



Influence of Soil Extractable Plant Nutrients on the Walnut Kernel Ionome in Southern Kyrgyzstan at Different Elevations

Zhyldyz Oskonbaeva¹ · Rainer Georg Joergensen² · Florian Wichern¹

Received: 15 February 2024 / Accepted: 4 November 2024 / Published online: 20 November 2024
© The Author(s) 2024

Abstract

Background and Aims Climate change causes altered precipitation patterns and temperature increases, which may affect food quantity and quality. In Kyrgyzstan anticipated temperature changes are expected to influence the physiology of walnuts (*Juglans regia* L.) and soil properties relevant to plant nutrition, thereby impacting walnut fruit quality. This study explores the relationship between plant available nutrients in soil and walnut fruit nutrient content as affected by future temperature changes.

Methods The soil samples were collected in the walnut forests of Southern Kyrgyzstan from top- and subsoils at three elevation levels (1000, 1300, and 1600 m above sea level). The walnut samples were collected from the same sampling sites and both soil Mehlich-3 extracts and acid digests of walnut fruits analyzed by ICP-OES.

Results The results revealed no consistent relationship between Mehlich-3 extractable elements and walnut extractable elements, except for a weak negative correlation with zinc (Zn). Stronger relationships were observed among soil elements, but no clear associations with elevation levels were found. The walnut kernel ionome exhibited differences, particularly in calcium (Ca) and potassium (K) concentrations, with the low elevation site showing higher Ca and lower K concentrations compared to the high elevation site.

Conclusions Differences in average temperature as caused by elevation did not affect available plant nutrients in the soil but altered the walnut kernel ionome and thus affected the walnut quality in the investigated forest systems. Future investigations should focus on climate change effects, such as altered precipitation patterns and drought, which may impact walnut fruit development and kernel properties.

Keywords *Juglans regia* · Walnut Element Ionome · Soil Extractable Elements · Walnut Forest · Soil Properties

1 Introduction

Climate change with global warming and effects on ecosystems has become an important research topic. Many studies are focusing on temperature increases around the world because climate change results in temperature increase, which is also pronounced in Central Asia. The observed

(Chontoev and Bazhanova 2021; Haag et al. 2019; Hu et al. 2014) and modeled (Lioubimtseva and Cole 2006; Liu et al. 2020) research data show the average temperature increase by 0.3 to 1.0 °C in Central Asia during the last 60 years. The predicted (Chontoev and Bazhanova 2021) research data show the average temperature will increase by 1.4 to 2.4 °C in 2100. Central Asian countries are prone to droughts due to the semi-arid climate of the region and are therefore affected more severely by climate change induced weather-pattern changes (Jiang and Zhou 2023). The temperature increase along with the altered precipitation may affect ecosystems and plants and therefore may alter food quantity and quality (Cowles et al. 2018; Raj et al. 2022; Raza et al. 2019). The expected changes in temperature in Kyrgyzstan in particular in the walnut-fruit forests may influence walnut plant physiology (Luedeling et al. 2011) and thus fruit quality (Alae-Carew et al. 2020; Christopoulos and Ouzounidou 2021), as

✉ Zhyldyz Oskonbaeva
zhyldyz.oskonbaeva@hochschule-rhein-waal.de

¹ Soil Science and Plant Nutrition, Sustainable Food Systems Research Centre, Rhine-Waal University of Applied Sciences, Kleve, Germany

² Department of Soil Biology and Plant Nutrition, University of Kassel, Nordbahnhofstr. 1a, 37213 Witzenhausen, Germany

well as soil processes (Brevik 2013; Mekonnen et al. 2018), such as mineralization and therefore plant nutrition. These forests play an important role for locals and internationally represent an important resource contributing to the goals of Convention on Biological Diversity (CBN), which is to conserve and protect biodiversity, especially genetic diversity of ancestral strains of nut tree species (Cantarello et al. 2014; Temirbekov 2010). Increasing temperatures in Kyrgyzstan thus might result in changes of walnut quality in general and in particular in their nutrient content. Soil properties influence nutrient uptake of walnuts trees (Fortier et al. 2020). Roots take up nutrients from the soil solution mainly as inorganic ions. The rate of nutrient uptake is determined by the concentration near the root. Although the rate of nutrient uptake is unrelated to the rate of water uptake, the concentration of nutrients at root surfaces is highly dependent on soil water content (Burley 2004).

Over the last four decades, changes in plant and soil nutrient concentrations along altitudinal gradients have been intensively studied (Grubb 2003; Körner 1989; Sundqvist et al. 2013). The microbial and chemical properties of soils along an elevation gradient did not show any differences between sites from Kyrgyz walnut-fruit forests with similar vegetation (Osmonbaeva et al. 2023). The plant available nutrients from the same ecosystem studied by Meisen et al. (2021) along an elevation gradient also did not show an altitudinal trend, where likely the similarity in vegetation was the driving factor for soil processes.

Researchers have assumed that soil organic carbon (SOC) concentration may increase while soil nutrient availability may decrease with increasing elevation because low temperatures at higher altitudes are likely to limit decomposition and other soil microbial processes (Sundqvist et al. 2013; Vincent et al. 2014). Higher temperatures may accelerate nutrient release from soil, potentially impacting walnut chemistry. Increased metabolic activity in plants due to rising temperatures could also influence nutrient uptake by walnuts. Soil depth is another factor affecting nutrient cycling and nutrient availability (Jobbágy and Jackson 2001; Li et al. 2022). The nutrient availability differs with soil depth, because SOC content decreases with depth which limits storage of some nutrients, such as N.

