropped. Then, WXO has to be removed from above PARMS line;
*WXO = (WXI-WBI)+WBO;

IF T<TB THEN DO;
MODEL W = Z1*WBO + Z2*WBI;
END;
ELSE DO;

IF T<(Z1*TEO+Z2*TEI) THEN DO;
 WO=(WXO-WBO)*T/(TEO**2)*((3*TEO-2*TMO)-(3*TEO-2*TMO-T)*(T/TEO)**(TEO/(TEO-
TMO)))+WBO;

 WI=(WXI-WBI)*(1+(TEI-T)/(TEI-TMI))*((T-TB)/(TEI-TB))**((TEI-TB)/(TEI-TMI))+WBI;
MODEL W = Z1*WO + Z2*WI;
END;
ELSE DO;
MODEL W = Z1*WXO + Z2*WXI;
END;
END;
 output out = b predicted = WP residual = res;
proc corr;
 var W WP;
proc print;
RUN;
```

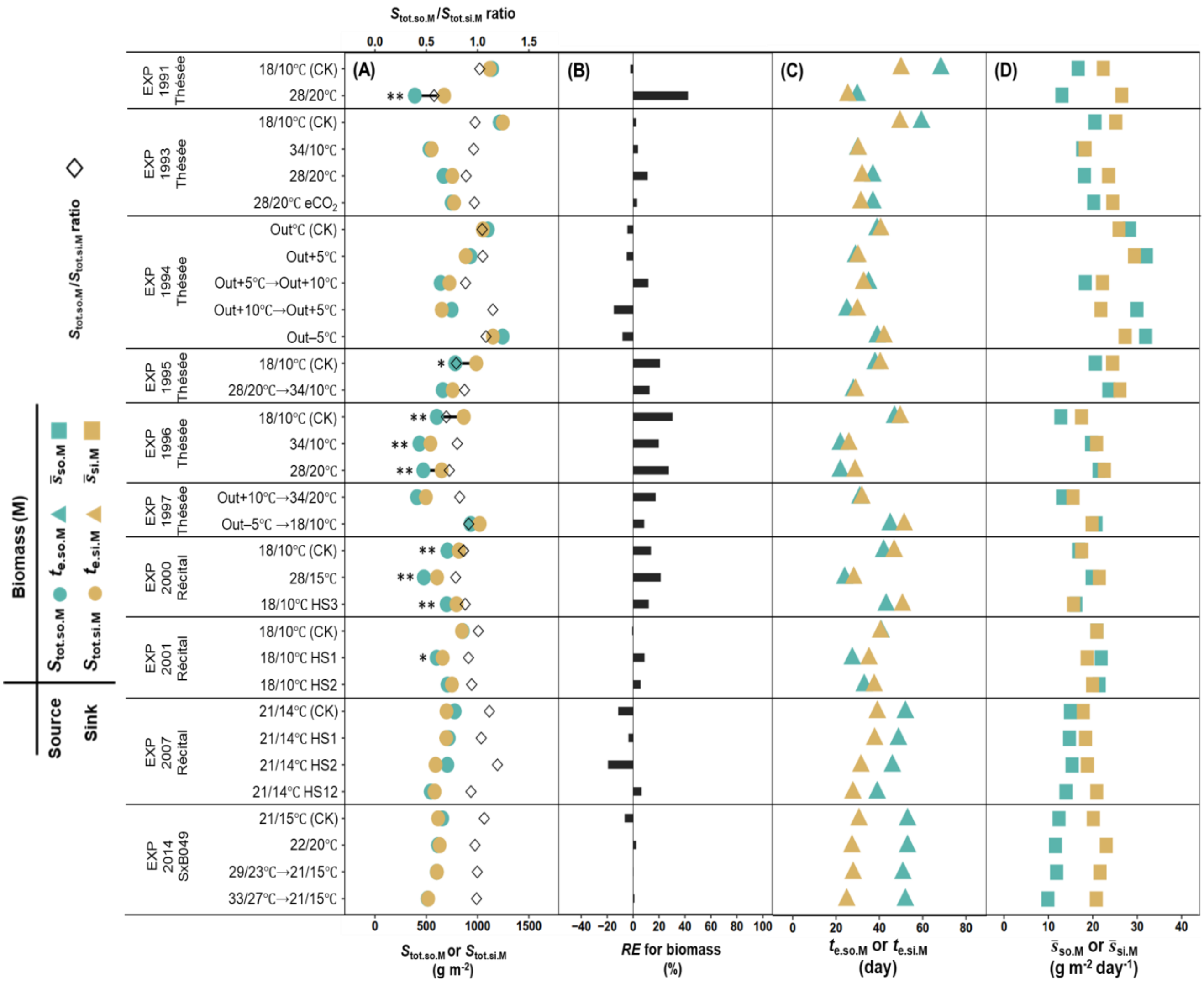

Figure S1. Estimated parameters of the source-sink model for biomass as affected by 'Temperature' factor. (A) Total source supply for biomass ($S_{tot.so.M}$) and sink demand for biomass ($S_{tot.si.M}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis biomass to final grain dry mass (RE for biomass). **(C)** Number of days after anthesis when the source activity for biomass decreases to zero ($t_{e.so.M}$) and when sink strength for biomass decreases to zero ($t_{e.si.M}$). **(D)** Mean source activity for biomass during the post-anthesis period ($\bar{s}_{so.M}$) and mean sink strength for biomass during the post-anthesis period ($\bar{s}_{si.M}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. * and ** indicate significant differences between source and sink at $P < 0.05$ and 0.01, respectively, according to F-tests. The negative value of RE in **(B)** means that the post-anthesis source supply has a surplus relative to sink demand; and its absolute value can be interpreted as the surplus that will add to the existing pre-anthesis accumulated reserves. Data are for the winter wheat genotypes Thésée and Récital and the spring wheat line SxB049 grown under various growth temperature regimes and exposed to different post-anthesis