

Online Resource / Supplementary file of

Systemic effects of foliar nitrogen application reshape root amino acid exudation in *VITIS VINIFERA* L. cv. Riesling

Plant and Soil

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Content

2. Biomass	2
3. Leaf nutrients	4
4. Root nutrients (C & N)	6
5. Root tip AA concentration	8
5.1. Univariate Analysis of root tip AA concentrations	8
5.2. PERMANOVA, RDA & vector details of root tip AA concentrations log1p & clr transformed	12
5.2.1. Log1p transformed data	12
5.2.2. CLR transformed data	18
6. Exuded AA	25
6.1. Univariate analysis exuded AA	25
6.2. RDA vector details log1p & CLR exuded AA	28

2. Biomass

*Supplementary Table 1 Results of one-way analysis of variance (ANOVA) for biomass traits of grapevines. Separate analyses were performed for each sampling date (29 August, 12 September and 26 September 2024) to test the effect of foliar N treatment (Control, Foliar N1 and Foliar N2) on shoot:root ratio and the biomass of leaves, roots, shoots and wood. Values represent P values. Asterisks indicate statistical significance (P < 0.05, ** P < 0.01, *** P < 0.001)*

Trait	29 August 2024	12 September 2024	26 September 2024
Shoot : root	0.771	0.016*	0.464
leaves	0.608	0.003**	0.548
roots	0.956	0.573	0.685
shoots	0.829	0.044*	0.081
wood	0.406	0.020*	0.193

Supplementary Table 2 Biomass traits of grapevines under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Values are presented as mean $\pm$ SD (n = 5). Biomass is expressed as g plant⁻¹, except for the shoot:root ratio, which is dimensionless. Different lowercase letters indicate significant differences among treatments within each sampling date according to Tukey's HSD (P < 0.05)

Trait	29 August 2024			12 September 2024			26 September 2024		
Trait	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
Shoot : root	4.52 $\pm$ 1.17 a	4.47 $\pm$ 1.50 a	4.01 $\pm$ 0.96 a	3.73 $\pm$ 0.55 ab	4.44 $\pm$ 0.33 a	3.28 $\pm$ 0.68 b	3.03 $\pm$ 0.23 a	3.95 $\pm$ 1.76 a	3.41 $\pm$ 0.84 a
leaves	11.80 $\pm$ 1.40 a	12.34 $\pm$ 2.73 a	10.90 $\pm$ 2.43 a	13.39 $\pm$ 2.59 b	17.25 $\pm$ 1.87 a	11.88 $\pm$ 1.18 b	13.61 $\pm$ 4.75 a	16.26 $\pm$ 3.41 a	15.25 $\pm$ 2.89 a
roots	5.19 $\pm$ 1.45 a	5.39 $\pm$ 0.84 a	5.23 $\pm$ 0.95 a	6.87 $\pm$ 1.68 a	7.52 $\pm$ 1.15 a	7.93 $\pm$ 1.80 a	7.73 $\pm$ 2.47 a	9.72 $\pm$ 6.11 a	9.96 $\pm$ 3.75 a
shoots	10.70 $\pm$ 1.84 a	11.35 $\pm$ 3.69 a	10.02 $\pm$ 4.20 a	11.94 $\pm$ 3.03 b	15.96 $\pm$ 2.01 a	13.23 $\pm$ 1.49 ab	10.19 $\pm$ 4.49 a	15.51 $\pm$ 4.00 a	16.43 $\pm$ 4.30 a
wood	17.18 $\pm$ 4.25 a	19.65 $\pm$ 1.99 a	19.59 $\pm$ 2.90 a	17.37 $\pm$ 2.16 b	22.36 $\pm$ 1.99 a	20.83 $\pm$ 3.04 ab	22.30 $\pm$ 3.41 a	18.97 $\pm$ 3.21 a	22.46 $\pm$ 2.96 a

3. Leaf nutrients

*Supplementary Table 3 Results of one-way analysis of variance (ANOVA) for leaf nutrient concentrations in grapevine leaves. Separate analyses were performed for each sampling date (29 August, 12 September and 26 September 2024) to test the effect of foliar N treatment (Control, Foliar N1 and Foliar N2) on leaf concentrations of C, C:N ratio, Ca, Cu, Fe, K, Mg, Mn, N, P and Zn. Values represent P values. Asterisks indicate statistical significance (P < 0.05, ** P < 0.01, *** P < 0.001)*

Nutrient	29 August 2024	12 September 2024	26 September 2024
C	0.013*	0.129	<0.001***
C:N.ratio	<0.001***	<0.001***	<0.001***
Ca	0.172	0.413	0.300
Cu	0.124	0.218	0.161
Fe	0.713	0.006**	0.262
K	0.057	0.094	0.171
Mg	0.168	0.264	0.837
Mn	0.556	0.124	0.290
N	<0.001***	<0.001***	<0.001***
P	0.004**	0.061	0.038*
Zn	0.109	0.097	0.339

Supplementary Table 4 Leaf nutrient concentrations in grapevine leaves under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Values are presented as mean $\pm$ SD (n = 5). Concentrations of C, N, P, K, Mg and Ca are expressed as %, whereas Cu, Fe, Mn and Zn are expressed as mg kg⁻¹ dry weight. Different lowercase letters indicate significant differences among treatments within each sampling date according to Tukey's HSD (P < 0.05)

Nutrient	29 August 2024			12 September 2024			26 September 2024		
Nutrient	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
C	42.52 $\pm$ 0.33 b	43.32 $\pm$ 0.27 ab	43.58 $\pm$ 0.74 a	42.89 $\pm$ 0.61 a	43.29 $\pm$ 0.27 a	43.42 $\pm$ 0.13 a	42.26 $\pm$ 0.16 c	42.69 $\pm$ 0.20 b	43.58 $\pm$ 0.34 a
C:N.ratio	27.93 $\pm$ 2.22 b	18.97 $\pm$ 0.71 a	16.72 $\pm$ 0.96 a	29.41 $\pm$ 2.87 c	20.22 $\pm$ 1.05 a	13.95 $\pm$ 1.22 b	31.35 $\pm$ 2.21 c	22.28 $\pm$ 2.29 b	15.56 $\pm$ 2.40 s
Ca	1.40 $\pm$ 0.17 a	1.46 $\pm$ 0.16 a	1.58 $\pm$ 0.10 a	1.36 $\pm$ 0.17 a	1.46 $\pm$ 0.18 a	1.48 $\pm$ 0.08 a	1.43 $\pm$ 0.14 a	1.31 $\pm$ 0.20 a	1.46 $\pm$ 0.09 a
Cu	241.20 $\pm$ 35.37 a	287.69 $\pm$ 56.87 a	196.00 $\pm$ 90.37 a	274.69 $\pm$ 58.77 a	225.87 $\pm$ 51.54 a	215.94 $\pm$ 49.35 a	314.93 $\pm$ 77.11 a	243.11 $\pm$ 54.19 a	251.39 $\pm$ 44.27 a
Fe	88.28 $\pm$ 22.96 a	93.07 $\pm$ 6.32 a	96.39 $\pm$ 12.23 a	83.44 $\pm$ 9.80 a	80.07 $\pm$ 3.28 a	97.73 $\pm$ 7.63 b	92.97 $\pm$ 17.11 a	84.60 $\pm$ 7.73 a	106.63 $\pm$ 29.71 a
K	1.81 $\pm$ 0.16 a	1.78 $\pm$ 0.11 a	2.10 $\pm$ 0.31 a	1.83 $\pm$ 0.21 a	1.80 $\pm$ 0.21 a	2.07 $\pm$ 0.15 a	2.20 $\pm$ 0.38 a	1.84 $\pm$ 0.29 a	1.80 $\pm$ 0.35 a
Mg	0.25 $\pm$ 0.03 a	0.25 $\pm$ 0.03 a	0.29 $\pm$ 0.04 a	0.28 $\pm$ 0.06 a	0.27 $\pm$ 0.02 a	0.31 $\pm$ 0.02 a	0.27 $\pm$ 0.03 a	0.25 $\pm$ 0.06 a	0.26 $\pm$ 0.05 a
Mn	76.70 $\pm$ 19.49 a	89.97 $\pm$ 25.18 a	88.37 $\pm$ 16.19 a	70.77 $\pm$ 15.21 a	87.25 $\pm$ 20.08 a	92.98 $\pm$ 12.77 a	77.26 $\pm$ 18.02 a	98.25 $\pm$ 24.35 a	84.78 $\pm$ 17.79 a
N	1.53 $\pm$ 0.12 c	2.29 $\pm$ 0.09 a	2.62 $\pm$ 0.20 b	1.47 $\pm$ 0.14 c	2.14 $\pm$ 0.11 a	3.13 $\pm$ 0.26 b	1.35 $\pm$ 0.09 c	1.93 $\pm$ 0.22 a	2.87 $\pm$ 0.52 b
P	0.24 $\pm$ 0.02 a	0.25 $\pm$ 0.03 a	0.32 $\pm$ 0.04 b	0.26 $\pm$ 0.05 a	0.26 $\pm$ 0.03 a	0.31 $\pm$ 0.02 a	0.37 $\pm$ 0.09 a	0.29 $\pm$ 0.03 a	0.28 $\pm$ 0.02 a
Zn	122.17 $\pm$ 19.68 a	163.26 $\pm$ 31.05 a	123.57 $\pm$ 41.15 a	158.02 $\pm$ 24.80 a	145.93 $\pm$ 23.77 a	179.58 $\pm$ 18.67 a	175.99 $\pm$ 21.69 a	180.93 $\pm$ 20.65 a	196.46 $\pm$ 23.41 a

4. Root nutrients (C & N)

*Supplementary Table 5 Results of one-way analysis of variance (ANOVA) for root nutrient concentrations in grapevine roots. Separate analyses were performed for each sampling date (29 August, 12 September and 26 September 2024) to test the effect of foliar N treatment (Control, Foliar N1 and Foliar N2) on root concentrations of C, N and the C:N ratio. Values represent P values. Asterisks indicate statistical significance (P < 0.05, ** P < 0.01, *** P < 0.001)*

