Article

Plant–soil feedback effects on conspecific and heterospecific successors of annual and perennial Central European grassland plants are correlated

In the format provided by the authors and unedited

Supplementary information

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Supplementary Table 1: List of 18 annual and perennial native plant species used in the presented study. Asterisks (*) indicate species that occur at the soil-collection site or in the direct surroundings of the soil-collection site (Botanical Garden, University of Konstanz; personal observation).

Annual species	Perennial species	Family
Sonchus oleraceus L.*	*Cichorium intybus* L.*	Asteraceae
Centaurea cyanus L.	*Centaurea jacea* L.*	Asteraceae
Anchusa arvensis (L.) M.Bieb.	*Anchusa officinalis* L.	Boraginaceae
Sinapis arvensis L.*	*Diplotaxis tenuifolia* (L.) DC.	Brassicaceae
Agrostemma githago L.	*Cerastium fontanum* Baumg.*	Caryophyllaceae
Vicia sativa L.*	*Vicia cracca* L.*	Fabaceae
Trifolium campestre Schreb.	*Trifolium medium* L.*	Fabaceae
Lamium purpureum L.*	*Prunella vulgaris* L.*	Lamiaceae
Clinopodium acinos (L.) Kuntze	*Salvia pratensis* L.*	Lamiaceae

Supplementary Table 2: Results of the linear mixed model for main and interactive effects of conditioning and responding plant group (annual vs. perennial) on plant-soil-feedback responses (PSF = ln(total biomass$_{conditioned}$/total biomass$_{control}$)). Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Fixed effects	X^2	df	P
Responding group	**4.34**	**1**	**0.037**
Conditioning group	0.33	1	0.566
Responding group*Conditioning group	0.32	1	0.575
log(Biomass phase 1)	0.64	1	0.424
Initial size difference	**42.48**	**1**	**<0.001**
Random effects	s.d.		
Block	0.073		
Soil mix	0.002		
Conditioning species	0.122		
Conditioning family	0.049		
Responding family	0.189		
Responding species			
Agrostemma githago	0.163		
Anchusa arvensis	0.110		
Anchusa officinalis	0.161		
Centaurea cyanus	0.145		
Centaurea jacea	0.121		
Cerastium fontanum	0.143		
Cichorium intybus	0.101		
Clinopodium acinos	0.131		
Diplotaxis tenuifolia	0.131		
Lamium purpureum	0.169		
Prunella vulgaris	0.175		
Salvia pratensis	0.101		
Sinapis arvensis	0.109		
Sonchus oleraceus	0.205		
Trifolium camprestre	0.183		
Trifolium medium	0.215		
Vicia cracca	0.223		
Vicia sativa	0.113		

Supplementary Table 3: Results of the linear mixed model for main and interactive effects of conditioning treatments (1: conspecific vs. heterospecific conditioning; 2: heterospecific conditioning by annuals vs. perennials) and responding plant group (annual vs. perennial) on plant-soil-feedback responses (PSF = ln(total biomass$_{conditioned}$/total biomass$_{control}$)). Significant effects ($p < 0.05$), as indicated by Log-likelihood ratio test, are indicated in bold.

Fixed effects	X^2	df	P
Responding group	**4.29**	**1**	**0.038**
Conditioning$_{conspecific/heterospecific}$	0.17	1	0.681
Heterospecific conditioning$_{annual/perennial}$	0.28	1	0.594
Responding group*Conditioning$_{conspecific/heterospecific}$	0.43	1	0.511
Responding group*Heterospecific conditioning$_{annual/perennial}$	0.22	1	0.641
log(Biomass phase 1)	0.65	1	0.422
Initial size difference	**42.34**	**1**	**<0.001**
Random effects	**s.d.**		
Block	0.073		
Soil mix	0.002		
Conditioning species	0.122		
Conditioning family	0.049		
Responding family	0.189		
Responding species			
Agrostemma githago	0.163		
Anchusa arvensis	0.110		
Anchusa officinalis	0.161		
Centaurea cyanus	0.145		
Centaurea jacea	0.121		
Cerastium fontanum	0.143		
Cichorium intybus	0.101		
Clinopodium acinos	0.131		
Diplotaxis tenuifolia	0.131		
Lamium purpureum	0.169		
Prunella vulgaris	0.175		
Salvia pratensis	0.101		
Sinapis arvensis	0.110		
Sonchus oleraceus	0.205		
Trifolium camprestre	0.183		
Trifolium medium	0.215		
Vicia cracca	0.223		
Vicia sativa	0.113		