Elevation gradients can act as proxy of future temperature increase, assuming that the temperature at low elevation will represent the temperature of high elevation in the future. The walnut-fruit forest in Southern Kyrgyzstan is a unique ecosystem with a long vegetation history and was chosen as the research area. Three different sites at three different elevation levels were chosen with same exposition, similar vegetation, similar geology, and no long term differences in precipitation.

The objective of our study was to investigate the influence of available nutrients in the soil on the element content of walnut fruits (*Juglans regia* L.) in the walnut-fruit forest of Southern Kyrgyzstan at three different elevation levels. The following two questions were investigated using an elevation gradient between 1000 and 1600 m above sea level:

- (i) Is there a relationship between soil extractable elements and walnut element concentration?
- (ii) Are there differences between elevation sites in nutrient uptake, assuming that there are nutrient mobilisation and uptake processes affected by temperature differences?

2 Materials and Methods

2.1 Study Area

The investigation area is situated in the Jalal-Abad region on the slopes of the Fergana and Chatkal mountain ridges in southern Kyrgyzstan (Fig. 1). The investigated walnut-fruit forest is located on the south-western Tien Shan between 41°25' to 41°39'N and 72°88' to 73°06'E. The study area is located in the major forestry districts (village name): Achi (Charbak), Kyzyl-Unkur (Kyzyl-Unkur) and Arslanbap (Jay-Terek), with sampling sites on south-east slopes, where a continental subtropical climate prevails. In the region, the long-term average minimum temperature is -18 °C in winter and the average maximum is 26 °C in summer. The long-term average temperature (1983–2004) was 9.2 °C (Winter et al. 2009).

The vegetation of the walnut forests is dominated by walnut (*Juglans regia* L.) combined with hawthorn (*Crataegus turkestanica* Pojark.), and wild apple (*Malus sieversii* var. *Kirgizorum*). According to Sakbaeva et al. (2013) gray, gray brown, gray dark brown, chestnut-hued and brown soils, which correspond to Mollisols according to the World Reference Base (WRB 2022) are common on the mountain slopes between 1000 and 2500 m asl in the region.

2.2 Sampling and Storage

The walnut and soil samples were collected in October 2019 at three different elevations, which ranged from 1000 m to 1600 m asl (Charbak at 1000 m asl, Kyzyl-Unkur at 1300 m asl and Jay-Terek at 1600 m asl). The average daily temperatures of the study sites at 1000, 1300, and 1600 m above sea level (asl) are 23.5 °C, 22 °C, and 20 °C in July as well as -1.2, -2.1, and -3.2 °C in January, respectively. The majority of the annual precipitation, which ranges from 700

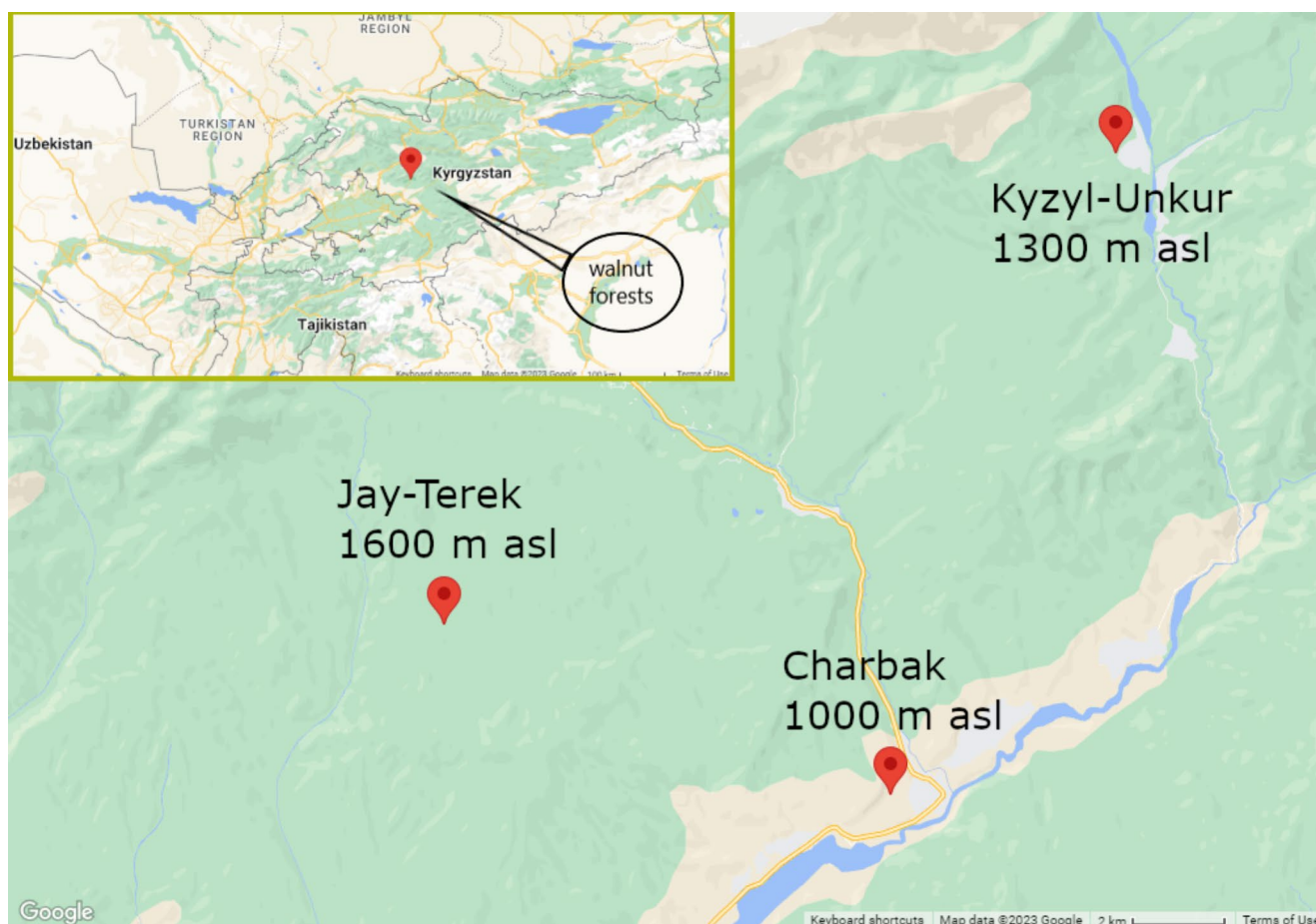


Fig. 1 Map of the walnut-fruit forest of Southern Kyrgyzstan showing sampling sites at different elevations www.google.com/maps