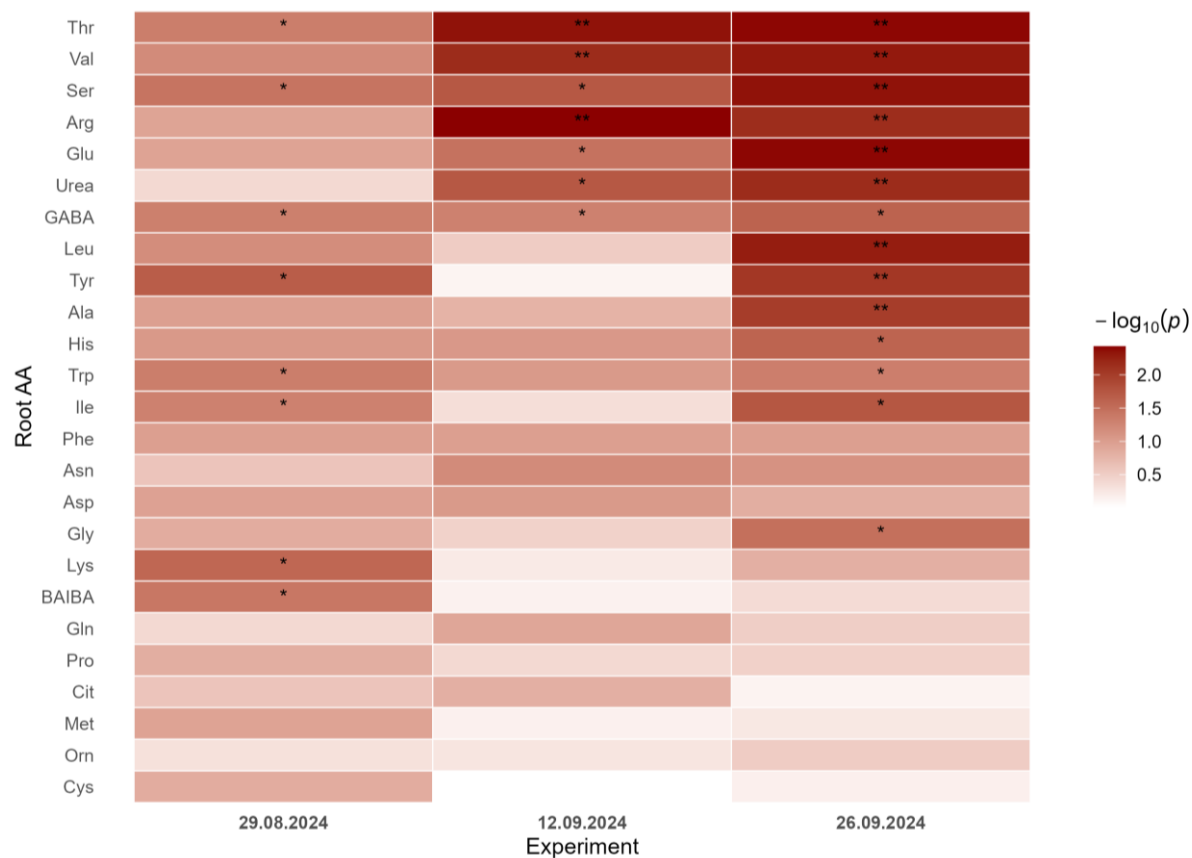
Nutrient	29 August 2024	12 September 2024	26 September 2024
C:N ratio	0.021*	0.009**	0.009**
carbon	0.210	0.466	0.608
nitrogen	0.029*	0.005**	0.001**

Supplementary Table 6 Root nutrient concentrations in grapevine roots under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Values are presented as mean $\pm$ SD (n = 5) and are expressed as % dry weight (DW). Different lowercase letters indicate significant differences among treatments within each sampling date according to Tukey's HSD (P < 0.05)

Nutrient	29 August 2024			12 September 2024			26 September 2024		
Nutrient	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
C:N ratio	47.81 $\pm$ 4.44 b	40.95 $\pm$ 2.96 a	41.97 $\pm$ 3.04 ab	52.16 $\pm$ 7.08 a	50.74 $\pm$ 1.92 a	42.49 $\pm$ 1.84 b	58.32 $\pm$ 10.37 b	48.61 $\pm$ 2.68 ab	43.29 $\pm$ 2.70 a
carbon	43.09 $\pm$ 0.97 a	42.81 $\pm$ 2.12 a	44.36 $\pm$ 0.54 a	43.79 $\pm$ 0.52 a	43.69 $\pm$ 0.49 a	43.41 $\pm$ 0.44 a	43.85 $\pm$ 0.94 a	43.96 $\pm$ 0.94 a	43.46 $\pm$ 0.49 a
nitrogen	0.91 $\pm$ 0.08 b	1.05 $\pm$ 0.11 ab	1.06 $\pm$ 0.07 a	0.85 $\pm$ 0.12 a	0.86 $\pm$ 0.03 a	1.02 $\pm$ 0.04 b	0.77 $\pm$ 0.11 b	0.91 $\pm$ 0.04 a	1.01 $\pm$ 0.06 a

5. Root tip AA concentration

5.1. Univariate Analysis of root tip AA concentrations



Supplementary Fig. 1 Exploratory heatmap of Kruskal–Wallis test results for individual root tip amino acid concentrations at each sampling date. Colours represent $-\log_{10}(P)$ values, with darker red indicating stronger statistical evidence against the null hypothesis (smaller P values). Asterisks indicate nominal statistical significance before false discovery rate (FDR) correction ($P < 0.05$, *; $P < 0.01$, **)

*Supplementary Table 7 Kruskal–Wallis test results for root tip amino acid concentrations under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Raw and Benjamini–Hochberg false discovery rate (FDR)-adjusted P values are presented for each amino acid. FDR correction was performed separately for each sampling date across all amino acids. Asterisks indicate statistical significance of the raw P values (P < 0.05, *, P < 0.01, **, P < 0.001, ***)*

	29 August 2024		12 September 2024		26 September 2024	
Amino acid	raw p	adj p (BH)	raw p	adj p (BH)	raw p	adj p (BH)
Total	0.046*		0.004**	*	<0.001***	
alanine	0.095	0.164	0.184	0.319	0.003**	0.009**
arginine	0.101	0.164	0.004**	0.021*	0.122	0.199
asparagine	0.158	0.187	0.046*	0.151	0.190	0.274
aspartic_acid	0.073	0.158	0.126	0.233	0.365	0.460
b_aminoisobutyric_acid	0.016*	0.142	0.449	0.584	0.771	0.771
citrulline	0.262	0.284	0.476	0.589	0.685	0.736
cystine	0.151	0.187	0.789	0.789	0.609	0.689
g_aminobutyric_acid	0.080	0.161	0.075	0.166	0.016*	0.035*
glutamic_acid	0.067	0.158	0.009**	0.033*	<0.001***	0.002**
glutamine	0.319	0.332	0.090	0.180	0.339	0.460
glycine	0.148	0.187	0.275	0.397	0.016*	0.035*
histidine	0.232	0.262	0.077	0.166	0.074	0.137
isoleucine	0.053	0.142	0.270	0.397	0.010*	0.026*
leucine	0.055	0.142	0.323	0.443	<0.001***	0.004**
lysine	0.028*	0.142	0.222	0.360	0.155	0.238
methionine	0.137	0.187	0.777	0.789	0.707	0.736
ornithine	0.132	0.187	0.623	0.704	0.382	0.460
phenylalanine	0.043*	0.142	0.058	0.152	0.090	0.155
proline	0.101	0.164	0.603	0.704	0.389	0.460
serine	0.037*	0.142	0.002**	0.017*	0.002**	0.006**
threonine	0.041*	0.142	0.002**	0.017*	<0.001***	0.002**
tryptophan	0.117	0.179	0.058	0.152	0.033*	0.067
tyrosine	0.019*	0.142	0.745	0.789	<0.001***	0.004**
urea	0.872	0.872	0.006**	0.025*	0.002**	0.007**
valine	0.033*	0.142	0.001**	0.017*	<0.001***	0.004**

Supplementary Table 8 Root tip amino acid concentrations under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Values are presented as mean $\pm$ SD (n = 5) and are expressed as nmol g⁻¹ root DW. Different lowercase letters indicate significant differences among treatments within each sampling date according to Bonferroni-adjusted pairwise comparisons