Supplementary Table 4: Results of the linear mixed model for main and interactive effects of conditioning and responding plant species on plant-soil-feedback responses (PSF = ln(total biomass$_{conditioned}$/total biomass$_{control}$)). Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Fixed effects	X^2	df	p
Responding species	**369.97**	**17**	**<0.001**
Conditioning species	**93.41**	**17**	**<0.001**
Responding species*Conditioning species	220.28	289	0.999
log(Biomass phase 1)	0.1	1	0.760
Initial size difference	**9.69**	**1**	**0.002**
Random effects	**s.d.**		
Block	0.085		
Soil mix	<0.000		

Supplementary Table 5: Results of the linear mixed model for the main effect of plant group (annual vs. perennial) on structural root traits 'specific root length', 'relative root weight' and 'average root diameter'. Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Model part	Factor	log(Specific root length)			sqrt(Relative root weight)			Average root diameter		
		X^2	df	P	X^2	df	P	X^2	df	P
Fixed	Group	**12.21**	**1**	**<0.001**	**8.26**	**1**	**0.004**	**4.05**	**1**	**0.044**
Random		**s.d.**			**s.d.**			**s.d.**		
	Species	0.50			0.12			0.71		

Supplementary Table 6: Results of general linear models assessing the effects of two structural root traits, specific root length (upper part) and relative root weight (lower part), the life history of the responding plant group (annual vs. perennial) and the two-way interactions on plant-soil feedback responses of 18 plant species (see Methods). Significant effects (p < 0.05), as indicated by F-tests, are indicated in bold and marginally significant results (0.05 < p < 0.10) are indicated in italics.

	Average PSF response		
	F	df	P
log(SRL)	*3.55*	*1*	*0.081*
Responding plant group (R)	0.01	1	0.936
log(SRL)*R	0.02	1	0.885
	F	df	P
sqrt(RRW)	**6.28**	**1**	**0.025**
Responding plant group (R)	0.01	1	0.917
sqrt(RRW)*R	0.03	1	0.876

Supplementary Table 7: Results of the linear mixed model for the main effects of NMDS-axes representing community composition of 1) complete fungal communities, 2) putative pathogen communities and 3) arbuscular mycorrhizal fungal communities on average plant-soil-feedback responses in soils conditioned by 18 different annual and perennial plant species. Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold and marginally significant results (0.05 < p < 0.10) are indicated in italics.

Model part	Factor	*Full community* X^2	df	P	*Putative Pathogens* X^2	df	P	*AMF* X^2	df	P
Fixed	NMDS1	1.74	1	0.187	2.10	1	0.147	<0.001	1	0.987
	NMDS2	**8.28**	**1**	**0.004**	*3.62*	*1*	*0.057*	0.083	1	0.773
	NMDS3	1.16	1	0.281	1.07	1	0.301	0.326	1	0.568
Random		s.d.			s.d.			s.d.		
	Block	0.09			0.08			0.08		

Supplementary Table 8: Results of the linear mixed model for the main effects of NMDS-axes representing community composition on average plant-soil-feedback responses in soils conditioned by 18 different annual and perennial plant species, considering the effect of whether soils were conditioned by legumes (yes/no). Analyses were run separately for 1) complete fungal communities, 2) putative pathogen communities or 3) arbuscular mycorrhizal fungal (AMF) communities. Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Model part	Factor	*Full community* X^2	df	P	*Putative pathogens* X^2	df	P	*AMF* X^2	df	P
Fixed	NMDS1	1.09	1	0.297	0.40	1	0.528	1.13	1	0.288
	NMDS2	1.45	1	0.228	0.19	1	0.660	0.13	1	0.714
	NMDS3	0.63	1	0.428	1.93	1	0.165	0.36	1	0.550
	Legume (L)	**8.36**	**1**	**0.004**	**14.29**	**1**	**<0.001**	**17.76**	**1**	**<0.001**
	NMDS1*L	0.33	1	0.564	0.22	1	0.645	0.01	1	0.910
	NMDS2*L	0.57	1	0.450	0.06	1	0.810	0.51	1	0.475
	NMDS3*L	0.72	1	0.395	1.23	1	0.267	0.02	1	0.881
Random		s.d.			s.d.			s.d.		
	Block	0.08			0.08			0.08		

Supplementary Table 9: Plant group (annual vs. perennial) effects on logit-transformed relative abundances of all putative pathogens and on logit-transformed relative abundances of putative generalist and specialist putative pathogens (see methods). Significant effects (p < 0.05) are indicated in bold and marginally significant results (0.05 < p < 0.10), as indicated by Log-likelihood ratio test, are indicated in italics.