heat shock (HS) regimes. CK represents the control treatment in each experiment. HS1, HS2, HS12 and HS3 represent heat shocks during the early-grain filling period, during the mid-grain filling period, during both early- and mid- grain filling periods and during late-grain filling period, respectively. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

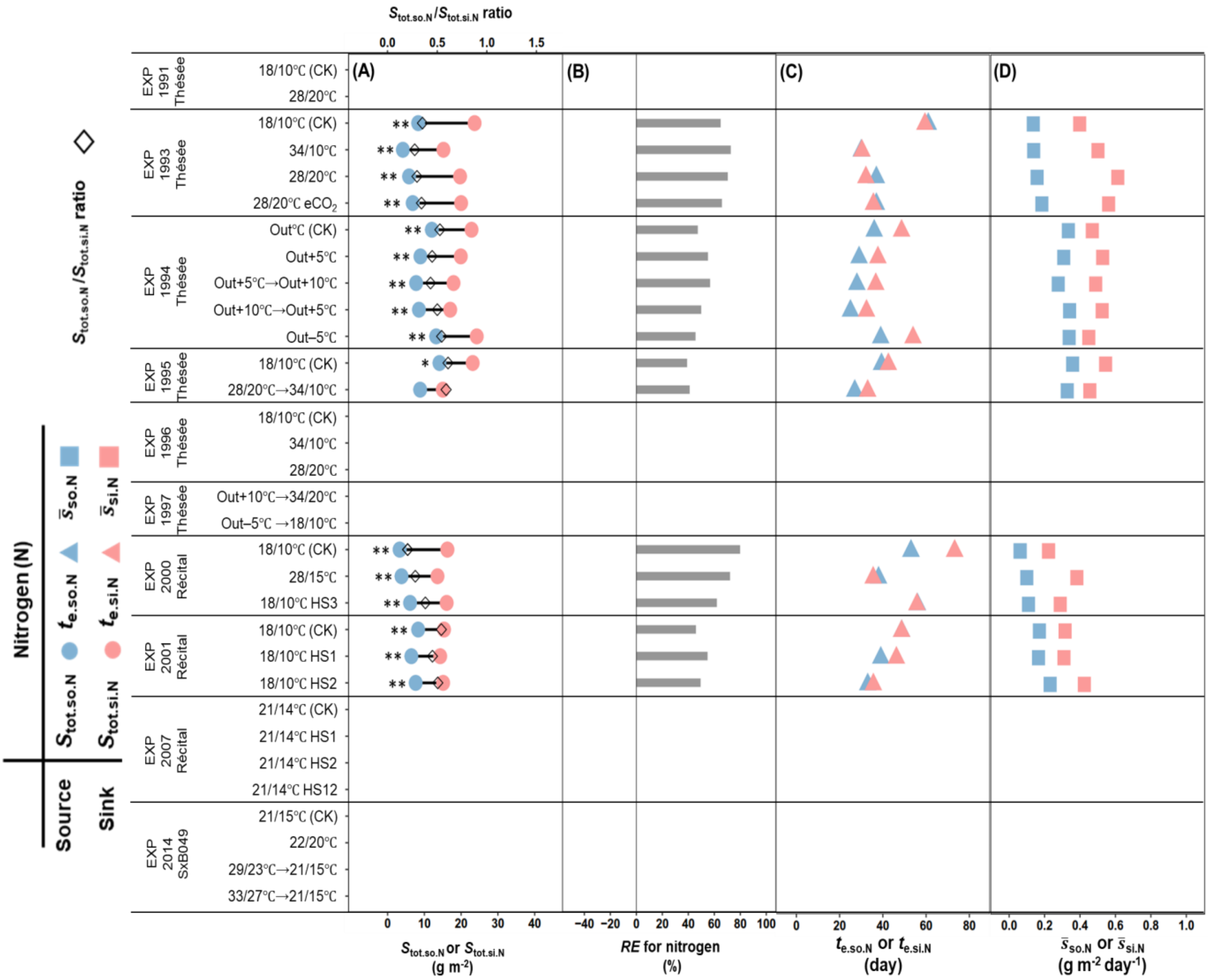

Figure S2. Estimated parameters of the source-sink model for nitrogen as affected by 'Temperature' factor. (A) Total source supply for nitrogen ($S_{tot.so.N}$) and sink demand for nitrogen ($S_{tot.si.N}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis nitrogen to final grain nitrogen (RE for nitrogen). **(C)** Number of days after anthesis when the source activity for nitrogen decreases to zero ($t_{e.so.N}$) and when sink strength for nitrogen decreases to zero ($t_{e.si.N}$). **(D)** Mean source activity for nitrogen during the post-anthesis period ($\bar{s}_{so.N}$) and mean sink strength for nitrogen during the post-anthesis period ($\bar{s}_{si.N}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. * and ** indicate significant differences between source and sink at $P < 0.05$ and 0.01, respectively, according to F-tests. There are missing values because source and sink nitrogen content was not determined in EXP1991, EXP1996, EXP1997, EXP2007 and EXP2014. Data are for the winter wheat genotypes Thésée and Récital and the spring wheat line SxB049 grown under various growth temperature regimes and exposed to different post-anthesis heat shock (HS) regimes. CK represents the control treatment in each experiment. HS1, HS2, HS12 and HS3 represent heat shocks during the early-grain filling period, during the mid-grain filling period, during both early- and mid- grain filling periods and during late-grain filling period, respectively. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