to 1000 mm at an elevation of 1000 to 2000 m asl, occurs during spring and winter (Sakbaeva et al. 2013). At every elevation in an area of 500 m², 10 trees per sampling site on the south-east slopes were randomly chosen with a mature walnut tree as central point. Twenty five fallen walnuts from each of ten representative individual trees were collected for kernel analyses. The nut samples were air dried and stored at 4 °C until analysis. After physical analysis kernels were ground and frozen at -18 °C. The soil samples were taken from the mineral topsoil at 0–30 cm and the subsoil at 30–60 cm depth with a soil corer during moist soil conditions. At every tree, ten sub-samples were taken by starting half-way between the trunk and the outer crown part and walking in a star-shaped circle around the tree. The sub-samples were mixed forming one replicate soil sample per tree per depth. The soil samples were stored in plastic bags at 4 °C. All soil samples were sieved (<2 mm) prior to analyses and air-dried where necessary.

2.3 Walnut Physical and Chemical Properties

The physical properties such as length, width, thickness and shell thickness of 25 walnut fruits from each tree were measured using a vernier caliper. The mass of walnut fruits and kernels were measured with a digital electronic balance (sensitivity 0.01 g). The sphericity and geometric mean diameter (Dg) were calculated according to Altuntas and Erkol (2010). Dry matter content was determined by drying samples for 24 h at 105 °C. Moisture content was determined and calculated using the moisture content method by AOAC (1999). Total C, N, and S were determined using an elemental analyser (Carlo Erba NA 1500 CNS Analyzer, Thermo Scientific) in subsamples of dried and milled walnut samples.

Mineral elements Calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P), sulphur (S), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn) and zinc (Zn) were extracted as described by Jones (2001) with modifications. Briefly, 0.5 g of kernel sample was weighed into a digestion tube and 5 mL HNO₃ (65%) was added for overnight incubation. Thereafter, samples were digested at 125 °C for

1 h. Then, 9 mL H₂O₂ (30%) was added in 3 steps into the digestion tube and boiled at 125 °C for 30 min until the solution was clear. The digest was diluted with distilled water, filtered and brought up to a final volume of 50 mL. Analysis was carried out with inductively coupled plasma atomic emission spectroscopy (ICP-OES, Optima 8000, Perkin Elmer, Waltham, USA).

2.4 Soil Physical and Chemical Properties

The soil texture was analyzed according to Gee and Or (2018) using a combined sieving and pipette method after pretreatment with H₂O₂ to remove SOM and HCl to remove carbonates. The soils contained 39–40% clay, 51–57% silt, and 1.3–7.7% sand at the three sites. Soil color varied from dark brown (10YR 4/3) to very dark brown (10YR 2/2) according to the Munsell Soil Color Charts.

Soil pH was assessed with a SevenMulti device (Mettler Toledo, Giessen, Germany) using air-dried sieved soil and deionized water (1:5 w/w). Extractable elements Ca, K, Mg, Na, P, Cu, Fe, Mn, and Zn were determined in Mehlich-3 solution. Briefly, 2 g air-dried soil sample was suspended in 20 mL Mehlich-3 solution and shaken for 5 min at 150 rev min⁻¹ (KS 4000, IKA, Staufen, Germany). The extracts were filtered (No. 305, VWR, Darmstadt, Germany) and diluted with water to make a 1/10 dilution and then analyzed by ICP-OES. Total soil C and N were determined using gas chromatography after combustion (Carlo Erba NA 1500 CNS Analyzer, Thermo Scientific) in subsamples of dried and milled soil samples. Carbonate content in the soil was determined using a calcimeter according to the operating instructions issued by the manufacturer (Eijkelkamp 2012). The difference between total C and carbonate C was used to calculate soil organic carbon (SOC).

2.5 Statistics

The open-source programming language R 3.6.3 with the R-Studio version 1.3.1073 was used for statistical analysis and graphical visualization. One way analysis of variance (ANOVA) was used for evaluation of site and soil depth differences followed by Tukey HSD when data was parametric. The Kruskal-Wallis test was used for non-parametric data to test for significant differences between sites and soil depths as well as for sites and walnut properties followed by Dunn's post hoc test. Significant differences were detected at $p < 0.05$. Results are arithmetic means of ten replicates per site and based on dry (24 h at 105 °C) soil and walnut weight. Pearson correlation coefficient was used to estimate the correlation between all measurable variables with a $p < 0.05$ significance threshold. Correlation coefficient interpretation: $r > 0.7$ strong positive, 0.7 to 0.5 moderate

positive, 0.5 to 0.3 weak positive, < -0.7 strong negative, -0.7 to -0.5 moderate negative, -0.5 to -0.3 weak negative (Rumsey 2016) with the value of $p < 0.05$.