Model part	Factor	*All pathogens*			*Generalist pathogens*			*Specialist pathogens*		
		X^2	df	P	X^2	df	P	X^2	df	P
Fixed	Group	0.97	1	0.326	0.73	1	0.392	*3.65*	*1*	*0.056*
	Read number	0.07	1	0.790	0.03	1	0.869	**23.92**	**1**	**<0.001**
Random		**s.d.**			**s.d.**			**s.d.**		
	Plant family	1.97			1.91			1.50		
	Block	0.15			0.15			0.10		
	Plant species									
	Agrostemma githago	0.59			0.31			0.11		
	Anchusa arvensis	0.38			0.19			0.03		
	Anchusa officinalis	0.35			0.17			0.10		
	Centaurea cyanus	0.29			0.15			0.10		
	Centaurea jacea	0.28			0.20			0.16		
	Cerastium fontanum	1.12			0.57			0.05		
	Cichorium intybus	0.51			0.26			0.10		
	Clinopodium acinos	0.15			0.06			0.08		
	Diplotaxis tenuifolia	0.68			0.34			0.04		
	Lamium purpureum	0.29			0.15			0.03		
	Prunella vulgaris	0.04			0.03			0.08		
	Salvia pratensis	1.07			0.53			0.14		
	Sinapis arvensis	0.24			0.16			0.08		
	Sonchus oleraceus	0.24			0.12			0.09		
	Trifolium camprestre	0.14			0.08			0.08		
	Trifolium medium	0.87			0.47			0.00		
	Vicia cracca	0.66			0.34			0.08		
	Vicia sativa	0.24			0.11			0.08		

Supplementary Table 10: Plant group (annual vs. perennial) effects on logit-transformed relative abundances of all arbuscular mycorrhizal fungi (AMF) and on logit-transformed relative abundances of generalist and specialist AMF (see methods). Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Model part	Factor	All AMF X^2	df	P	Generalist AMF X^2	df	P	Specialist AMF X^2	df	P
Fixed	Group	1.03	1	0.310	0.62	1	0.429	0.17	1	0.689
	Read number	1.27	1	0.259	0.57	1	0.451	**6.47**	**1**	**0.011**
Random		**s.d.**			**s.d.**			**s.d.**		
	Plant family	1.23			1.09			1.10		
	Block	0.88			0.65			0.89		
	Plant species									
	Agrostemma githago	<0.000			<0.000			<0.000		
	Anchusa arvensis	<0.000			<0.000			<0.000		
	Anchusa officinalis	<0.000			<0.000			<0.000		
	Centaurea cyanus	<0.000			<0.000			<0.000		
	Centaurea jacea	<0.000			<0.000			<0.000		
	Cerastium fontanum	<0.000			<0.000			<0.000		
	Cichorium intybus	<0.000			<0.000			<0.000		
	Clinopodium acinos	<0.000			<0.000			<0.000		
	Diplotaxis tenuifolia	<0.000			<0.000			<0.000		
	Lamium purpureum	<0.000			<0.000			<0.000		
	Prunella vulgaris	<0.000			<0.000			<0.000		
	Salvia pratensis	<0.000			<0.000			<0.000		
	Sinapis arvensis	<0.000			<0.000			<0.000		
	Sonchus oleraceus	<0.000			<0.000			<0.000		
	Trifolium camprestre	<0.000			<0.000			<0.000		
	Trifolium medium	<0.000			<0.000			<0.000		
	Vicia cracca	<0.000			<0.000			<0.000		
	Vicia sativa	<0.000			0.001			<0.000		

Supplementary Table 11: Plant-species-identity effects on logit-transformed total relative abundances of putative pathogens and AMF, and logit-transformed relative abundances of generalist and specialist putative pathogens and AMF (see methods). Significant effects (p < 0.05), as indicated by Log-likelihood ratio test, are indicated in bold.

Model part	Factor	All pathogens X^2	df	P	Generalist pathogens X^2	df	P	Specialist pathogens X^2	df	P
Fixed	Plant species	**314.47**	**17**	**<0.001**	**287.76**	**17**	**<0.001**	**67.35**	**17**	**<0.001**
	Read number	0.12	1	0.726	0.05	1	0.824	0.19	1	0.662
Random		**s.d.**			**s.d.**			**s.d.**		
	Block	0.00			0.00			0.00		

Model part	Factor	All AMF X^2	df	P	Generalist AMF X^2	df	P	Specialist AMF X^2	df	P
Fixed	Plant species	**61.23**	**17**	**<0.001**	**76.42**	**17**	**<0.001**	**46.86**	**17**	**<0.001**
	Read number	1.03	1	0.311	0.38	1	0.540	1.86	1	0.173
Random		**s.d.**			**s.d.**			**s.d.**		
	Block	0.00			0.00			0.28		

Supplementary Table 12: Effects of (logit-transformed) total, generalist and specialist pathogen and arbuscular mycorrhizal abundances on average plant-soil-feedback responses. Significant effects ($p < 0.05$), as indicated by Log-likelihood ratio test, are indicated in bold.