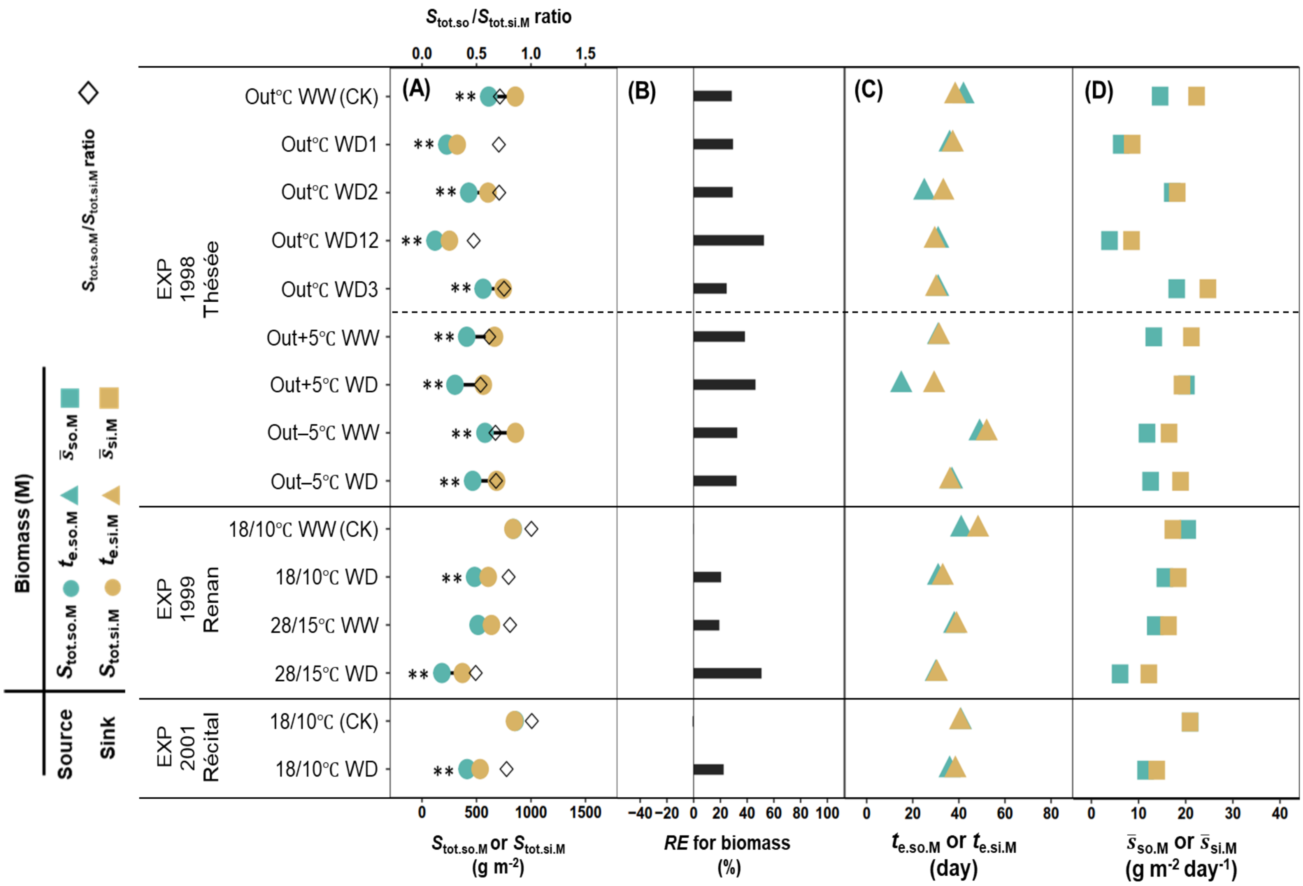

Figure S3. Estimated parameters of the source-sink model for biomass as affected by 'Water' factor. (A) Total source supply for biomass ($S_{tot.so.M}$) and sink demand for biomass ($S_{tot.si.M}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis biomass to final grain dry mass (RE for biomass). **(C)** Number of days after anthesis when the source activity for biomass decreases to zero ($t_{e.so.M}$) and when sink strength for biomass decreases to zero ($t_{e.si.M}$). **(D)** Mean source activity for biomass during the post-anthesis period ($\bar{s}_{so.M}$) and mean sink strength for biomass during the post-anthesis period ($\bar{s}_{si.M}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. * and ** indicate significant differences between source and sink at $P < 0.05$ and 0.01, respectively, according to *F*-tests. Data are for the winter wheat genotypes Thésée, Renan and Récital grown under different water supply regimes. CK, the control treatment in each experiment; WW, well-watered treatment; WD, water deficit stress. WD1, WD2, WD12 and WD3 represent water stress occurring during the pre-anthesis period, the post-anthesis period, both pre- and post-anthesis periods, and during the late-grain filling period, respectively. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

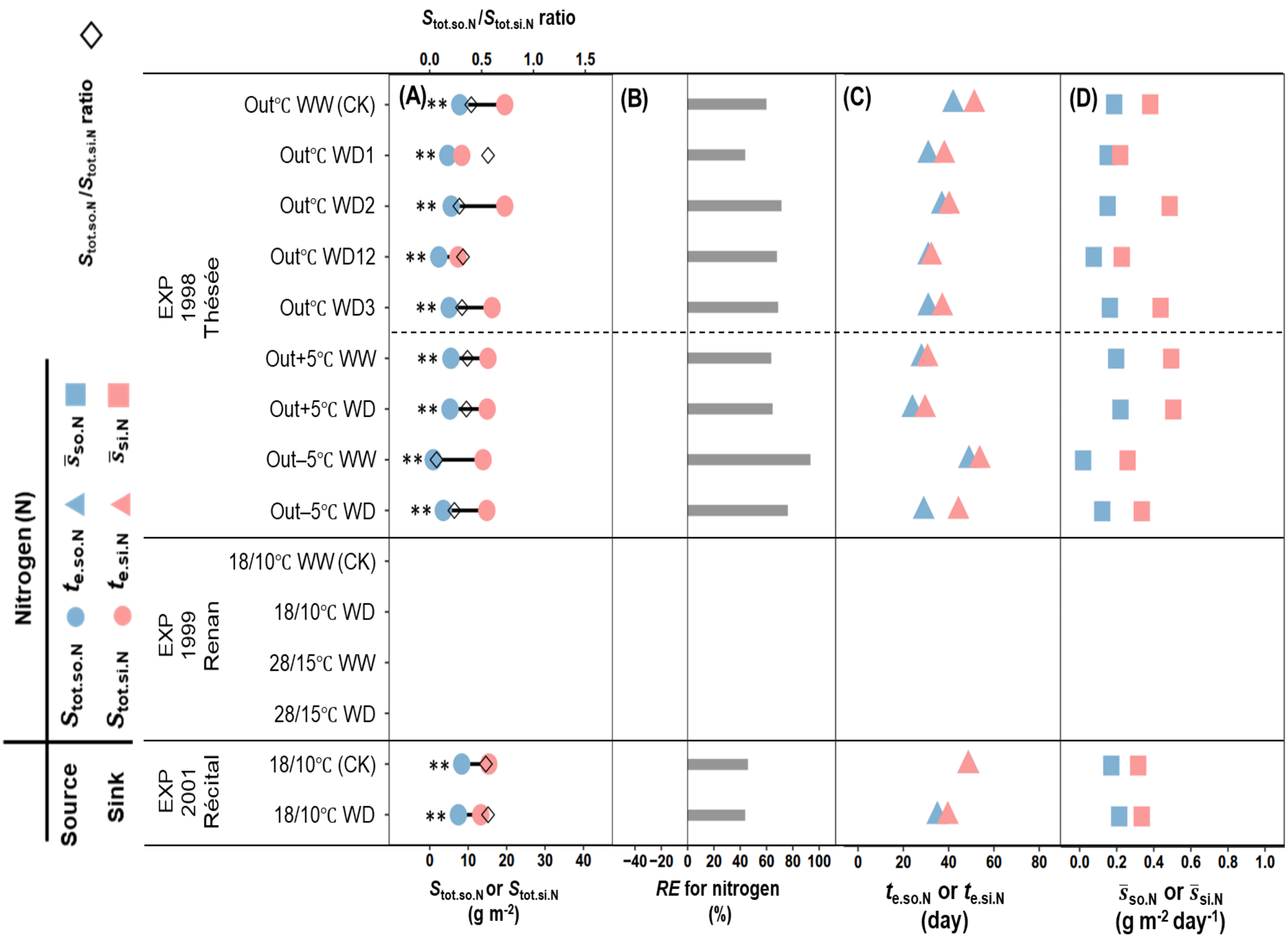

Figure S4. Estimated parameters of the source-sink model for nitrogen as affected by 'Water' factor. (A) Total source supply for nitrogen ($S_{tot.so.N}$) and sink demand for nitrogen ($S_{tot.si.N}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis nitrogen to final grain nitrogen (RE for