3 Results

3.1 Walnut Physical Properties and Nutrient Content

The physical properties of walnuts revealed large variability within sites, especially for nut mass and nut length (Fig. 2), and only slight differences for two properties between elevation levels (Table 1). Firstly, nuts from medium elevation differed slightly from the nuts at high elevation in shell thickness. Secondly, the kernel percentage, which ranged from 44 to 47%, slightly decreased with increasing elevation. As a core quality property, nut mass ranged from 7.63 to 9.42 g and the kernel mass from 3.37 to 4.25 g, revealing no differences between sites. The element concentrations in walnut kernels also mostly did not differ significantly between studied elevation sites except for Ca and K (Table 2). While Ca content declined with increasing elevation, K content was higher at highest elevations (Fig. 3). Fe and Mn contents varied significantly with highest Fe values at medium elevation and highest Mn values at highest elevation (Table 2).

3.2 Soil Chemical Properties and Plant Available Nutrients

The soil chemical properties along the investigated elevation gradient were different between top- and subsoil and revealed (Table 3) some differences between sites, which mostly did not follow an elevation gradient. Only pH of the studied soil samples significantly decreased with increasing elevation for both soil depths and ranged from 6.9 to 7.9 in the topsoil and from 7.7 to 8.5 in the subsoil. Soil organic carbon (SOC) was similar at all three sites in the topsoil. In the subsoil there was a slight difference in SOC between sites, which did not however follow the elevation gradient. Most of the Mehlich-3 extractable elements (Table 4) showed weak significant differences between studied sites except for Cu, which did not reveal any differences. However, concentrations of elements did not follow the elevation gradient.

3.3 Soil and Walnut Element Correlations

The walnut element content did not correlate with Mehlich-3 extractable plant nutrients, except for Zn, which was negatively related (Fig. 4). Stronger correlations were found between Mehlich-3 extractable elements in the soil.

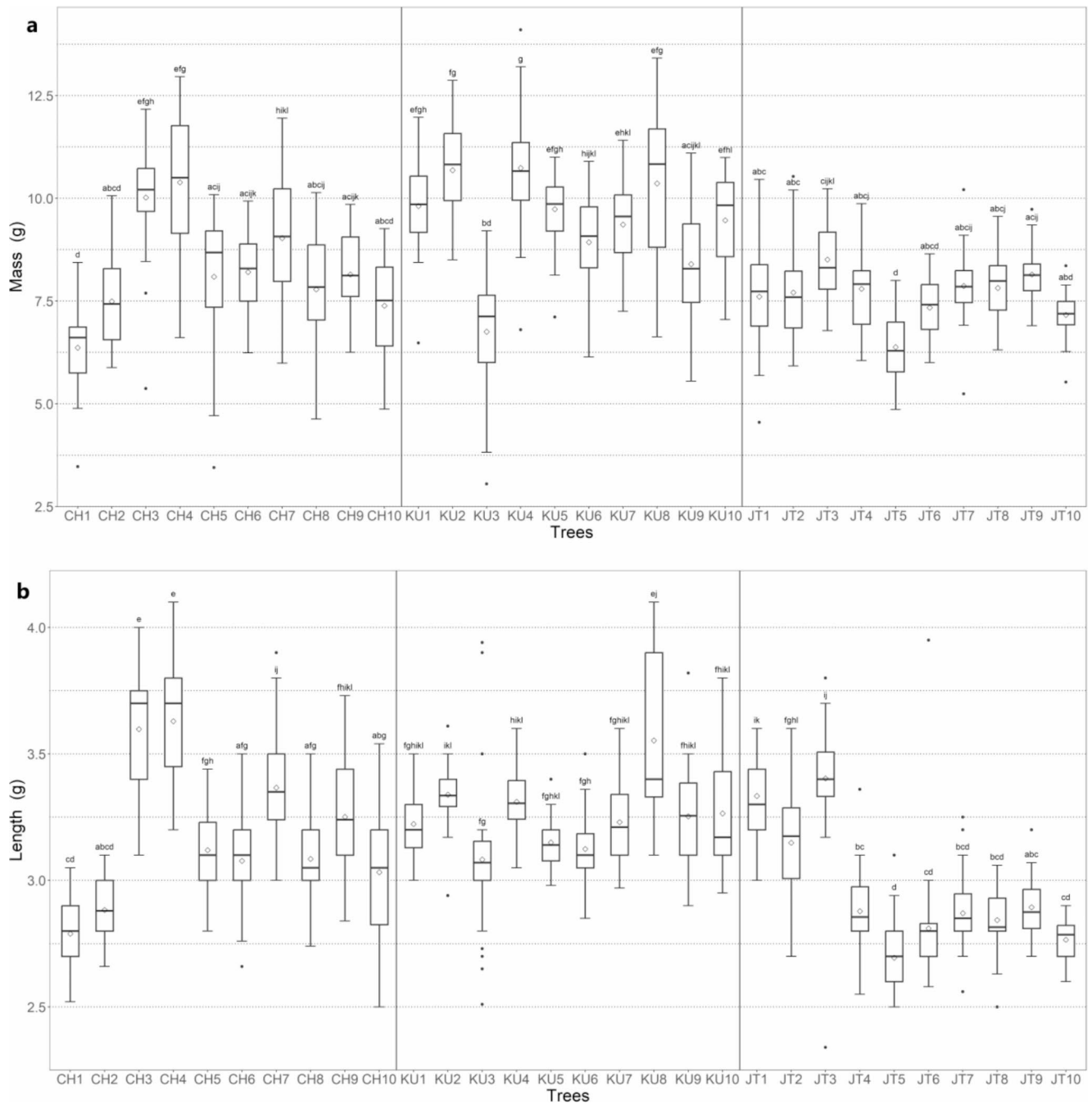


Fig. 2 Physical properties (**a** - mass, **b** - length) of walnut fruits at the three sites along an elevation gradient (Charbak (CH) low=1000 m asl; Kyzyl-Unkur (KU) medium=1300 m asl; Jay-Terek (JT) high=1600 m asl; asl=above sea level)