Model	Fixed effect: relative abundance			Random effect: block
	X^2	df	P	s.d.
All pathogens	**4.83**	**1**	**0.028**	0.08
Generalist pathogens	**4.94**	**1**	**0.026**	0.08
Specialist pathogens	0.48	1	0.490	0.07
All AMF	0.48	1	0.676	0.08
Generalist AMF	0.24	1	0.624	0.08
Specialist AMF	0.01	1	0.903	0.07

Supplementary Table 13: Effects of (logit-transformed) total and generalist pathogen abundances on average plant-soil-feedback responses, considering the effect of whether soils were conditioned by legumes (yes/no). Significant effects ($p < 0.05$), as indicated by Log-likelihood ratio test, are indicated in bold.

Model part	Factor	*Pathogens*			*Generalist pathogens*		
		X^2	df	P	X^2	df	P
Fixed	Relative abundance (R)	1.09	1	0.296	1.13	1	0.288
	Legume conditioning (L)	**15.51**	**1**	**<0.001**	**15.42**	**1**	**<0.001**
	R*L	1.08	1	0.299	1.00	1	0.318
Random		s.d.			s.d.		
	Block	0.08			0.08		

Supplementary Table 14: Taxonomic identity of the 20 most prevalent putative pathogenic ASVs in plant-conditioned soils, based on maximum relative abundance in single samples. Columns 'Plant species' and 'Samples' indicate the number of conditioning species and conditioned soil samples in which ASVs where detected (total number of samples = 87), while average and maximum abundance indicate the average ASV abundance across all samples, and maximum ASV abundance in a single sample, respectively. Asterisks (*) indicate ASVs that are considered as host-generalists in our study, based on their occurrence in at least 2/3 (i.e. 12) of the plant species. Species ordering is based on average abundance across samples.

ID	Family	Genus	Species	Plant species	Samples	Average abundance (%)	Maximum abundance (%)
ASV2	Pleosporaceae	*Bipolaris*	*sp.*	18*	49	4.81	92.06
ASV3	Pleosporaceae	*Bipolaris*	*sp.*	16*	36	3.88	83.54
ASV13	Sarcoscyphaceae	*Pithya*	*sp.*	15*	46	1.06	35.95
ASV18	Mycosphaerellaceae	*Mycocentrospora*	*sp.*	18*	37	0.67	42.90
ASV36	Plectosphaerellaceae	*Gibellulopsis*	*piscis*	18*	87	0.45	4.33
ASV40	Sarcoscyphaceae	*Pithya*	*sp.*	15*	46	0.44	12.89
ASV59	Bionectriaceae	*Clonostachys*	*rosea*	18*	84	0.24	4.93
ASV65	Pleosporaceae	*Bipolaris*	*sp.*	8	20	0.20	8.80
ASV103	Nectriaceae	*Cylindrocarpon*	*sp.*	18*	81	0.11	2.38
ASV111	Olpidiaceae	*Olpidium*	*brassicae*	18*	41	0.10	3.19
ASV114	Pleosporaceae	*Bipolaris*	*sp.*	9	23	0.10	4.54
ASV154	Nectriaceae	*Gibberella*	*intricans*	18*	78	0.07	0.73
ASV167	Nectriaceae	*Cylindrocarpon*	*sp.*	18*	80	0.06	1.00
ASV171	Mycosphaerellaceae	*Mycosphaerella*	*tassiana*	18*	82	0.06	2.07
ASV231	Pleosporaceae	*Bipolaris*	*sp.*	5	15	0.04	3.26
ASV260	Pleosporaceae	*Curvularia*	*sp.*	18*	69	0.03	0.81
ASV282	Magnaporthaceae	*Magnaporthiopsis*	*sp.*	15*	33	0.03	1.68
ASV415	Physodermataceae	*Paraphysoderma*	*sp.*	16*	34	0.02	1.26
ASV458	Magnaporthaceae		*sp.*	13*	20	0.02	1.20
ASV427	Olpidiaceae	*Olpidium*	*brassicae*	15*	31	0.02	0.98

Supplementary Table 15: List of chemical properties of, and detectable elements/compounds in, the tap water used for irrigation of the experimental pots, as provided by the local drinking water facility (Stadtwerke Konstanz GmbH, Konstanz, Germany). Actual measurements were performed by Eurofins Institut Jäger GmbH (Tübingen, Germany).

Measurement	Value*
pH	7.92
Electrical conductivity	332 µS/cm
Total organic carbon	0.9 mg/l
Oxygen (O_2)	10.8 mg/l
Nitrate (NO_3)	3.9 mg/l
Uranium (U)	0.0011 mg/l
Chromium (Cr)	0.0005 mg/l
Chlorine (Cl)	7.6 mg/l
Sodium (Na)	6.2 mg/l
Calcium (Ca)	51.3 mg/l
Kalium (K)	1.4 mg/l
Magnesium (Mg)	8.7 mg/l
Bicarbonate (HCO_3)	160 mg/l

*Water sample collection date: 23-08-2021