nitrogen). **(C)** Number of days after anthesis when the source activity for nitrogen decreases to zero ($t_{e.so.N}$) and when sink strength for nitrogen decreases to zero ($t_{e.si.N}$). **(D)** Mean source activity for nitrogen during the post-anthesis period ($\bar{s}_{so.N}$) and mean sink strength for nitrogen during the post-anthesis period ($\bar{s}_{si.N}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. ** indicates significant differences between source and sink at $P < 0.05$ and 0.01, respectively, according to *F*-tests. There are missing values because source and sink nitrogen content was not determined in EXP1999. Data are for the winter wheat genotypes Thésée, Renan and Récital grown under different water supply regimes. CK, the control treatment in each experiment; WW, well-watered treatment; WD, water deficit stress. WD1, WD2, WD12 and WD3 represent water stress occurring during the pre-anthesis period, the post-anthesis period, both pre- and post-anthesis periods, and during the late-grain filling period, respectively. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

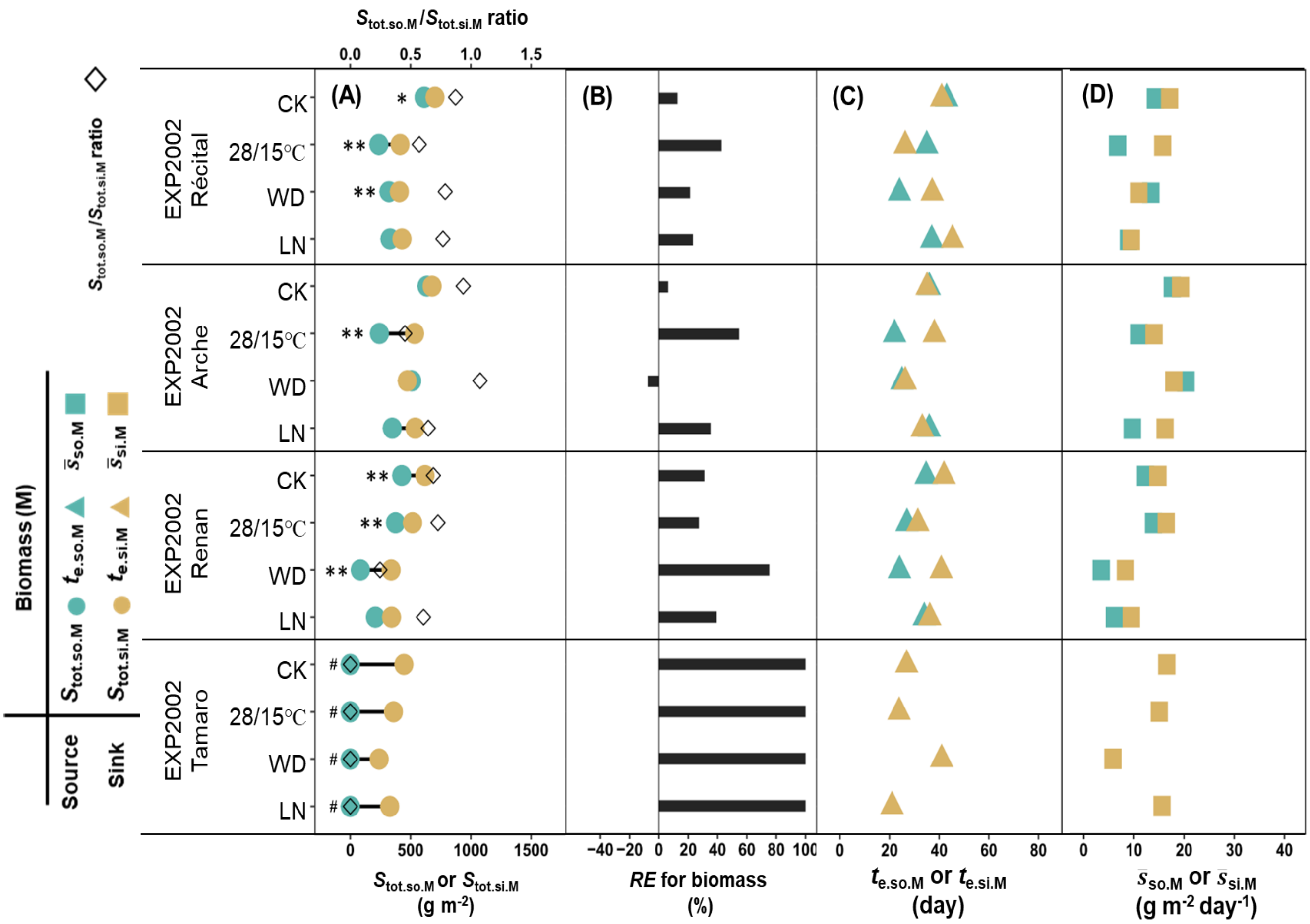

Figure S5. Estimated parameters of the source-sink model for biomass of different genotypes (Récital, Arche, Renan, and Tamaro). (A) Total source supply for biomass ($S_{tot.so.M}$) and sink demand for biomass ($S_{tot.si.M}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis biomass to final grain dry mass (RE for biomass). **(C)** Number of days after anthesis when the source activity for biomass decreases to zero ($t_{e.so.M}$) and when sink strength for biomass decreases to zero ($t_{e.si.M}$). **(D)** Mean source activity for biomass during the post-anthesis period ($\bar{s}_{so.M}$) and mean sink strength for biomass during the post-anthesis