Table 1 Physical properties of walnuts (*Juglans regia* L.) along an elevation gradient

Elevation (m a.s.l.)	Length cm	Width	Thickness	Shell thickness	Dg g	Nut mass	Kernel mass	Sphericity %	Kernel mass proportion
1000									
Mean	3.24	2.84	2.74	0.18 ^b	2.92	8.29	3.92	92	47 ^a
SD	0.48	0.16	0.16	0.01	0.22	1.22	0.54	2.73	1.36
CV (± %)	15	6	6	4	7	15	14	3	2.87
1300									
Mean	3.26	3.01	2.96	0.21 ^a	3.07	9.42	4.25	94	45 ^b
SD	0.15	0.17	0.17	0.02	2.38	1.20	0.58	2.70	1.81
CV (± %)	4	6	6	11	3	13	14	3	4.01
1600									
Mean	2.96	2.46	2.74	0.17 ^c	2.92	7.63	3.37	95	44 ^b
SD	0.24	0.10	0.10	0.01	0.10	0.60	0.30	4.92	2.21
CV (± %)	8	3	2	4	3	8	9	5	5
<i>p</i> value	NS	NS	NS	< 0.01	NS	NS	NS	NS	< 0.01

Dg=geometric mean diameter, SD=standard deviation, CV=mean coefficient of variation between replicate samples ($n=10$); a.s.l.=above sea level; NS=not significant

In particular, P was positively related to a number of other elements, such as total N, Mg, Fe and Zn. In contrast, K was negatively related to Fe, P and Na and positively related to Mn. No such strong relationships were found for walnut kernel elements. Only P and Mg were strongly positively correlated and Ca and Mg moderately positively. Zn was weakly positively related to Mn, and Cu and Mn negatively to Ca. Soil pH only weakly affected walnut kernel Ca content positively and Mn content slightly negatively. However, soil pH was strongly negatively related to Mehlich-3 extractable Fe and P and somewhat more weakly to Mg. For K and Mn there was a weak negative correlation.

4 Discussion

An elevation gradient was chosen as a proxy of future temperature increase, assuming that the temperature at low elevation will represent the temperature of high elevation in the future. As the studied soil and walnut properties showed high variability within sites, there were almost no differences between elevation levels for many soil and walnut fruit properties. This may be due to comparable annual precipitation, vegetation, and parent material at the three sites. Previous studies by Meisen et al. (2021) and Oskonbaeva et al. (2023) in the same walnut-fruit forest systems have also shown that soil chemical properties were not different between the different elevation sites and that they also showed quite similar soil biological properties (Oskonbaeva et al. 2023). However, other studies investigating altitudinal effects on soil chemical properties have reported contrasting results, with either a decrease (Drollinger et al. 2017; Simsek et al. 2023) or an increase (He et al. 2016; Kamal et al. 2023) in soil organic C and total N for the litter caused by

reduced decomposition at higher elevation. The soil organic matter content is also affected by plant input quantity and quality and thus vegetation differences can more strongly influence SOM content than temperature differences caused by elevation (Massaccesi et al. 2020) as in our investigation where similar vegetation was present across the elevation gradient.

In the case of the physical properties of walnut fruits, no significant differences were observed between elevation levels, except for shell thickness and kernel mass proportion, confirming the earlier observation that elevation, especially temperature has no effect on the physical properties of walnut fruits (Meisen et al. 2021). Other studies revealed effects on physical and chemical properties of walnuts as caused by temperature differences due to altitude (Büyüksolak et al. 2020; Zeneli et al. 2005). However, we did not observe any clear elevation-based trend in shell thickness among the studied walnut fruits. This could be due to the allelic variation in walnuts which affects the walnut physical properties (Martínez et al. 2010). While Arzani et al. (2008) found a correlation between shell thickness and nut mass, our study did not yield similar results. One possible reason for the difference in shell thickness could be the influence of shading and light intensity at the sites. Zhao et al. (2019) examined the effect of shading and reported that it increased the thickness of walnut shells. Light intensity has also been linked to shell development in nuts, with variations observed even within the same cultivar when grown in different locations (Zhao et al. 2011). Additionally, lignin content, which was not measured in this study, has been identified as a significant factor influencing the shell structure of nuts (Zhao et al. 2019). Path analysis revealed that tree form, anthesis time, and shell thickness directly and positively influenced the harvest day (Beyhan and Demir 2006), which in return

Table 2 Element concentration of walnut (*Juglans regia* L.) kernels along an elevation gradient

Elevation (m a.s.l.)	Ca	K	Mg	Na	P	S	Cu	Fe	Mn	Zn	Cr
	mg 100 g ⁻¹										
1000											
Mean	195 ^a	417 ^b	155	9.4	356	300 ^a	1.7	3.2 ^b	3.8 ^b	3.0	0.01
SD	25	84	6.3	2.6	34	59	0.2	0.5	0.2	0.2	0.03
CV (± %)	13	20	4	27	10	25	14	11	8	8	14
1300											
Mean	174 ^a	403 ^b	157	10	355	200 ^b	1.5	4.1 ^a	2.9 ^b	2.7	0.02
SD	15	17	10	3.0	34	49	0.2	0.5	0.2	0.2	0.03
CV (± %)	8	4	6	29	10	27	14	11	8	5	19
1600											
Mean	159 ^b	465 ^a	154	9.6	345	327 ^a	1.6	3.9 ^a	8.5 ^a	3.1	0.02
SD	13	23	3.1	3.2	32	25	0.1	1.7	2	0.1	0.02
CV (± %)	10	12	11	12	13	16	15	20	25	23	23
p-value	<0.01	<0.01	NS	NS	NS	<0.05	NS	<0.05	<0.05	NS	NS

SD = standard deviation; CV = mean coefficient of variation between replicate samples ($n = 10$); a.s.l. = above sea level; NS = not significant

affects the kernel percentage of nuts. It is important to note that shell thickness can vary significantly among different walnut varieties and even between trees of the same variety (Amézquita et al. 2023; Bernard et al. 2017). Additionally, the interaction of multiple factors makes it a complex phenomenon difficult to precisely determine the impact of each factor on shell thickness and kernel percentage. We assume that the temperature increase will not influence the physical properties of walnut fruits at these ecosystems in general, as they occasionally experience high temperatures at all elevation levels due to the high temperature amplitude throughout the year.