	29 August 2024			12 September 2024			26 September 2024		
Amino acid	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
total	27.78 $\pm$ 13.37 a	57.78 $\pm$ 25.79 a	58.51 $\pm$ 17.30 a	31.86 $\pm$ 10.85 b	59.17 $\pm$ 11.75 a	58.33 $\pm$ 11.57 a	29.66 $\pm$ 6.25 c	52.35 $\pm$ 14.69 a	70.70 $\pm$ 8.85 b
alanine	4.62 $\pm$ 2.90 a	10.15 $\pm$ 6.44 a	11.20 $\pm$ 3.89 a	6.02 $\pm$ 4.35 a	13.64 $\pm$ 8.20 a	9.55 $\pm$ 5.05 a	5.75 $\pm$ 1.46 a	8.01 $\pm$ 3.53 a	12.62 $\pm$ 2.04 b
arginine	0.57 $\pm$ 0.47 a	1.77 $\pm$ 1.13 a	1.59 $\pm$ 0.87 a	0.31 $\pm$ 0.18 a	0.84 $\pm$ 0.58 a	1.91 $\pm$ 0.86 b	0.41 $\pm$ 0.28 a	4.04 $\pm$ 5.67 a	4.89 $\pm$ 1.27 a
asparagine	0.99 $\pm$ 0.70 a	2.13 $\pm$ 1.13 a	1.68 $\pm$ 0.75 a	0.83 $\pm$ 0.18 a	1.77 $\pm$ 0.92 a	1.84 $\pm$ 0.58 a	0.69 $\pm$ 0.31 a	1.57 $\pm$ 1.20 a	1.74 $\pm$ 0.99 a
aspartic acid	2.12 $\pm$ 1.07 a	4.15 $\pm$ 1.58 a	3.64 $\pm$ 1.22 a	2.62 $\pm$ 1.23 a	3.76 $\pm$ 1.79 a	4.52 $\pm$ 0.91 a	2.77 $\pm$ 1.82 a	5.69 $\pm$ 3.73 a	6.34 $\pm$ 5.68 a
β aminoisobutyric acid	0.01 $\pm$ 0.02 ab	0.01 $\pm$ 0.01 a	0.03 $\pm$ 0.01 b	0.00 $\pm$ 0.00 a	0.02 $\pm$ 0.04 a	0.05 $\pm$ 0.08 a	0.01 $\pm$ 0.01 a	0.01 $\pm$ 0.01 a	0.01 $\pm$ 0.01 a
citrulline	0.01 $\pm$ 0.01 a	0.04 $\pm$ 0.05 a	0.01 $\pm$ 0.01 a	0.04 $\pm$ 0.05 a	0.05 $\pm$ 0.02 a	0.07 $\pm$ 0.04 a	0.03 $\pm$ 0.01 a	0.06 $\pm$ 0.08 a	0.04 $\pm$ 0.03 a
cystine	0.06 $\pm$ 0.02 a	0.11 $\pm$ 0.06 a	0.11 $\pm$ 0.04 a	0.07 $\pm$ 0.05 a	0.08 $\pm$ 0.09 a	0.06 $\pm$ 0.02 a	0.04 $\pm$ 0.03 a	0.03 $\pm$ 0.01 a	0.03 $\pm$ 0.02 a
γ aminobutyric acid	3.27 $\pm$ 1.81 a	8.20 $\pm$ 4.78 a	7.98 $\pm$ 3.32 a	2.53 $\pm$ 1.40 a	5.34 $\pm$ 2.40 a	5.59 $\pm$ 2.35 a	2.70 $\pm$ 0.60 b	4.67 $\pm$ 3.77 ab	8.30 $\pm$ 2.40 a
glutamic acid	6.11 $\pm$ 3.03 a	13.41 $\pm$ 6.21 a	12.36 $\pm$ 4.53 a	8.19 $\pm$ 3.88 b	13.42 $\pm$ 1.49 ab	16.01 $\pm$ 3.97 a	8.97 $\pm$ 1.80 c	13.96 $\pm$ 2.81 a	19.46 $\pm$ 3.50 b
glutamine	3.49 $\pm$ 1.02 a	4.82 $\pm$ 1.99 a	5.72 $\pm$ 3.16 a	4.02 $\pm$ 1.52 a	8.65 $\pm$ 4.47 a	6.26 $\pm$ 2.21 a	2.26 $\pm$ 1.47 a	5.14 $\pm$ 4.68 a	4.45 $\pm$ 2.17 a
glycine	0.40 $\pm$ 0.23 a	0.82 $\pm$ 0.47 a	0.70 $\pm$ 0.19 a	0.51 $\pm$ 0.24 a	0.86 $\pm$ 0.44 a	0.76 $\pm$ 0.28 a	0.44 $\pm$ 0.12 b	0.56 $\pm$ 0.12 ab	0.68 $\pm$ 0.08 a
histidine	0.17 $\pm$ 0.05 a	0.50 $\pm$ 0.24 a	0.84 $\pm$ 0.98 a	0.19 $\pm$ 0.09 a	0.34 $\pm$ 0.11 a	0.35 $\pm$ 0.14 a	0.15 $\pm$ 0.07 a	0.40 $\pm$ 0.26 a	0.43 $\pm$ 0.20 a
isoleucine	0.58 $\pm$ 0.31 a	1.11 $\pm$ 0.49 a	1.18 $\pm$ 0.30 a	0.64 $\pm$ 0.27 a	0.86 $\pm$ 0.18 a	0.78 $\pm$ 0.16 a	0.43 $\pm$ 0.09 b	0.55 $\pm$ 0.17 ab	0.79 $\pm$ 0.19 a
leucine	0.67 $\pm$ 0.36 a	1.37 $\pm$ 0.71 a	1.46 $\pm$ 0.35 a	0.61 $\pm$ 0.37 a	0.93 $\pm$ 0.30 a	0.82 $\pm$ 0.31 a	0.45 $\pm$ 0.08 a	0.61 $\pm$ 0.14 a	0.96 $\pm$ 0.20 b
lysine	0.14 $\pm$ 0.07 b	0.39 $\pm$ 0.20 a	0.36 $\pm$ 0.10 ab	0.07 $\pm$ 0.02 a	0.11 $\pm$ 0.12 a	0.23 $\pm$ 0.22 a	0.08 $\pm$ 0.05 a	0.11 $\pm$ 0.08 a	0.22 $\pm$ 0.17 a

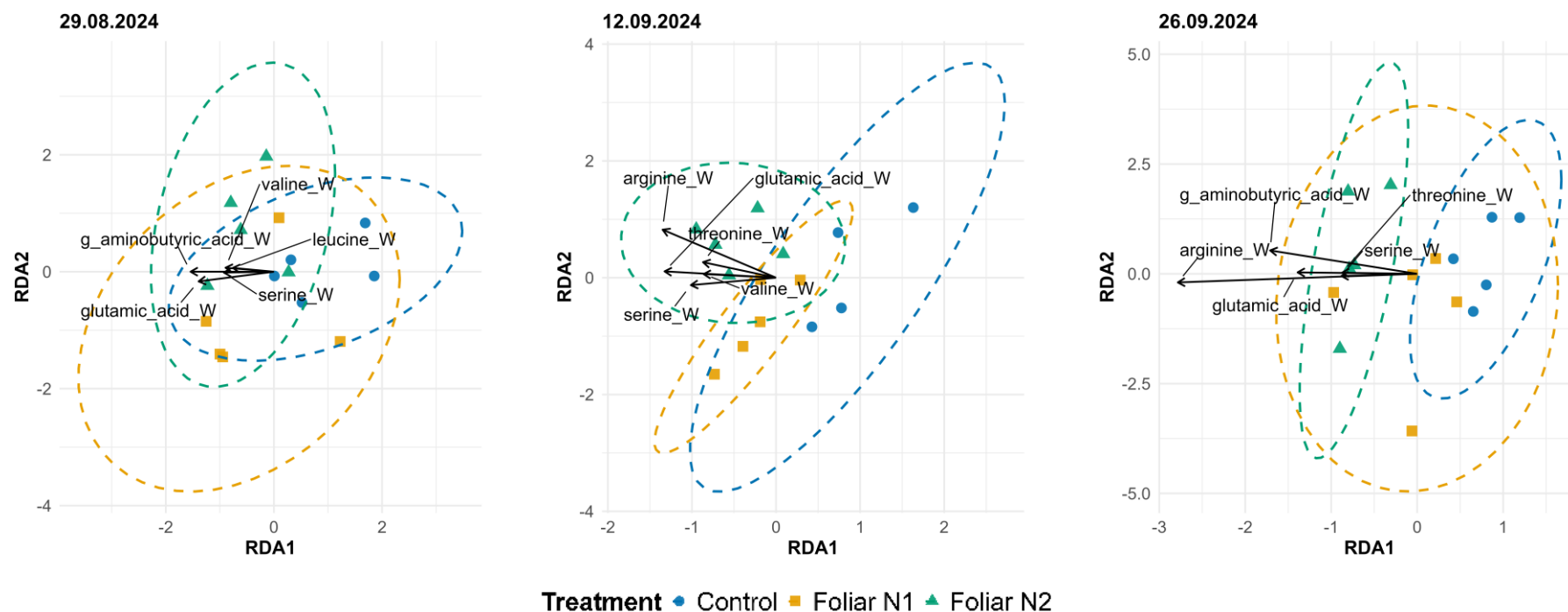
	29 August 2024			12 September 2024			26 September 2024		
Amino acid	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
methionine	0.04 ± 0.03 a	0.08 ± 0.02 a	0.08 ± 0.05 a	0.08 ± 0.04 a	0.08 ± 0.05 a	0.10 ± 0.05 a	0.07 ± 0.02 a	0.09 ± 0.02 a	0.09 ± 0.06 a
ornithine	0.05 ± 0.03 a	0.14 ± 0.11 a	0.07 ± 0.03 a	0.06 ± 0.02 a	0.09 ± 0.04 a	0.07 ± 0.06 a	0.06 ± 0.03 a	0.08 ± 0.06 a	0.10 ± 0.03 a
phenylalanine	0.46 ± 0.22 b	0.76 ± 0.26 ab	0.83 ± 0.17 a	0.39 ± 0.14 a	0.56 ± 0.19 a	0.78 ± 0.31 a	0.60 ± 0.10 a	0.75 ± 0.27 a	0.89 ± 0.14 a
proline	0.27 ± 0.19 a	0.63 ± 0.43 a	0.69 ± 0.22 a	0.32 ± 0.29 a	0.29 ± 0.15 a	0.17 ± 0.28 a	0.22 ± 0.11 a	0.13 ± 0.15 a	0.28 ± 0.22 a
serine	1.15 ± 0.53 a	2.34 ± 0.98 a	2.38 ± 0.65 a	1.62 ± 0.52 b	2.87 ± 0.44 a	2.96 ± 0.52 a	1.46 ± 0.24 b	2.28 ± 0.42 a	2.90 ± 0.68 a
threonine	0.68 ± 0.35 b	1.32 ± 0.49 ab	1.49 ± 0.53 a	0.73 ± 0.23 b	1.23 ± 0.22 ab	1.69 ± 0.46 a	0.60 ± 0.13 c	1.07 ± 0.28 a	1.53 ± 0.28 b
tryptophan	0.19 ± 0.11 a	0.41 ± 0.19 a	0.62 ± 0.48 a	0.19 ± 0.10 a	0.28 ± 0.09 a	0.40 ± 0.16 a	0.16 ± 0.11 b	0.37 ± 0.26 ab	0.55 ± 0.21 a
tyrosine	0.38 ± 0.19 b	0.72 ± 0.30 ab	0.86 ± 0.20 a	0.45 ± 0.23 a	0.54 ± 0.16 a	0.54 ± 0.21 a	0.29 ± 0.10 a	0.30 ± 0.08 a	0.56 ± 0.09 b
urea	0.39 ± 0.37 a	0.41 ± 0.10 a	0.47 ± 0.17 a	0.39 ± 0.09 b	0.85 ± 0.17 a	0.84 ± 0.30 a	0.26 ± 0.09 b	0.61 ± 0.20 a	0.76 ± 0.21 a
valine	0.98 ± 0.42 b	1.99 ± 0.82 ab	2.17 ± 0.70 a	0.99 ± 0.33 b	1.74 ± 0.29 a	2.01 ± 0.40 a	0.79 ± 0.14 a	1.26 ± 0.42 a	2.10 ± 0.53 b

5.2. PERMANOVA, RDA & vector details of root tip AA concentrations log1p & clr transformed

5.2.1. Log1p transformed data

Supplementary Table 9 Results of permutational multivariate analysis of variance (PERMANOVA) based on Euclidean distances of log1p-transformed root tip amino acid (AA) concentrations, testing the effect of foliar N treatment within each sampling date. Reported values include R², pseudo-F values and permutation-based P values for the global model, together with P values for homogeneity of multivariate dispersion (betadisper). Pairwise comparisons within each sampling date are presented as false discovery rate (FDR)-adjusted P values (P_{adj}), with raw P values shown in parentheses. Asterisks indicate significance based on adjusted P values