period ($\bar{s}_{si.M}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. * and ** indicate significant differences between source and sink at $P < 0.05$ and 0.01, respectively, according to F-tests. $^{\#}$ indicates that an F-test could not be performed as source supply was set to be zero because aboveground biomass increased initially but decreased during the later grain filling period and thus hardly accumulated over the whole post-anthesis period. The negative value of RE in **(B)** means that the post-anthesis source supply has a surplus relative to sink demand; and its absolute value can be interpreted as the surplus that will add to the existing pre-anthesis accumulated reserves. Data are for four winter wheat cultivars (Récital, Arche, Renan, and Tamaro) grown under heat, drought, and low nitrogen regimes. CK, the control treatment in each experiment; WD, water deficit stress; LN, low nitrogen supply. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

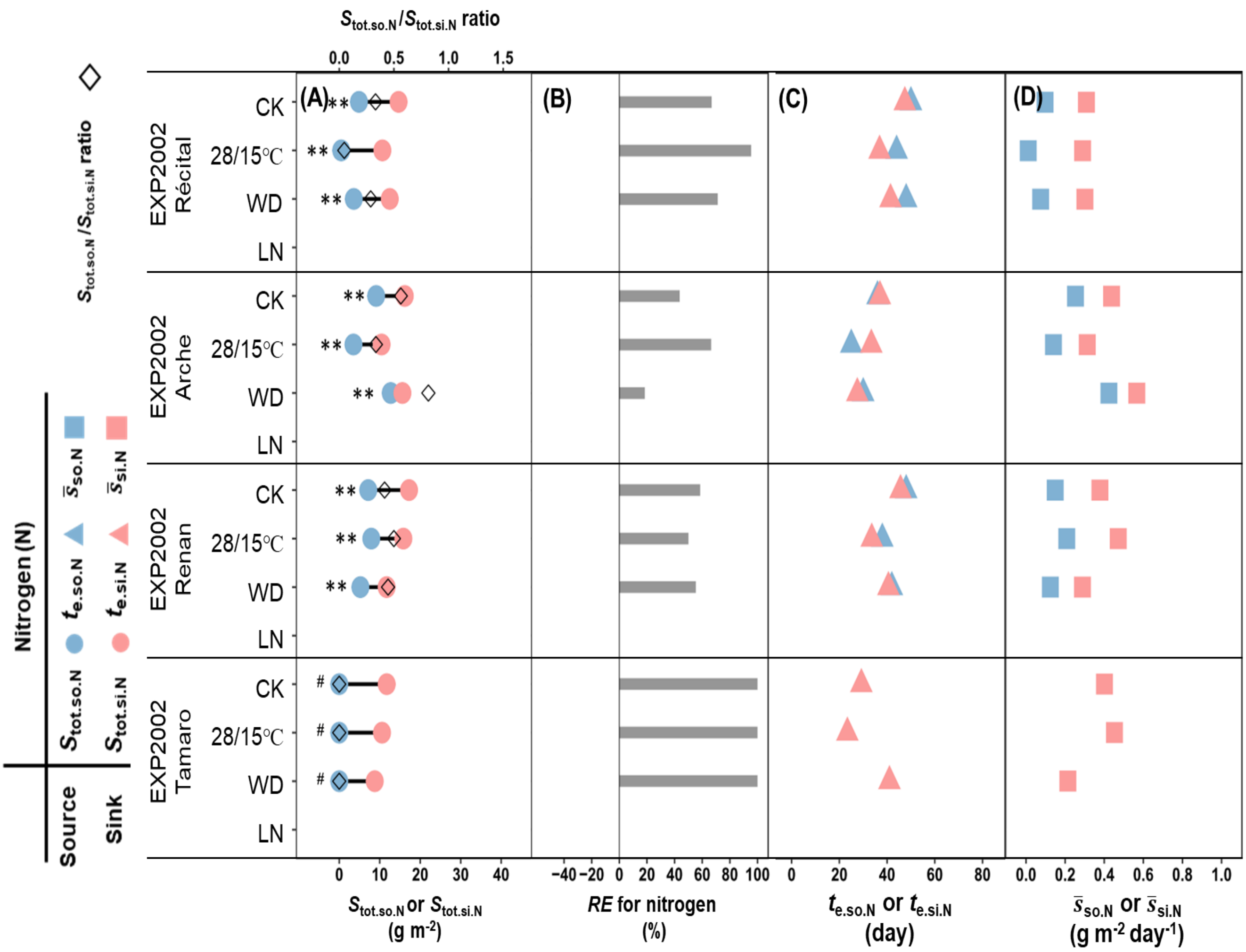

Figure S6. Estimated parameters of the source-sink model for nitrogen for different genotypes (Récital, Arche, Renan, and Tamaro). (A) Total source supply for nitrogen ($S_{tot.so.N}$) and sink demand for nitrogen ($S_{tot.si.N}$), and their ratios during the post-anthesis period. **(B)** Contribution of pre-anthesis nitrogen to final grain nitrogen (RE for nitrogen). **(C)** Number of days after anthesis when the source activity for nitrogen decreases to zero ($t_{e.so.N}$) and when sink strength for nitrogen decreases to zero ($t_{e.si.N}$). **(D)** Mean source activity for nitrogen during the post-anthesis period ($\bar{s}_{so.N}$) and mean sink strength for nitrogen during the post-anthesis period ($\bar{s}_{si.N}$). In **(A)**, the horizontal bars between source and sink