In terms of the elemental composition of walnuts, our results showed high variability within sites, but almost no differences between elevation levels except for Ca and K contents. This variability can be due to genotypic variability and spatial heterogeneity of nutrient availability in soil, which affect the growth, yield, and quality of walnuts (Devin and Bujdosó 2022; Guney et al. 2021). The Ca content in walnuts showed a significant decrease with increasing elevation levels, and this could be attributed to genetics and physiological processes. Calcium content of studied Kyrgyz walnut fruits were higher than Swedish (Rodushkin et al. 2008), Turkish (Ozcan 2009), Romanian (Cosmulescu et al. 2009) and lower than Iranian walnuts (Aryapak and Ziarati 2014). Furthermore, Ca plays a role in numerous vital plant functions, such as promoting the absorption of nutrients by roots and aiding their transportation within the plant (White and Broadley 2003). The differences in Ca and K along the elevation gradient may be also due to the change in mineral content at the ripening stage of the walnut kernel (Amin et al. 2017). It is likely, that the walnuts at lower sites ripened a little earlier but sampling took place at the same time. Moreover, Ca ions have a dual effect on K and anions, inhibiting the inward flow of K while stimulating the opening of inward anion channels (Blatt 2000) and this could be another reason for increased Ca content and decreased K content with elevation. The K content of Kyrgyz walnut fruits was in the range of Canadian and French (Juranović Cindrić et al. 2018), Romanian (Cosmulescu et al. 2009) and lower than Iranian (Aryapak and Ziarati 2014) and Swedish (Rodushkin et al. 2008) walnuts. The K content in walnuts was found to vary significantly between different elevation levels, which may be attributed to differences in radiation. We assumed that trees at higher elevations tend to receive higher levels of radiation, which can contribute to the higher potassium levels. Temperature increase due to climate change may not affect walnut quality, in particular the elemental composition in the investigated forest systems.

The correlation analysis conducted in this study showed relationships, especially between Mehlich-3 extractable