Comparison	29 August 2024	12 September 2024	26 September 2024
Overall PERMANOVA + Dispersion	p=0.046* (R ² =0.35, F=3.24); Disp p=0.879	p=0.012* (R ² =0.34, F=2.80); Disp p=0.903	p=0.001** (R ² =0.49, F=5.67); Disp p=0.212
Control vs Foliar N1	p _{adj} =0.088 (p=0.059), R ² =0.33, F=3.86	p _{adj} =0.042* (p=0.028), R ² =0.29, F=2.90	p _{adj} =0.030* (p=0.020), R ² =0.31, F=3.56
Control vs Foliar N2	p _{adj} =0.088 (p=0.032), R ² =0.44, F=6.37	p _{adj} =0.039* (p=0.013), R ² =0.39, F=4.52	p _{adj} =0.030* (p=0.014), R ² =0.68, F=16.80
Foliar N1 vs Foliar N2	p _{adj} =0.938 (p=0.938), R ² =0.02, F=0.20	p _{adj} =0.364 (p=0.364), R ² =0.12, F=1.06	p _{adj} =0.123 (p=0.123), R ² =0.19, F=1.90



Supplementary Fig. 2 Redundancy analysis (RDA) of $\log_{10}$ -transformed root tip amino acid (AA) concentrations constrained by foliar N treatment at three independent sampling dates (29 August, 12 September and 26 September 2024). Points represent individual grapevines, with blue circles, orange squares and green triangles indicating the Control, Urea 1 and Urea 2 treatments, respectively. Dashed ellipses indicate treatment groups. Arrows represent amino acids (AAs) associated with the constrained ordination structure. To improve readability, only the five amino acids with the highest envfit r^2 values ($r^2 > 0.50$) are displayed. Vector direction indicates the association of individual AAs with treatment separation, whereas vector length reflects the strength of this association

Supplementary Table 10 Summary of redundancy analysis (RDA) models for log1p-transformed root tip amino acid (AA) concentrations. Reported values include the proportion of variation explained by foliar N treatment (R^2), adjusted R^2 , global permutation test P values (P_{global}), and P values for the first and second constrained axes (P_{axis1} , P_{axis2}). Significance was assessed using permutation tests ($n = 999$)

Experiment	R2	R2adj	p_global	p_axis1	p_axis2
29 August 2024	0.35	0.24	0.046	0.050	0.930
12 September 2024	0.34	0.22	0.013	0.007	0.411
26 September 2024	0.49	0.40	0.001	0.002	0.674

Supplementary Table 11 Results of the envfit analysis for redundancy analysis (RDA) of log1p-transformed root tip amino acid (AA) concentrations. For each amino acid and sampling date, vector coordinates (v1, v2), vector magnitude (mag), coefficient of determination (envfit r²), and permutation-based P values (envfit P) are reported

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
29 August 2024	alanine_W	-0.5870	0.0937	0.5944	0.805	0.001
29 August 2024	γ_aminobutyric_acid_W	-0.5628	0.0002	0.5628	0.908	0.001
29 August 2024	glutamic_acid_W	-0.5088	-0.0605	0.5124	0.903	0.001
29 August 2024	arginine_W	-0.3871	-0.0632	0.3922	0.837	0.001
29 August 2024	aspartic_acid_W	-0.3445	-0.0871	0.3553	0.839	0.001
29 August 2024	serine_W	-0.3387	-0.0051	0.3388	0.915	0.001
29 August 2024	valine_W	-0.3271	0.0250	0.3281	0.910	0.001
29 August 2024	asparagine_W	-0.2830	-0.1064	0.3023	0.741	0.001
29 August 2024	leucine_W	-0.2775	0.0240	0.2785	0.932	0.001
29 August 2024	threonine_W	-0.2733	0.0255	0.2745	0.881	0.001
29 August 2024	histidine_W	-0.2369	0.0624	0.2450	0.214	0.011
29 August 2024	isoleucine_W	-0.2328	0.0122	0.2331	0.888	0.001
29 August 2024	glutamine_W	-0.2143	0.0389	0.2178	0.197	0.031
29 August 2024	tyrosine_W	-0.2021	0.0400	0.2060	0.822	0.001
29 August 2024	proline_W	-0.1940	0.0227	0.1953	0.796	0.001
29 August 2024	tryptophan_W	-0.1789	0.0607	0.1889	0.371	0.002
29 August 2024	glycine_W	-0.1663	-0.0456	0.1724	0.612	0.001
29 August 2024	phenylalanine_W	-0.1646	0.0158	0.1653	0.839	0.001
29 August 2024	lysine_W	-0.1397	-0.0178	0.1408	0.863	0.001
29 August 2024	ornithine_W	-0.0317	-0.0449	0.0550	0.384	0.002
29 August 2024	cystine_W	-0.0334	-0.0038	0.0337	0.650	0.001
29 August 2024	methionine_W	-0.0282	-0.0017	0.0283	0.318	0.006
29 August 2024	citrulline_W	-0.0114	-0.0154	0.0192	0.105	0.077
29 August 2024	β_aminoisobutyric_acid_W	-0.0061	0.0132	0.0145	0.104	0.096
12 September 2024	arginine_W	-0.4382	0.2671	0.5132	0.585	0.001
12 September 2024	alanine_W	-0.3323	-0.2798	0.4344	0.540	0.001
12 September 2024	glutamic_acid_W	-0.4305	0.0352	0.4319	0.558	0.002
12 September 2024	glutamine_W	-0.3467	-0.2091	0.4049	0.040	0.276
12 September 2024	γ_aminobutyric_acid_W	-0.4020	-0.0424	0.4043	0.512	0.003
12 September 2024	asparagine_W	-0.3475	-0.0153	0.3478	0.128	0.091

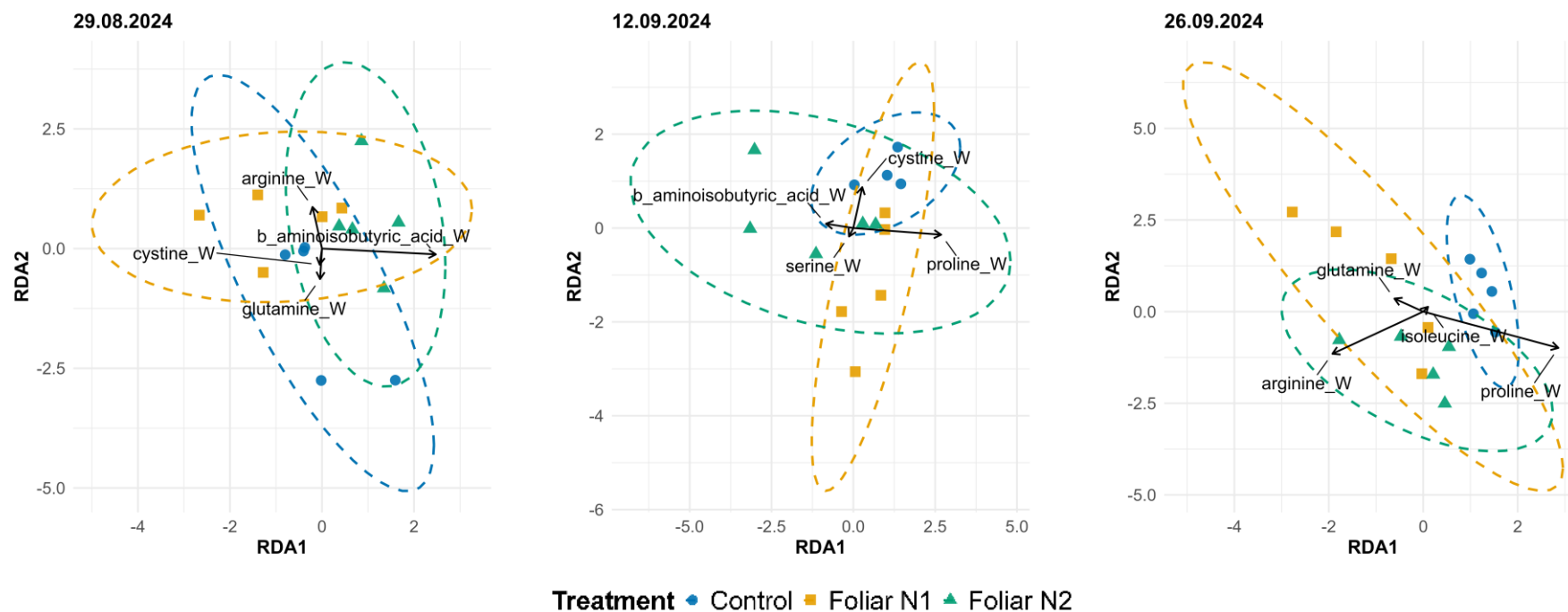
Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
12 September 2024	serine_W	-0.3290	-0.0412	0.3316	0.622	0.001
12 September 2024	aspartic_acid_W	-0.2903	0.0910	0.3042	0.294	0.016
12 September 2024	threonine_W	-0.2822	0.0864	0.2952	0.850	0.001
12 September 2024	valine_W	-0.2799	0.0202	0.2806	0.631	0.001
12 September 2024	phenylalanine_W	-0.1367	0.0699	0.1536	0.296	0.010
12 September 2024	proline_W	0.1137	-0.0620	0.1296	0.073	0.179
12 September 2024	glycine_W	-0.1161	-0.0524	0.1274	0.210	0.027
12 September 2024	lysine_W	-0.0784	0.0581	0.0976	0.036	0.308
12 September 2024	tryptophan_W	-0.0819	0.0529	0.0975	0.368	0.007
12 September 2024	leucine_W	-0.0713	-0.0586	0.0923	0.380	0.003
12 September 2024	histidine_W	-0.0824	-0.0089	0.0828	0.333	0.008
12 September 2024	isoleucine_W	-0.0551	-0.0421	0.0694	0.322	0.010
12 September 2024	β -aminoisobutyric_acid_W	-0.0266	0.0151	0.0306	0.003	0.736
12 September 2024	tyrosine_W	-0.0233	-0.0035	0.0235	0.212	0.031
12 September 2024	cystine_W	0.0122	-0.0142	0.0187	0.229	0.036
12 September 2024	citrulline_W	-0.0133	0.0111	0.0173	0.041	0.292
12 September 2024	ornithine_W	-0.0095	-0.0137	0.0167	0.092	0.117
12 September 2024	methionine_W	0.0000	0.0118	0.0118	0.030	0.355
26 September 2024	arginine_W	-0.9615	-0.0676	0.9638	0.784	0.001
26 September 2024	γ -aminobutyric_acid_W	-0.5908	0.1840	0.6188	0.815	0.001
26 September 2024	alanine_W	-0.4651	0.1273	0.4822	0.408	0.003
26 September 2024	glutamic_acid_W	-0.4803	0.0114	0.4804	0.770	0.001
26 September 2024	glutamine_W	-0.3830	-0.1955	0.4300	0.648	0.001
26 September 2024	aspartic_acid_W	-0.3947	-0.1491	0.4220	0.559	0.001
26 September 2024	valine_W	-0.3557	0.0683	0.3622	0.617	0.001
26 September 2024	asparagine_W	-0.3108	-0.0690	0.3184	0.431	0.003
26 September 2024	serine_W	-0.3046	-0.0172	0.3050	0.680	0.001
26 September 2024	threonine_W	-0.3021	0.0086	0.3023	0.752	0.001
26 September 2024	leucine_W	-0.1912	0.0571	0.1996	0.554	0.001
26 September 2024	tryptophan_W	-0.1900	0.0047	0.1900	0.477	0.002
26 September 2024	histidine_W	-0.1485	-0.0457	0.1553	0.453	0.002
26 September 2024	isoleucine_W	-0.1445	0.0408	0.1501	0.349	0.001
26 September 2024	tyrosine_W	-0.1227	0.0759	0.1442	0.316	0.008