data points indicate the source-sink difference. ** indicates significant differences between source and sink at $P < 0.01$, according to *F*-tests. # indicates that an *F*-test could not be performed as source supply was set to be zero because aboveground nitrogen hardly accumulated over the whole post-anthesis period. There are missing values because source and sink nitrogen content was not determined for the LN treatments. Data are for four winter wheat cultivars (Récital, Arche, Renan, and Tamaro) grown under heat, drought, and low nitrogen regimes. CK, the control treatment in each experiment; WD, water deficit stress; LN, low nitrogen supply. Treatment details and codes for experiments and treatments listed in the left are given in Table S1.

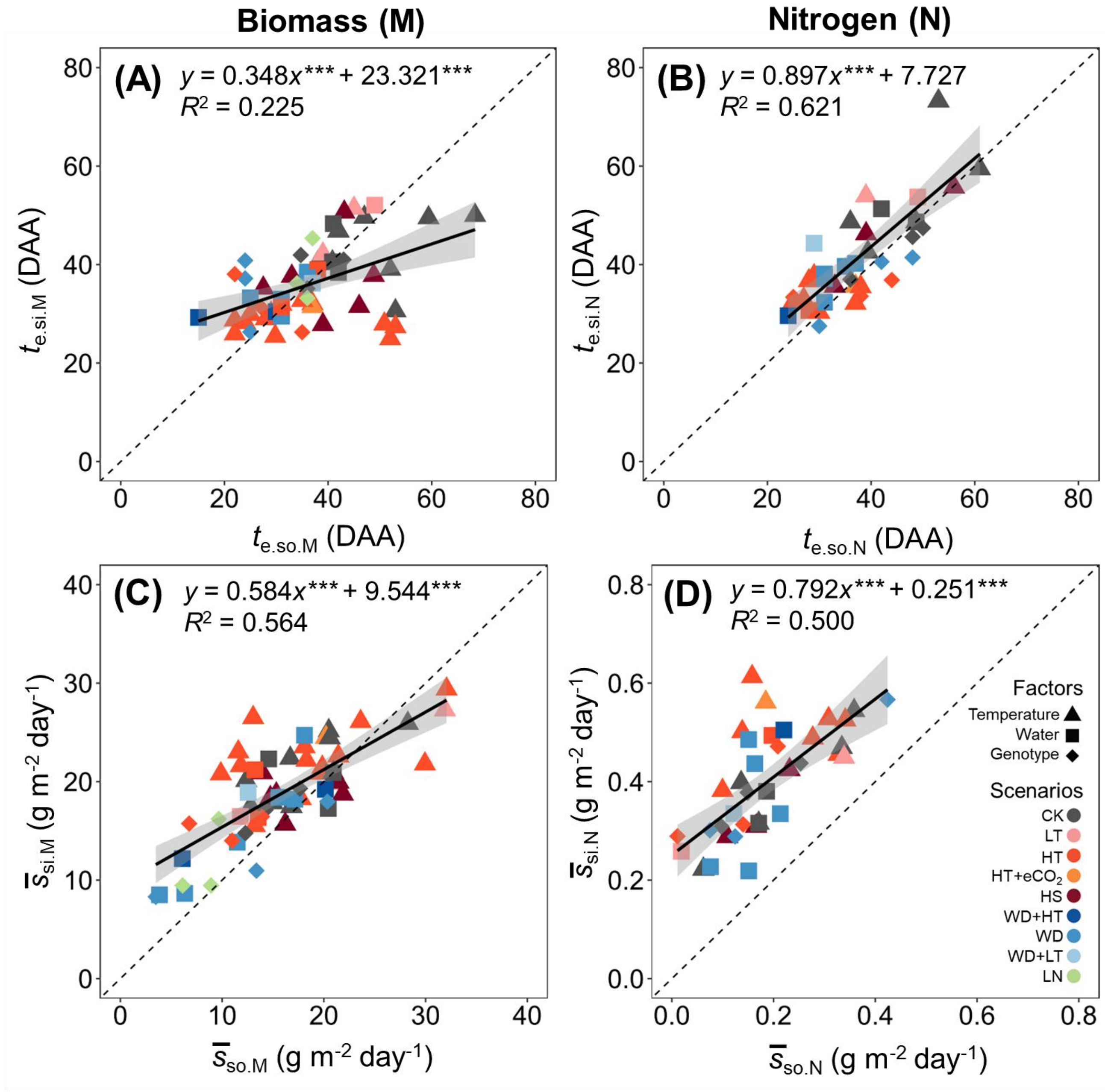

Figure S7. Relationships between post-anthesis source and sink components for wheat genotypes grown under different heat, drought, and nitrogen supply regimes. (A) Correlation between number of days after anthesis when the source activity for biomass decreases to zero ($t_{e.so.M}$) and when sink strength for biomass decreases to zero ($t_{e.si.M}$). **(B)** Correlation between number of days after anthesis when the source activity for nitrogen decreases to zero ($t_{e.so.N}$) and when sink strength for nitrogen decreases to zero ($t_{e.si.N}$). **(C)** Correlation between mean source activity for biomass during the post-anthesis period ($\bar{s}_{so.M}$) and mean sink strength for biomass during the post-anthesis period ($\bar{s}_{si.M}$). **(D)** Correlation between mean source activity for nitrogen during the post-anthesis period ($\bar{s}_{so.N}$) and mean sink strength for nitrogen during the post-anthesis period ($\bar{s}_{si.N}$). Dashed lines are the 1:1 relationship. *** indicates