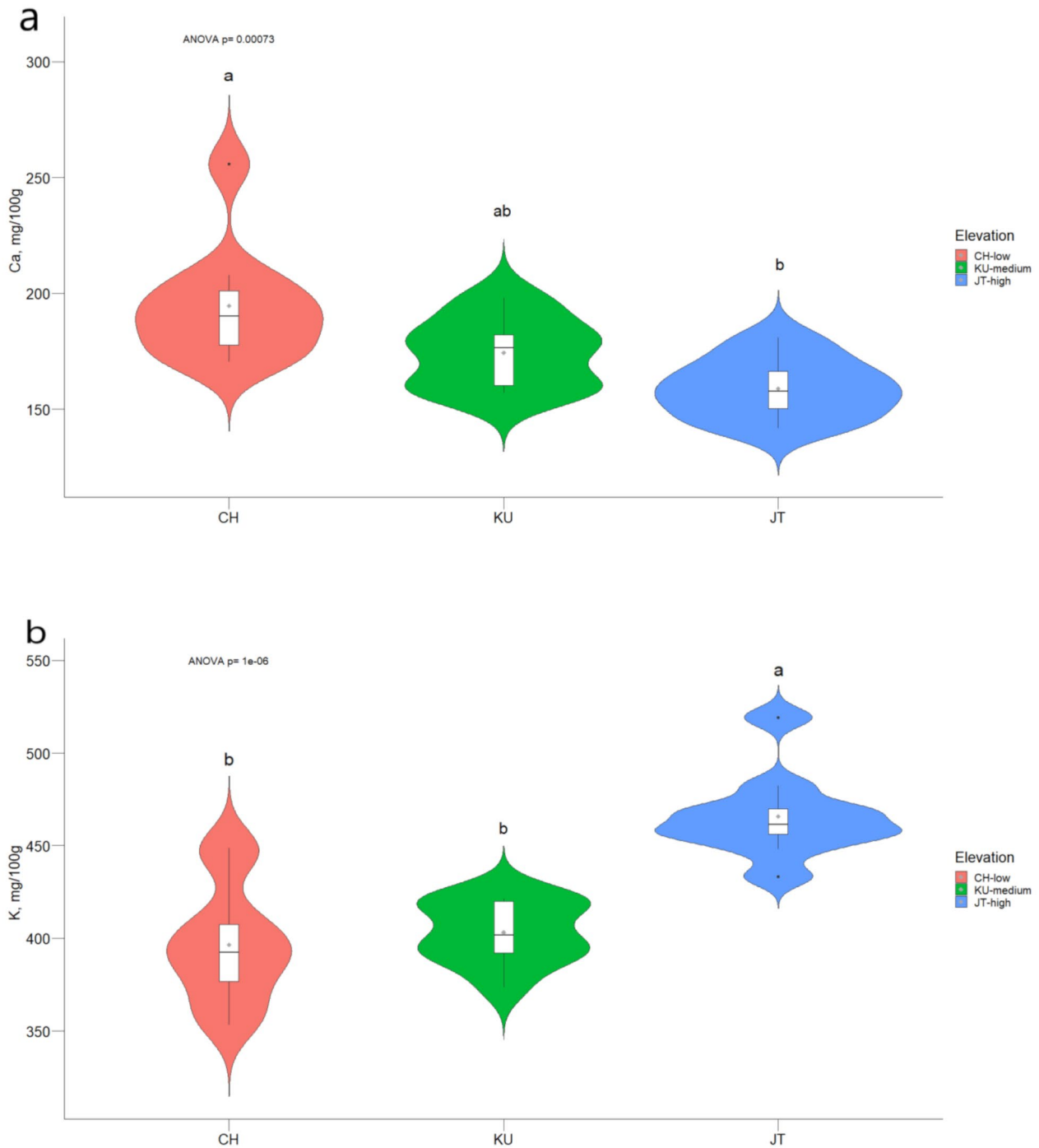


Fig. 3 Calcium (Ca) **(a)** and potassium (K) **(b)** content in walnut kernels at the three sites along an elevation gradient (Charbak (CH) low = 1000 m asl; Kyzyl-Unkur (KU) medium = 1300 m asl; Jay-Terek (JT) high = 1600 m asl; asl = above sea level)

elements in the soil. However, the relationship between soil and walnut elements was very weak, indicating that extractable elements in the soil do not provide reliable information about the elements in walnut fruits. Walnut trees appear to take up nutrients in the required amounts, independent of

soil chemical composition and extractable fractions. Correlation analysis also showed that Zn in walnuts was related to Mehlich-extractable Zn. This could be due to the fact that Zn content in plants is influenced by Zn availability in the soil (Marschner 1993; Noulas et al. 2018). The reason could

Table 3 Soil chemical properties of soil along an elevation gradient at two soil depths

Depth (cm)	Elevation (m a.s.l.)	pH (H ₂ O)	SOC (mg g ⁻¹ soil)	Total N
0–30	1000	7.9 ^a	56	3.7 ^b
0–30	1300	7.2 ^b	66	4.7 ^a
0–30	1600	6.9 ^c	58	4.6 ^a
CV (± %)		5.5	18	16
<i>p</i> -value		<0.01	NS	0.01
30–60	1000	8.5 ^a	35 ^a	1.4 ^b
30–60	1300	7.7 ^b	27 ^b	2.1 ^a
30–60	1600	7.4 ^b	29 ^b	2.2 ^a
CV (± %)		9.2	18	21
<i>p</i> -value		<0.01	<0.05	<0.01

CV = mean coefficient of variation between replicate samples (*n* = 10); a.s.l = above sea level

Note: Data are from Osmonbaeva et al. (2023)

Table 4 Extractable elements (Mehlich-3) of soils along an elevation gradient at two soil depths

Depth (cm)	Elevation (m a.s.l.)	Mg mg kg ⁻¹	Na	P	Cu	Fe	Mn	Zn
0–30	1000	421	12 ^b	11 ^b	6.4	146 ^b	217 ^a	5.4
0–30	1300	511	52 ^a	27 ^a	7.2	250 ^a	159 ^b	6.1
0–30	1600	483	17 ^b	21 ^{ab}	6.5	238 ^a	190 ^{ab}	5.7
CV (± %)		10	42	32	31	13	14	23
<i>p</i> -value		<0.01	<0.01	<0.01	NS	<0.01	<0.01	<0.01
30–60	1000	402	16 ^b	1.2 ^b	5.0	85 ^b	108 ^{ab}	1.6
30–60	1300	446	43 ^a	8.9 ^a	5.6	194 ^a	90 ^b	1.9
30–60	1600	439	18 ^b	5.1 ^{ab}	6.7	175 ^a	130 ^{ab}	2.1
CV (± %)		15	47	48	32	22	27	34
<i>p</i> -value		NS	<0.05	<0.05	NS	<0.01	<0.05	NS

CV = mean coefficient of variation between replicate samples (*n* = 10); a.s.l = above sea level

Note: Data are from Osmonbaeva et al. (2023)

be the physiological processes and mechanisms within the plant which influence the Zn content and its interactions with other elements (Jiang et al. 2018). For instance, certain plant species or cultivars may have specific mechanisms to increase Zn uptake or enhance Zn transport within the plant (Hamzah Saleem et al. 2022). Some elements in the soil, such as Fe, Cu, and Mn, can compete with Zn for uptake by plant roots (Rai et al. 2021). High levels of these elements or imbalances in their ratios with Zn can affect the absorption and utilization of Zn by plants. Furthermore, plants require Zn as a vital micronutrient since it plays a significant role in various crucial cellular functions, enzyme activation, and maintaining ion homeostasis (Alsafran et al. 2022; Yang et al. 2020). The genotype and harvest or crop year also affect the mineral content of walnuts (Rabadán et al. 2018) and this should be subject of future research. Our results showed that differences in average temperature as caused by elevation did not affect available plant nutrients or the walnut fruit ionome in general. This means the long term temperature increase in the context of climate change will not affect the

quality of walnut fruits in these forest ecosystems, regarding elemental content.

We assumed that elevation level acts as a good proxy for temperature differences and assumed that this has an influence on nutrient dynamics and uptake, but apparently, soil extractable elements are not directly related to walnut elements in these ecosystems. Other soil properties more strongly influence extractability of these elements, and nutrient accumulation in walnuts is somewhat decoupled from extractable elements. Nonetheless, walnut yield may, at the same time, be affected by extractable nutrient quantities.