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
26 September 2024	phenylalanine_W	-0.1083	0.0103	0.1088	0.259	0.012
26 September 2024	glycine_W	-0.1031	0.0045	0.1032	0.162	0.041
26 September 2024	proline_W	-0.0187	0.0797	0.0818	0.235	0.023
26 September 2024	lysine_W	-0.0748	0.0268	0.0794	0.066	0.162
26 September 2024	ornithine_W	-0.0241	0.0026	0.0243	0.112	0.092
26 September 2024	citrulline_W	-0.0087	-0.0141	0.0166	0.059	0.200
26 September 2024	methionine_W	-0.0110	-0.0059	0.0125	0.067	0.149
26 September 2024	cystine_W	0.0057	0.0068	0.0088	0.116	0.080
26 September 2024	β _aminoisobutyric_acid_W	-0.0024	0.0004	0.0024	0.110	0.104

5.2.2. CLR transformed data

Supplementary Table 12 Results of permutational multivariate analysis of variance (PERMANOVA) based on Euclidean distances of clr-transformed root tip amino acid (AA) concentrations, testing the effect of foliar N treatment within each sampling date. Reported values include R^2 , pseudo-F values and permutation-based P values for the global model, together with P values for homogeneity of multivariate dispersion (betadisper). Pairwise comparisons within each sampling date are presented as false discovery rate (FDR)-adjusted P values (P_{adj}), with raw P values shown in parentheses. Asterisks indicate significance based on adjusted P values

Comparison	29 August 2024	12 September 2024	26 September 2024
Overall PERMANOVA + Dispersion	p=0.060 ($R^2=0.24$, $F=1.94$); Disp p=0.465	p=0.123 ($R^2=0.22$, $F=1.58$); Disp p=0.098	p=0.061 ($R^2=0.23$, $F=1.77$); Disp p=0.005
Control vs Foliar N1	p _{adj} =0.354 (p=0.354), $R^2=0.13$, $F=1.17$	p _{adj} =0.722 (p=0.722), $R^2=0.09$, $F=0.71$	p _{adj} =0.057 (p=0.038), $R^2=0.21$, $F=2.14$
Control vs Foliar N2	p _{adj} =0.259 (p=0.173), $R^2=0.16$, $F=1.54$	p _{adj} =0.276 (p=0.092), $R^2=0.24$, $F=2.26$	p _{adj} =0.042* (p=0.014), $R^2=0.26$, $F=2.78$
Foliar N1 vs Foliar N2	p _{adj} =0.060 (p=0.020), $R^2=0.28$, $F=3.11$	p _{adj} =0.402 (p=0.268), $R^2=0.16$, $F=1.51$	p _{adj} =0.423 (p=0.423), $R^2=0.11$, $F=0.96$



Supplementary Fig. 3 Redundancy analysis (RDA) of clr-transformed root tip amino acid (AA) concentrations constrained by foliar N treatment at three independent sampling dates (29 August, 12 September and 26 September 2024). Points represent individual grapevines, with blue circles, orange squares and green triangles indicating the Control, Urea 1 and Urea 2 treatments, respectively. Dashed ellipses indicate treatment groups. Arrows represent amino acids (AAs) associated with the constrained ordination structure. To improve readability, only the five amino acids with the highest envfit r^2 values ($r^2 > 0.50$) are displayed. Vector direction indicates the association of individual AAs with treatment separation, whereas vector length reflects the strength of this association

Supplementary Table 13 Summary of redundancy analysis (RDA) models for clr-transformed root tip amino acid (AA) concentrations. Reported values include the proportion of variation explained by foliar N treatment (R^2), adjusted R^2 , global permutation test P values (P_{global}), and P values for the first and second constrained axes (P_{axis1} , P_{axis2}). Significance was assessed using permutation tests ($n = 999$)

Experiment	R2	R2adj	p_global	p_axis1	p_axis2
29 August 2024	0.24	0.12	0.058	0.041	0.627
12 September 2024	0.22	0.08	0.145	0.109	0.844
26 September 2024	0.23	0.10	0.063	0.096	0.407

Supplementary Table 14 Results of the envfit analysis for redundancy analysis (RDA) of clr-transformed root tip amino acid (AA) concentrations. For each amino acid and sampling date, vector coordinates ($v1$, $v2$), vector magnitude (mag), coefficient of determination ($\text{envfit } r^2$), and permutation-based P values ($\text{envfit } P$) are reported

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
29 August 2024	β _aminoisobutyric_acid_W	1.1051	-0.0541	1.1064	0.756	0.001
29 August 2024	citrulline_W	-0.7154	0.0060	0.7155	0.239	0.015
29 August 2024	arginine_W	-0.0920	0.3884	0.3992	0.453	0.001
29 August 2024	ornithine_W	-0.2601	-0.1823	0.3176	0.110	0.093
29 August 2024	glutamine_W	-0.0185	-0.2851	0.2857	0.342	0.006
29 August 2024	proline_W	0.1901	0.0403	0.1943	0.009	0.525
29 August 2024	tryptophan_W	0.1277	0.1297	0.1820	0.147	0.059
29 August 2024	histidine_W	0.0777	0.1611	0.1788	0.085	0.152

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
29 August 2024	methionine_W	-0.1225	0.1041	0.1607	0.009	0.538
29 August 2024	cystine_W	-0.0225	-0.1500	0.1517	0.324	0.006
29 August 2024	aspartic_acid_W	-0.1171	-0.0929	0.1495	0.129	0.069
29 August 2024	asparagine_W	-0.1479	-0.0061	0.1480	0.160	0.053
29 August 2024	lysine_W	-0.0337	0.1419	0.1458	0.118	0.086
29 August 2024	glycine_W	-0.0933	-0.0751	0.1198	0.089	0.110
29 August 2024	phenylalanine_W	0.0017	-0.1030	0.1030	0.241	0.010
29 August 2024	alanine_W	0.0730	0.0713	0.1021	0.003	0.745
29 August 2024	glutamic_acid_W	-0.0742	-0.0261	0.0787	0.026	0.343
29 August 2024	γ_aminobutyric_acid_W	-0.0030	0.0686	0.0687	0.100	0.099
29 August 2024	tyrosine_W	0.0630	0.0018	0.0630	0.003	0.717
29 August 2024	leucine_W	0.0426	-0.0134	0.0446	0.001	0.798
29 August 2024	valine_W	0.0187	-0.0379	0.0423	0.002	0.792
29 August 2024	serine_W	-0.0252	-0.0331	0.0416	0.024	0.381
29 August 2024	isoleucine_W	0.0128	-0.0338	0.0362	0.000	0.918
29 August 2024	threonine_W	0.0133	-0.0201	0.0241	0.001	0.842
12 September 2024	proline_W	1.3433	-0.0711	1.3452	0.971	0.001
12 September 2024	arginine_W	-0.5045	-0.0396	0.5061	0.110	0.098
12 September 2024	cystine_W	0.1366	0.4360	0.4569	0.624	0.001
12 September 2024	β_aminoisobutyric_acid_W	-0.4195	0.0456	0.4220	0.325	0.020
12 September 2024	methionine_W	0.0663	0.2674	0.2755	0.008	0.574

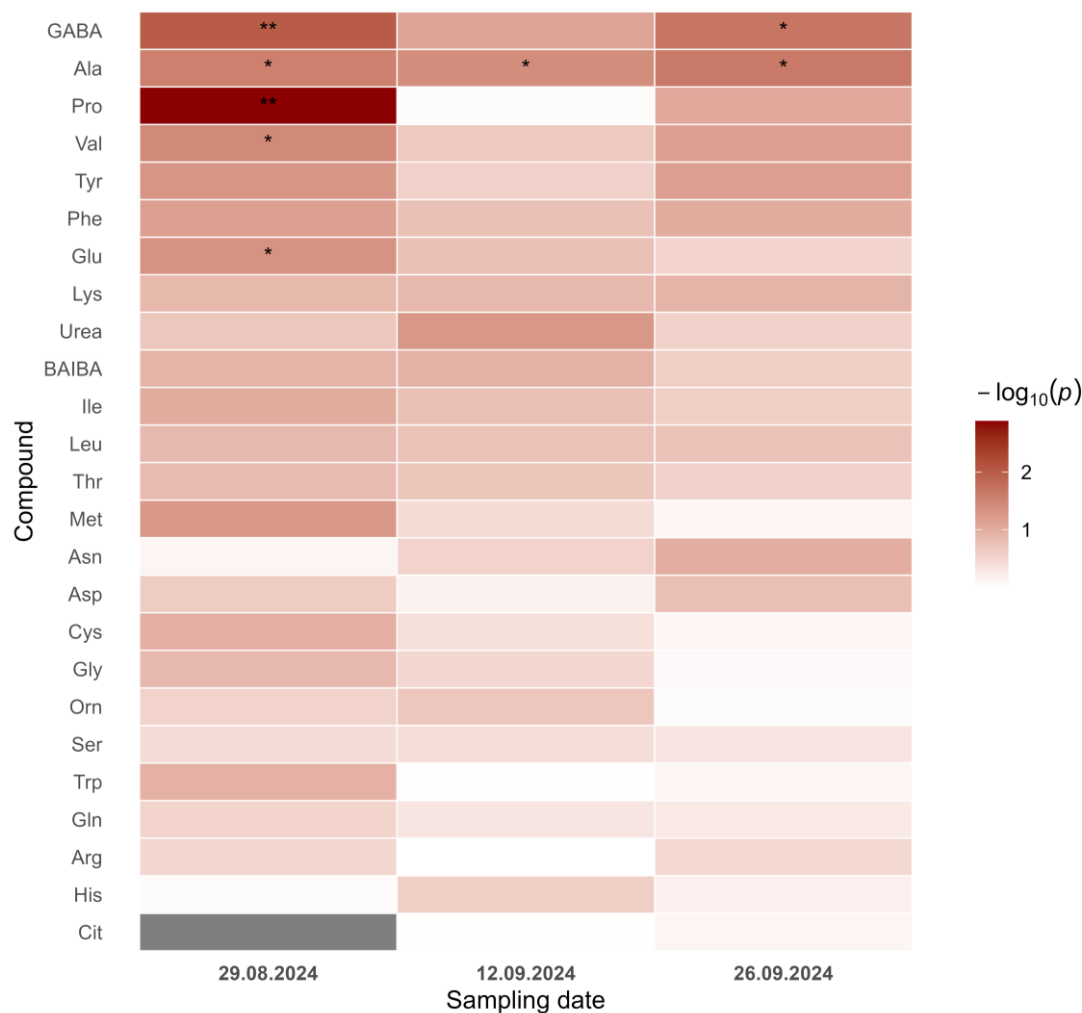
Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
12 September 2024	ornithine_W	0.2594	-0.0348	0.2617	0.014	0.506
12 September 2024	citrulline_W	-0.1691	-0.0992	0.1961	0.015	0.503
12 September 2024	asparagine_W	-0.1498	-0.1095	0.1856	0.042	0.285
12 September 2024	alanine_W	0.0728	-0.1658	0.1810	0.004	0.683
12 September 2024	threonine_W	-0.1715	-0.0281	0.1738	0.147	0.068
12 September 2024	lysine_W	-0.1082	0.0984	0.1463	0.001	0.850
12 September 2024	glutamine_W	0.0298	-0.1336	0.1369	0.010	0.546
12 September 2024	tryptophan_W	-0.1231	0.0538	0.1343	0.016	0.478
12 September 2024	γ_aminobutyric_acid_W	-0.0794	-0.0971	0.1254	0.009	0.563
12 September 2024	phenylalanine_W	-0.1073	0.0516	0.1190	0.012	0.519
12 September 2024	tyrosine_W	0.0923	0.0750	0.1189	0.104	0.123
12 September 2024	serine_W	-0.0662	-0.0906	0.1122	0.331	0.007
12 September 2024	valine_W	-0.0991	-0.0526	0.1122	0.131	0.092
12 September 2024	glutamic_acid_W	-0.0953	-0.0376	0.1024	0.026	0.373
12 September 2024	isoleucine_W	0.0968	0.0229	0.0995	0.086	0.137
12 September 2024	aspartic_acid_W	-0.0919	0.0319	0.0973	0.054	0.207
12 September 2024	leucine_W	0.0910	-0.0148	0.0922	0.077	0.145
12 September 2024	glycine_W	0.0231	-0.0596	0.0639	0.006	0.636
12 September 2024	histidine_W	-0.0264	-0.0484	0.0551	0.012	0.511
26 September 2024	proline_W	1.0956	-0.3786	1.1592	0.813	0.001
26 September 2024	arginine_W	-0.7367	-0.4403	0.8582	0.617	0.001