significant difference at $P < 0.001$. The shaded area depicts the 95% confidence interval of the predictions. Data are for factors of 'Temperature' (long-term temperature changes and short-term heat shocks regimes; Fig. S2), 'Water' (different water supply regimes; Fig. S4), and 'Genotype' (the four winter wheat genotypes Thésée, Récital, Renan, Arche and Tamaro grown under heat, drought, and nitrogen supply regimes; Fig. S6). CK, control treatment; LT, low growth temperature (Out−5°C); HT, high growth temperature; eCO_2, elevated atmospheric CO_2; HS, heat shock; WD, water deficit stress and LN, low nitrogen supply.

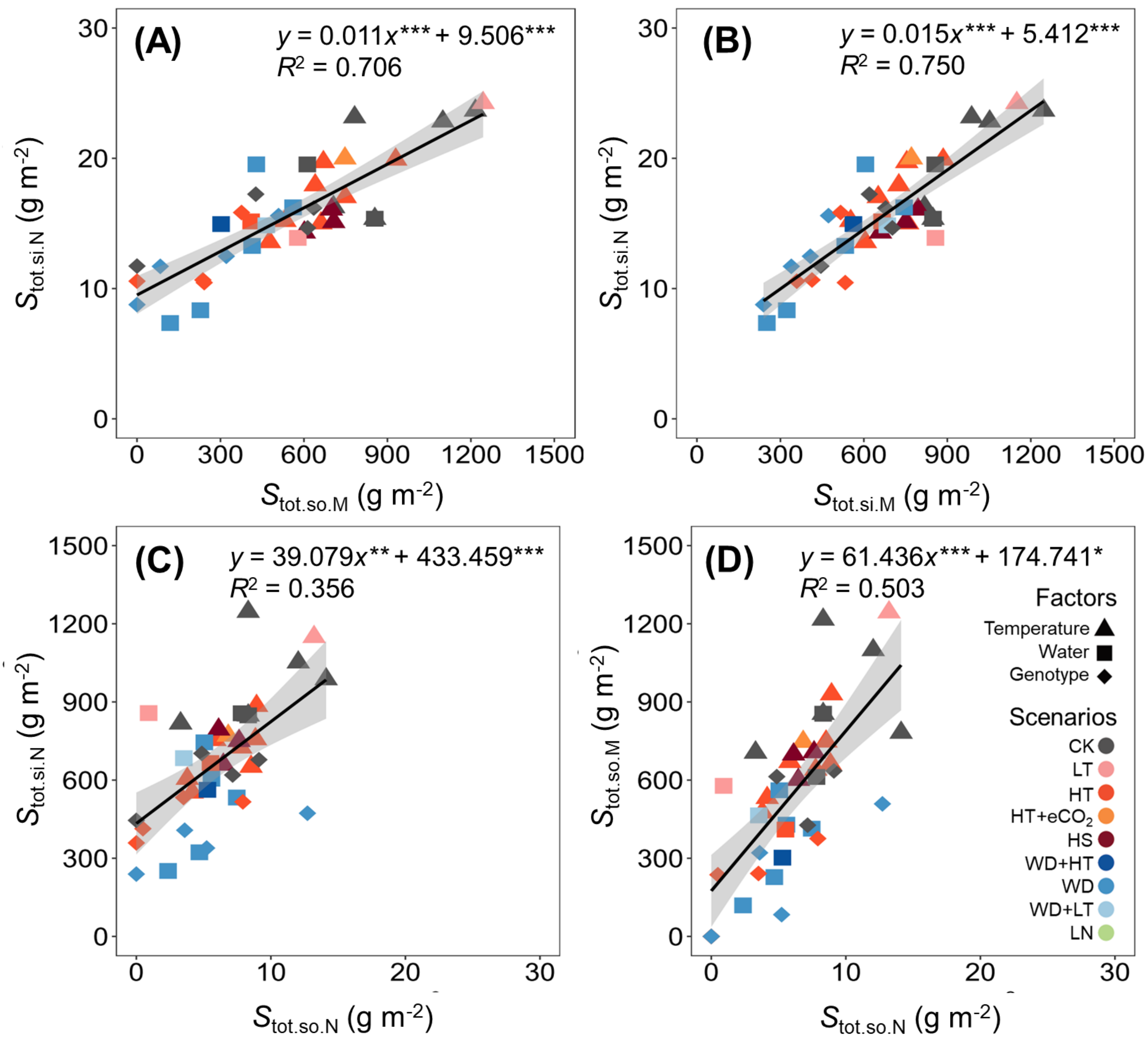

Figure S8. Relationships among post-anthesis total source supply for biomass ($S_{tot.so.M}$) and nitrogen ($S_{tot.so.N}$), and grain sink demand for biomass ($S_{tot.si.M}$) and nitrogen ($S_{tot.si.N}$). Data are for factors of 'Temperature' (long-term temperature changes and short-term heat shocks regimes; Fig. S1), 'Water' (different water supply regimes; Fig. S3), and 'Genotype' (the four winter wheat genotypes Thésée, Récital, Renan, Arche and Tamaro grown under heat, drought, and nitrogen supply regimes; Fig. S5). CK, control treatment; LT, low growth temperature (Out−5°C); HT, high growth temperature; eCO_2, elevated atmospheric CO_2; HS, heat shock; and LN, low nitrogen supply. Solid lines are linear regression (*, ** and *** indicate the significance of the slope and intercepts of the linear regressions at $P < 0.05$, 0.01 and 0.001, respectively). The shaded area indicates the 95% confidence interval of the predictions. CK, control treatment; LT, low growth temperature (Out−5°C); HT, high growth temperature; eCO_2, elevated atmospheric CO_2; HS, heat shock; WD, water deficit stress and LN, low nitrogen supply.