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
26 September 2024	cystine_W	0.2902	0.4110	0.5031	0.227	0.011
26 September 2024	methionine_W	0.0677	0.3388	0.3455	0.192	0.027
26 September 2024	ornithine_W	0.3163	-0.1368	0.3446	0.000	0.931
26 September 2024	glutamine_W	-0.2339	0.1365	0.2708	0.396	0.005
26 September 2024	histidine_W	-0.2684	0.0336	0.2705	0.231	0.012
26 September 2024	tryptophan_W	-0.2290	-0.1357	0.2662	0.109	0.110
26 September 2024	β_aminoisobutyric_acid_W	0.0406	-0.2185	0.2222	0.018	0.429
26 September 2024	citrulline_W	0.1050	0.1718	0.2014	0.096	0.118
26 September 2024	aspartic_acid_W	-0.1477	0.1288	0.1959	0.155	0.058
26 September 2024	asparagine_W	-0.1655	0.0454	0.1716	0.157	0.046
26 September 2024	γ_aminobutyric_acid_W	-0.0476	-0.1620	0.1689	0.178	0.032
26 September 2024	phenylalanine_W	0.0687	0.1438	0.1594	0.295	0.010
26 September 2024	glycine_W	0.0335	0.1363	0.1404	0.208	0.032
26 September 2024	threonine_W	-0.1206	-0.0023	0.1206	0.285	0.012
26 September 2024	lysine_W	-0.0074	-0.1055	0.1058	0.000	0.971
26 September 2024	serine_W	-0.0536	0.0856	0.1010	0.224	0.018
26 September 2024	tyrosine_W	0.0835	-0.0509	0.0977	0.027	0.343
26 September 2024	valine_W	-0.0765	-0.0572	0.0955	0.157	0.045
26 September 2024	glutamic_acid_W	-0.0600	0.0346	0.0692	0.021	0.405
26 September 2024	isoleucine_W	0.0392	0.0504	0.0638	0.333	0.006
26 September 2024	alanine_W	-0.0009	-0.0283	0.0283	0.004	0.685

Experiment	AminoAcid	v1	v2	mag	envfit_r ²	envfit_p
26 September 2024	leucine_W	0.0074	-0.0002	0.0074	0.094	0.109

6. Exuded AA

6.1. Univariate analysis exuded AA



Supplementary Fig. 4 Exploratory heatmap of Kruskal–Wallis test results for individual exuded amino acids at each sampling date. Colours represent $-\log_{10}(P)$ values, with darker red indicating stronger statistical evidence against the null hypothesis (smaller P values). Asterisks indicate nominal statistical significance before false discovery rate (FDR) correction ($P < 0.05$, *; $P < 0.01$, **). Grey cells indicate compounds for which concentrations were below the analytical detection limit and were therefore not included in the statistical analysis

*Supplementary Table 15 Kruskal–Wallis test results for amino acid exudation rates under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Raw and Benjamini–Hochberg false discovery rate (FDR)-adjusted P values are presented for each amino acid. FDR correction was performed separately for each sampling date across all amino acids. Asterisks indicate statistical significance of the raw P values ($P < 0.05$, *, $P < 0.01$, **, $P < 0.001$, ***)*

Amino acid	29.08.2024		12.09.2024		26.09.2024	
	raw	FDR	raw	FDR	raw	FDR
Total	0.027 *		0.048		0.032 *	
alanine	0.027 *	0.169	0.039 *	0.442	0.023 *	0.281
arginine	0.318	0.362	0.970	0.970	0.330	0.504
asparagine	0.733	0.763	0.289	0.470	0.102	0.332
aspartic.acid	0.237	0.312	0.677	0.800	0.164	0.426
b_aminoisobutyricacid	0.117	0.216	0.112	0.442	0.249	0.458
citrulline			0.932	0.970	0.733	0.825
cystine	0.105	0.216	0.403	0.523	0.762	0.825
g_aminobutyric_acid	0.010 **	0.122	0.077	0.442	0.021 *	0.281
glutamic_acid	0.046 *	0.173	0.164	0.442	0.298	0.485
glutamine	0.298	0.355	0.482	0.597	0.543	0.744
glycine	0.137	0.216	0.310	0.475	0.827	0.860
histidine	0.878	0.878	0.249	0.458	0.651	0.825
isoleucine	0.093	0.216	0.174	0.442	0.249	0.458
leucine	0.141	0.216	0.179	0.442	0.185	0.436
lysine	0.134	0.216	0.141	0.442	0.121	0.350
methionine	0.055	0.173	0.357	0.516	0.733	0.825
ornithine	0.289	0.355	0.208	0.442	0.878	0.878
phenylalanine	0.066	0.183	0.174	0.442	0.093	0.332
proline	0.001 **	0.032 *	0.878	0.970	0.085	0.332
serine	0.368	0.400	0.395	0.523	0.468	0.676
threonine	0.147	0.216	0.196	0.442	0.264	0.458
tryptophan	0.110	0.216	0.932	0.970	0.739	0.825
tyrosine	0.051	0.173	0.264	0.458	0.065	0.332
urea	0.208	0.289	0.054	0.442	0.264	0.458
valine	0.036 *	0.173	0.221	0.442	0.067	0.332

Supplementary Table 16 Amino acid exudation rates under the Control, Foliar N1 and Foliar N2 treatments at three independent sampling dates (29 August, 12 September and 26 September 2024). Values are presented as mean $\pm$ SD (n = 5) and are expressed as nmol g⁻¹ root DW h⁻¹. Different lowercase letters indicate significant differences among treatments within each sampling date according to Bonferroni-adjusted pairwise comparisons

Amino acid	29.08.2024			12.09.2024			26.09.2024		
	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2	Control	Foliar N1	Foliar N2
Total	1.95 $\pm$ 1.03 a	6.13 $\pm$ 2.73 b	3.64 $\pm$ 2.66 ab	11.73 $\pm$ 2.53 a	16.97 $\pm$ 5.08 a	18.33 $\pm$ 6.19 a	8.03 $\pm$ 3.16 a	18.88 $\pm$ 10.66 ab	22.87 $\pm$ 8.85 b
alanine	0.26 $\pm$ 0.21 a	1.00 $\pm$ 0.34 b	0.64 $\pm$ 0.62 ab	1.63 $\pm$ 0.55 a	3.42 $\pm$ 1.29 b	2.56 $\pm$ 1.31 ab	0.90 $\pm$ 0.47 a	3.59 $\pm$ 2.04 b	2.47 $\pm$ 1.44 ab
arginine	0.01 $\pm$ 0.02 a	0.05 $\pm$ 0.09 a	0.02 $\pm$ 0.02 a	0.08 $\pm$ 0.08 a	0.16 $\pm$ 0.20 a	0.14 $\pm$ 0.13 a	0.07 $\pm$ 0.02 a	0.06 $\pm$ 0.04 a	0.13 $\pm$ 0.10 a
asparagine	0.01 $\pm$ 0.02 a	0.02 $\pm$ 0.04 a	0.01 $\pm$ 0.02 a	0.27 $\pm$ 0.29 a	0.94 $\pm$ 1.20 a	0.46 $\pm$ 0.36 a	0.13 $\pm$ 0.09 a	0.19 $\pm$ 0.12 a	0.44 $\pm$ 0.29 a
aspartic.acid	0.07 $\pm$ 0.05 a	0.30 $\pm$ 0.32 a	0.14 $\pm$ 0.11 a	0.36 $\pm$ 0.20 a	0.46 $\pm$ 0.23 a	0.59 $\pm$ 0.40 a	0.15 $\pm$ 0.12 a	0.22 $\pm$ 0.19 a	0.36 $\pm$ 0.18 a
b_aminoisobutyricacid	0.01 $\pm$ 0.01 a	0.00 $\pm$ 0.00 a	0.00 $\pm$ 0.00 a	0.15 $\pm$ 0.12 a	0.56 $\pm$ 0.47 a	0.49 $\pm$ 0.32 a	0.49 $\pm$ 0.79 a	0.86 $\pm$ 1.26 a	3.45 $\pm$ 5.97 a
citrulline	0.00 $\pm$ 0.00 a	0.00 $\pm$ 0.00 a	0.00 $\pm$ 0.00 a	0.04 $\pm$ 0.02 a	0.06 $\pm$ 0.05 a	0.05 $\pm$ 0.03 a	0.02 $\pm$ 0.01 a	0.04 $\pm$ 0.04 a	0.06 $\pm$ 0.08 a
cystine	0.01 $\pm$ 0.01 a	0.06 $\pm$ 0.03 a	0.05 $\pm$ 0.11 a	0.10 $\pm$ 0.10 a	0.22 $\pm$ 0.20 a	0.03 $\pm$ 0.01 a	0.01 $\pm$ 0.01 a	0.02 $\pm$ 0.01 a	0.03 $\pm$ 0.04 a
g_aminobutyric_acid	0.05 $\pm$ 0.03 a	1.18 $\pm$ 0.66 b	0.45 $\pm$ 0.66 ab	4.24 $\pm$ 1.02 a	6.20 $\pm$ 3.22 a	7.73 $\pm$ 2.51 a	3.14 $\pm$ 2.11 a	7.94 $\pm$ 3.96 ab	9.45 $\pm$ 2.95 b
glutamic_acid	0.34 $\pm$ 0.13 a	1.02 $\pm$ 0.71 b	0.72 $\pm$ 0.47 ab	0.72 $\pm$ 0.46 a	1.16 $\pm$ 0.47 a	1.70 $\pm$ 1.13 a	0.54 $\pm$ 0.47 a	0.79 $\pm$ 0.25 a	1.11 $\pm$ 0.61 a
glutamine	0.01 $\pm$ 0.03 a	0.11 $\pm$ 0.17 a	0.14 $\pm$ 0.26 a	0.69 $\pm$ 0.65 a	0.66 $\pm$ 0.29 a	0.86 $\pm$ 0.43 a	0.35 $\pm$ 0.23 a	0.55 $\pm$ 0.33 a	0.65 $\pm$ 0.52 a
glycine	0.11 $\pm$ 0.06 a	0.26 $\pm$ 0.08 a	0.24 $\pm$ 0.18 a	0.48 $\pm$ 0.21 a	0.32 $\pm$ 0.07 a	0.40 $\pm$ 0.11 a	0.34 $\pm$ 0.29 a	0.45 $\pm$ 0.44 a	0.59 $\pm$ 0.63 a
histidine	0.05 $\pm$ 0.03 a	0.05 $\pm$ 0.04 a	0.04 $\pm$ 0.02 a	0.11 $\pm$ 0.05 a	0.08 $\pm$ 0.04 a	0.11 $\pm$ 0.03 a	0.09 $\pm$ 0.06 a	0.12 $\pm$ 0.12 a	0.18 $\pm$ 0.20 a
isoleucine	0.07 $\pm$ 0.10 a	0.12 $\pm$ 0.04 a	0.06 $\pm$ 0.05 a	0.31 $\pm$ 0.10 a	0.23 $\pm$ 0.10 a	0.36 $\pm$ 0.15 a	0.13 $\pm$ 0.07 a	0.37 $\pm$ 0.36 a	0.30 $\pm$ 0.25 a
leucine	0.06 $\pm$ 0.06 a	0.13 $\pm$ 0.05 a	0.06 $\pm$ 0.06 a	0.19 $\pm$ 0.03 a	0.17 $\pm$ 0.06 a	0.27 $\pm$ 0.09 a	0.12 $\pm$ 0.06 a	0.28 $\pm$ 0.23 a	0.28 $\pm$ 0.25 a
lysine	0.03 $\pm$ 0.02 a	0.07 $\pm$ 0.04 a	0.04 $\pm$ 0.03 a	0.02 $\pm$ 0.02 a	0.03 $\pm$ 0.02 a	0.02 $\pm$ 0.01 a	0.04 $\pm$ 0.03 a	0.08 $\pm$ 0.07 a	0.11 $\pm$ 0.10 a
methionine	0.00 $\pm$ 0.00 a	0.02 $\pm$ 0.02 a	0.01 $\pm$ 0.01 a	0.03 $\pm$ 0.01 a	0.02 $\pm$ 0.01 a	0.04 $\pm$ 0.02 a	0.02 $\pm$ 0.01 a	0.02 $\pm$ 0.03 a	0.02 $\pm$ 0.03 a
ornithine	0.03 $\pm$ 0.02 a	0.04 $\pm$ 0.02 a	0.04 $\pm$ 0.03 a	0.16 $\pm$ 0.08 a	0.10 $\pm$ 0.12 a	0.10 $\pm$ 0.06 a	0.11 $\pm$ 0.11 a	0.11 $\pm$ 0.12 a	0.17 $\pm$ 0.21 a
phenylalanine	0.05 $\pm$ 0.10 a	0.16 $\pm$ 0.07 a	0.03 $\pm$ 0.05 a	0.17 $\pm$ 0.02 a	0.20 $\pm$ 0.03 a	0.21 $\pm$ 0.06 a	0.10 $\pm$ 0.09 a	0.21 $\pm$ 0.18 a	0.27 $\pm$ 0.15 a
proline	0.00 $\pm$ 0.00 a	0.02 $\pm$ 0.01 b	0.00 $\pm$ 0.00 a	0.24 $\pm$ 0.05 a	0.32 $\pm$ 0.34 a	0.22 $\pm$ 0.13 a	0.09 $\pm$ 0.07 a	0.55 $\pm$ 0.58 a	0.36 $\pm$ 0.35 a
serine	0.18 $\pm$ 0.09 a	0.30 $\pm$ 0.13 a	0.25 $\pm$ 0.14 a	0.69 $\pm$ 0.31 a	0.49 $\pm$ 0.10 a	0.61 $\pm$ 0.17 a	0.49 $\pm$ 0.43 a	0.78 $\pm$ 0.78 a	0.95 $\pm$ 1.06 a
threonine	0.12 $\pm$ 0.09 a	0.22 $\pm$ 0.07 a	0.13 $\pm$ 0.08 a	0.23 $\pm$ 0.08 a	0.23 $\pm$ 0.05 a	0.33 $\pm$ 0.14 a	0.16 $\pm$ 0.10 a	0.31 $\pm$ 0.24 a	0.29 $\pm$ 0.19 a
tryptophan	0.00 $\pm$ 0.00 a	0.01 $\pm$ 0.01 a	0.00 $\pm$ 0.01 a	0.04 $\pm$ 0.02 a	0.04 $\pm$ 0.03 a	0.05 $\pm$ 0.04 a	0.02 $\pm$ 0.02 a	0.03 $\pm$ 0.03 a	0.04 $\pm$ 0.08 a
tyrosine	0.03 $\pm$ 0.05 a	0.20 $\pm$ 0.08 a	0.12 $\pm$ 0.11 a	0.28 $\pm$ 0.14 a	0.37 $\pm$ 0.07 a	0.23 $\pm$ 0.19 a	0.13 $\pm$ 0.12 a	0.48 $\pm$ 0.41 a	0.34 $\pm$ 0.42 a
urea	1.60 $\pm$ 1.15 a	4.83 $\pm$ 6.63 a	5.80 $\pm$ 4.74 a	2.82 $\pm$ 1.65 a	6.96 $\pm$ 3.47 a	7.16 $\pm$ 7.54 a	3.75 $\pm$ 1.38 a	8.34 $\pm$ 5.29 a	13.31 $\pm$ 12.82 a
valine	0.43 $\pm$ 0.26 a	0.81 $\pm$ 0.17 a	0.46 $\pm$ 0.16 a	0.50 $\pm$ 0.12 a	0.53 $\pm$ 0.13 a	0.77 $\pm$ 0.32 a	0.39 $\pm$ 0.12 a	0.82 $\pm$ 0.47 a	0.83 $\pm$ 0.46 a

6.2. RDA vector details log1p & CLR exuded AA

Supplementary Table 17 Results of the envfit analysis for redundancy analysis (RDA) of log1p-transformed amino acid (AA) exudation rates. For each amino acid and sampling date, vector coordinates (v1, v2), vector magnitude (mag), coefficient of determination (envfit r²), and permutation-based P values (envfit P) are reported

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
29.08.2024	γ_aminobutyric_acid	-0.6949	0.0313	0.6956	0.848	0.001
29.08.2024	alanine	-0.4577	-0.0343	0.4590	0.864	0.001
29.08.2024	glutamic_acid	-0.3630	-0.0743	0.3705	0.835	0.001
29.08.2024	valine	-0.2497	0.0825	0.2630	0.547	0.001
29.08.2024	aspartic.acid	-0.1751	0.0160	0.1759	0.472	0.001
29.08.2024	tyrosine	-0.1487	-0.0177	0.1498	0.265	0.013
29.08.2024	glycine	-0.1174	-0.0532	0.1289	0.555	0.004
29.08.2024	phenylalanine	-0.1057	0.0631	0.1231	0.590	0.002
29.08.2024	glutamine	-0.0735	-0.0767	0.1063	0.498	0.004
29.08.2024	threonine	-0.0860	0.0325	0.0919	0.563	0.001
29.08.2024	serine	-0.0905	-0.0111	0.0912	0.291	0.012
29.08.2024	leucine	-0.0690	0.0286	0.0747	0.671	0.001
29.08.2024	isoleucine	-0.0527	0.0284	0.0599	0.330	0.009
29.08.2024	cystine	-0.0500	-0.0193	0.0536	0.023	0.403
29.08.2024	arginine	-0.0397	0.0104	0.0410	0.088	0.109
29.08.2024	lysine	-0.0377	0.0114	0.0394	0.096	0.116

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
29.08.2024	proline	-0.0183	0.0084	0.0201	0.147	0.035
29.08.2024	methionine	-0.0185	0.0037	0.0189	0.101	0.087
29.08.2024	ornithine	-0.0135	-0.0052	0.0144	0.310	0.005
29.08.2024	asparagine	-0.0092	0.0084	0.0124	0.035	0.282
29.08.2024	histidine	0.0024	0.0063	0.0068	0.000	0.891
29.08.2024	tryptophan	-0.0066	0.0000	0.0066	0.087	0.127
29.08.2024	β _aminoisobutyricacid	0.0051	0.0036	0.0062	0.049	0.178
12.09.2024	alanine	-0.3819	-0.2203	0.4409	0.492	0.002
12.09.2024	γ _aminobutyric_acid	-0.3829	0.1962	0.4302	0.724	0.001
12.09.2024	glutamic_acid	-0.3314	0.1354	0.3580	0.598	0.001
12.09.2024	asparagine	-0.2249	-0.1800	0.2881	0.089	0.100
12.09.2024	β _aminoisobutyricacid	-0.2596	-0.0406	0.2627	0.275	0.008
12.09.2024	valine	-0.0929	0.1142	0.1472	0.756	0.001
12.09.2024	cystine	-0.0054	-0.1381	0.1382	0.379	0.004
12.09.2024	aspartic.acid	-0.1084	0.0598	0.1239	0.193	0.025
12.09.2024	glutamine	-0.0777	0.0859	0.1159	0.000	0.928
12.09.2024	serine	0.0743	0.0702	0.1023	0.026	0.360
12.09.2024	tyrosine	-0.0064	-0.0969	0.0971	0.014	0.456
12.09.2024	glycine	0.0746	0.0496	0.0896	0.076	0.151
12.09.2024	isoleucine	0.0102	0.0842	0.0848	0.105	0.098
12.09.2024	threonine	-0.0415	0.0653	0.0774	0.463	0.001