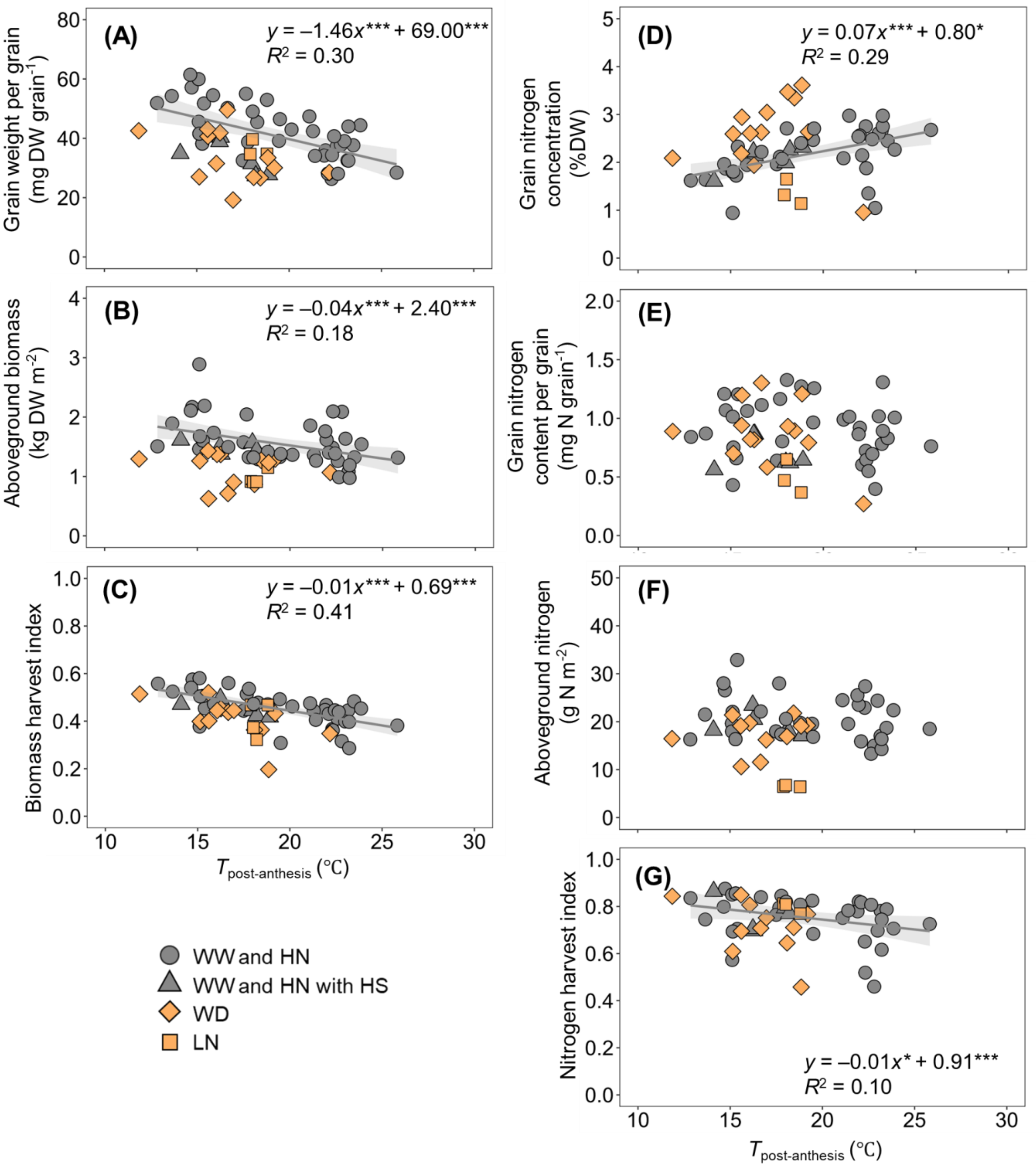

Figure S9. Temperature responses of yield and production traits for either biomass or nitrogen. (A-C) Temperature responses of grain weight per grain, aboveground shoot biomass and harvest index for biomass at maturity. **(D-G)** Temperature responses of grain nitrogen concentration, grain nitrogen content per grain, aboveground shoot nitrogen content and harvest index for nitrogen at maturity. Lines are linear regression fitted to the data for the well water and high nitrogen supply regimes and are shown only when significant at $P = 0.05$. * and *** indicate statistical significance at $P < 0.05$ and 0.001, respectively. The shaded area depicts the 95% confidence interval of the predictions. WW, well-watered; WD, water deficit; HN, non-limiting nitrogen; LN, low nitrogen supply; HS, heat shock.