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
12.09.2024	leucine	-0.0233	0.0692	0.0730	0.223	0.025
12.09.2024	proline	-0.0124	-0.0508	0.0523	0.006	0.654
12.09.2024	arginine	-0.0500	-0.0128	0.0516	0.006	0.623
12.09.2024	ornithine	0.0487	0.0057	0.0491	0.002	0.785
12.09.2024	phenylalanine	-0.0340	0.0091	0.0352	0.057	0.206
12.09.2024	histidine	0.0132	0.0275	0.0305	0.040	0.280
12.09.2024	citrulline	-0.0127	-0.0095	0.0159	0.032	0.294
12.09.2024	methionine	-0.0003	0.0119	0.0119	0.025	0.378
12.09.2024	lysine	-0.0090	-0.0048	0.0102	0.002	0.760
12.09.2024	tryptophan	0.0004	0.0057	0.0057	0.000	0.899
26.09.2024	γ -aminobutyric_acid	-0.7372	0.0318	0.7379	0.686	0.001
26.09.2024	alanine	-0.5367	-0.2530	0.5933	0.861	0.001
26.09.2024	β -aminoisobutyricacid	-0.3767	0.2955	0.4787	0.841	0.001
26.09.2024	glutamic_acid	-0.2117	0.0685	0.2225	0.336	0.006
26.09.2024	proline	-0.1924	-0.1048	0.2191	0.624	0.001
26.09.2024	valine	-0.2004	-0.0229	0.2017	0.738	0.001
26.09.2024	tyrosine	-0.1498	-0.0997	0.1799	0.610	0.001
26.09.2024	asparagine	-0.1313	0.1080	0.1700	0.031	0.313
26.09.2024	serine	-0.1478	0.0250	0.1499	0.315	0.009
26.09.2024	glutamine	-0.1283	0.0104	0.1287	0.053	0.223
26.09.2024	isoleucine	-0.1169	-0.0452	0.1253	0.633	0.001

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
26.09.2024	aspartic.acid	-0.1027	0.0639	0.1210	0.208	0.029
26.09.2024	leucine	-0.0996	-0.0165	0.1010	0.552	0.001
26.09.2024	phenylalanine	-0.0958	0.0233	0.0986	0.417	0.002
26.09.2024	glycine	-0.0870	0.0368	0.0944	0.239	0.023
26.09.2024	threonine	-0.0820	-0.0214	0.0847	0.533	0.001
26.09.2024	histidine	-0.0448	0.0279	0.0528	0.233	0.039
26.09.2024	arginine	-0.0235	0.0391	0.0456	0.160	0.063
26.09.2024	lysine	-0.0420	0.0118	0.0436	0.372	0.008
26.09.2024	ornithine	-0.0243	0.0336	0.0415	0.140	0.072
26.09.2024	citrulline	-0.0211	0.0051	0.0217	0.205	0.051
26.09.2024	tryptophan	-0.0165	0.0057	0.0175	0.136	0.100
26.09.2024	cystine	-0.0121	0.0071	0.0140	0.073	0.159
26.09.2024	methionine	-0.0001	-0.0002	0.0002	0.133	0.076

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Supplementary Table 18 Results of the envfit analysis associated with the redundancy analysis (RDA) of centred log-ratio (CLR)-transformed amino acid (AA) exudation profiles. For each amino acid and sampling date, vector coordinates (v1, v2), vector magnitude (mag), coefficient of determination (envfit r²), and permutation-based P values (envfit P) are reported

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
29.08.2024	β_aminoisobutyricacid	0.9299	0.2946	0.9754	0.701	0.001
29.08.2024	proline	-0.7072	0.5282	0.8827	0.381	0.005
29.08.2024	histidine	0.7731	-0.0891	0.7782	0.424	0.002
29.08.2024	γ_aminobutyric_acid	-0.7084	-0.2858	0.7639	0.334	0.001
29.08.2024	glutamine	-0.1983	-0.7335	0.7598	0.740	0.001
29.08.2024	phenylalanine	-0.6599	0.3180	0.7326	0.189	0.036
29.08.2024	cystine	-0.4598	0.3888	0.6021	0.443	0.002
29.08.2024	tyrosine	-0.5851	-0.0587	0.5880	0.170	0.036
29.08.2024	methionine	-0.4099	-0.1655	0.4420	0.064	0.173
29.08.2024	asparagine	0.3349	0.1666	0.3740	0.022	0.389
29.08.2024	serine	0.3414	-0.0248	0.3423	0.406	0.004
29.08.2024	ornithine	0.2915	-0.0873	0.3043	0.230	0.023
29.08.2024	threonine	0.2604	0.0675	0.2691	0.385	0.002
29.08.2024	arginine	-0.2089	-0.1696	0.2690	0.000	0.904
29.08.2024	valine	0.2557	0.0427	0.2593	0.295	0.014
29.08.2024	glycine	0.2138	-0.0900	0.2320	0.018	0.392
29.08.2024	leucine	0.1469	0.1720	0.2262	0.070	0.146
29.08.2024	glutamic_acid	0.1956	-0.0941	0.2171	0.070	0.133

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
29.08.2024	aspartic.acid	-0.1085	-0.1821	0.2120	0.029	0.340
29.08.2024	lysine	0.1931	0.0633	0.2032	0.065	0.169
29.08.2024	isoleucine	0.1224	0.0165	0.1235	0.036	0.271
29.08.2024	alanine	0.0247	-0.0523	0.0579	0.000	0.892
29.08.2024	tryptophan	-0.0378	-0.0254	0.0455	0.002	0.741
12.09.2024	cystine	0.2705	0.6515	0.7054	0.760	0.001
12.09.2024	asparagine	-0.6822	0.1368	0.6957	0.351	0.003
12.09.2024	β _aminoisobutyricacid	-0.5598	0.0033	0.5598	0.315	0.009
12.09.2024	ornithine	0.4166	-0.0924	0.4268	0.079	0.131
12.09.2024	tyrosine	0.0525	0.3305	0.3347	0.045	0.215
12.09.2024	tryptophan	0.2618	0.1783	0.3167	0.062	0.188
12.09.2024	methionine	0.1930	-0.2414	0.3091	0.208	0.021
12.09.2024	glutamic_acid	-0.2586	-0.1467	0.2973	0.424	0.003
12.09.2024	alanine	-0.2257	0.1359	0.2635	0.006	0.612
12.09.2024	histidine	0.2038	-0.1541	0.2555	0.282	0.010
12.09.2024	isoleucine	0.1749	-0.1623	0.2386	0.542	0.001
12.09.2024	glycine	0.2275	-0.0450	0.2319	0.085	0.121
12.09.2024	lysine	-0.2012	0.0417	0.2055	0.024	0.344
12.09.2024	leucine	0.0888	-0.1827	0.2031	0.390	0.002
12.09.2024	serine	0.1935	-0.0587	0.2022	0.076	0.147
12.09.2024	γ _aminobutyric_acid	-0.1160	-0.1392	0.1812	0.165	0.046

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
12.09.2024	proline	0.1523	0.0932	0.1786	0.000	0.930
12.09.2024	valine	-0.0012	-0.1387	0.1387	0.282	0.015
12.09.2024	threonine	0.0217	-0.1325	0.1342	0.212	0.027
12.09.2024	glutamine	-0.0586	-0.1145	0.1286	0.000	0.949
12.09.2024	aspartic.acid	-0.0790	-0.0698	0.1054	0.083	0.136
12.09.2024	citrulline	0.0122	0.0877	0.0885	0.000	0.917
12.09.2024	arginine	-0.0806	0.0278	0.0853	0.000	0.889
12.09.2024	phenylalanine	-0.0063	-0.0088	0.0108	0.006	0.646
26.09.2024	proline	-0.6157	0.1957	0.6461	0.814	0.001
26.09.2024	methionine	0.4061	0.3401	0.5298	0.483	0.005
26.09.2024	β _aminoisobutyricacid	0.1488	-0.4163	0.4421	0.782	0.001
26.09.2024	tyrosine	-0.4090	0.0047	0.4090	0.172	0.042
26.09.2024	arginine	0.3115	0.0327	0.3132	0.235	0.019
26.09.2024	citrulline	0.2963	0.1015	0.3132	0.072	0.180
26.09.2024	alanine	-0.2969	-0.0568	0.3023	0.272	0.016
26.09.2024	ornithine	0.2260	0.1020	0.2479	0.080	0.131
26.09.2024	aspartic.acid	0.1747	-0.1695	0.2434	0.124	0.077
26.09.2024	asparagine	0.1248	-0.2008	0.2365	0.008	0.580
26.09.2024	γ _aminobutyric_acid	-0.1270	-0.1726	0.2143	0.276	0.005
26.09.2024	glycine	0.1050	0.0856	0.1355	0.023	0.365
26.09.2024	isoleucine	-0.1273	0.0292	0.1306	0.045	0.249

Experiment	AminoAcid	v1	v2	mag	envfit_r2	envfit_p
26.09.2024	cystine	-0.1090	0.0687	0.1288	0.125	0.082
26.09.2024	histidine	0.1184	0.0266	0.1214	0.102	0.096
26.09.2024	phenylalanine	-0.0203	-0.1133	0.1151	0.173	0.040
26.09.2024	lysine	-0.0203	-0.0797	0.0823	0.050	0.225
26.09.2024	glutamine	-0.0408	0.0695	0.0806	0.002	0.743
26.09.2024	leucine	-0.0686	0.0416	0.0802	0.000	0.992
26.09.2024	serine	0.0501	0.0585	0.0770	0.003	0.674
26.09.2024	tryptophan	-0.0621	0.0435	0.0758	0.010	0.573
26.09.2024	glutamic_acid	-0.0163	-0.0710	0.0728	0.023	0.387
26.09.2024	threonine	-0.0180	0.0553	0.0582	0.050	0.238
26.09.2024	valine	-0.0304	0.0249	0.0393	0.012	0.500