5 Conclusions

The present research offers an opportunity to compare various elevation levels differing in average temperatures within an ecosystem with similar vegetation, geological background, and long-term precipitation patterns. The results of this study suggest that the expected long-term temperature increase caused by climate change may not

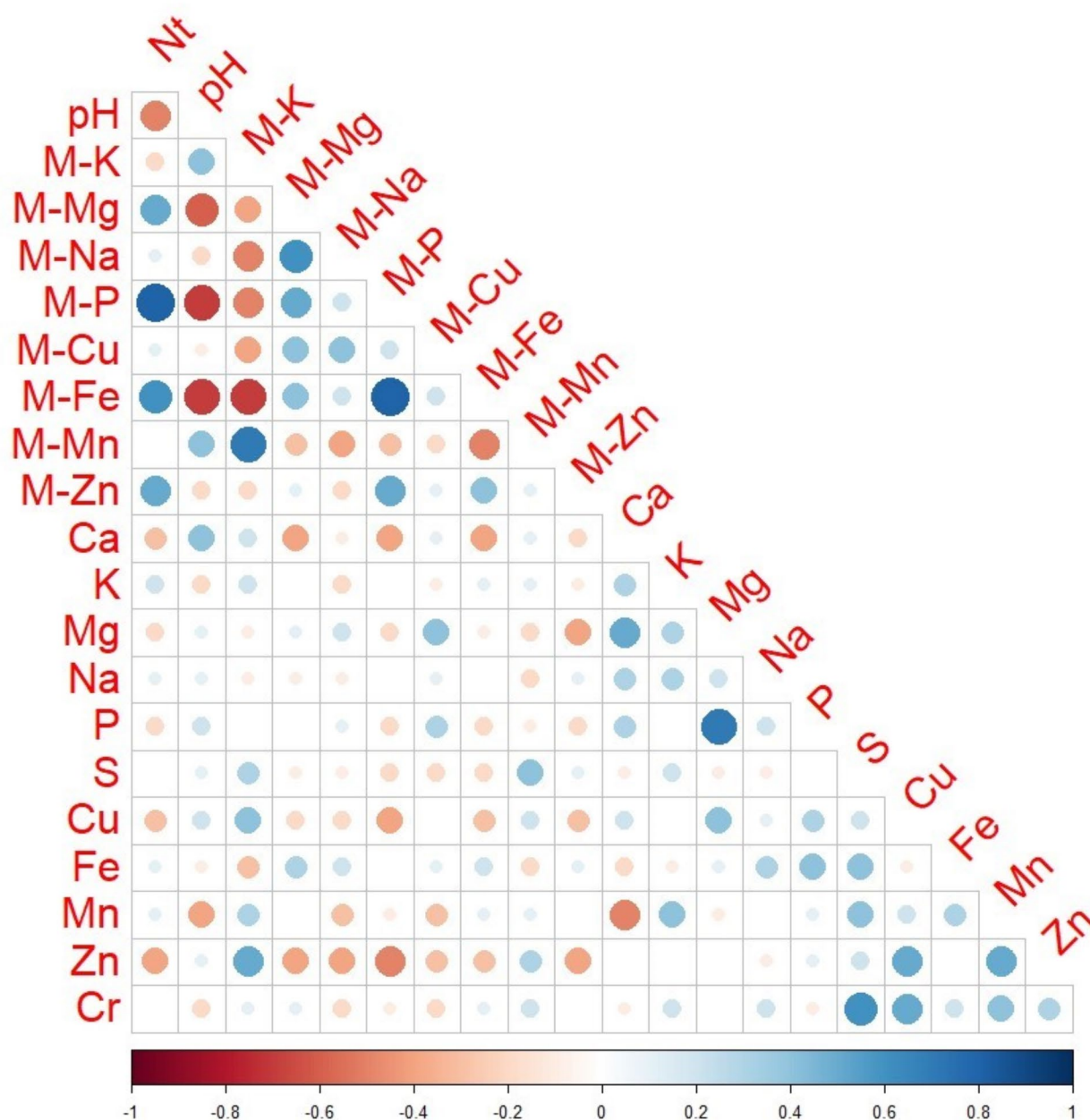


Fig. 4 Correlation triangle between Mehlich-3 extractable soil nutrients and walnut nutrients. The size of the dots represents the magnitude of the correlation, and the colour represents positive (blue) or

negative (red) relationships; white indicates a value near 0 (no relationship); Nt -total nitrogen

affect the physical properties and elemental composition of walnut fruits in the investigated forest systems. We assumed that differences in elevation sites would serve as a suitable indicator for temperature variations, which, in turn, would affect nutrient dynamics and uptake. However, it appears that the extractable elements found in the soil do not directly correspond to the elements present in walnut fruits within these ecosystems. It is likely that walnut trees

have the ability to take up nutrients in the necessary quantities regardless of the chemical composition and extractable fractions of the soil. This suggests that either the Mehlich-3 extraction method is not a reliable predictor of nutrient uptake, or the walnut tree possesses a flexible mechanism for accessing these nutrients. However, further investigations are warranted to better understand the complex relationship between soil properties, nutrient dynamics, and

walnut tree physiology. Nonetheless, the impacts of climate change, including drought and changes in precipitation patterns, have the potential to affect the development of walnut fruit and should be the focus of future research.

Acknowledgements We would like to thank Diana Werner for C/N/S analyses from the University of Rostock, Bernd-Theo Hetjens for support with ICP measurements and Conor Watson for checking English.

CRedit Authorship Contribution Zhyldyz Oskonbaeva: Writing – original draft, Visualisation, Methodology, Investigation. Rainer Georg Joergensen: Writing – review & editing, Visualization, Supervision. Florian Wichern: Writing – review & editing, Validation, Supervision, Data curation, Conceptualization.

Funding Open Access funding enabled and organized by Projekt DEAL. German Academic Exchange Service (DAAD) Grant number funded this work: 57440921.

Data Availability Data will be made available on request.

Declarations

Competing Interests The authors have no competing interests in the course of this study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alsafran M, Usman K, Ahmed B, Rizwan M, Saleem MH, Al Jabri H (2022) Understanding the phytoremediation mechanisms of potentially toxic elements: a proteomic overview of recent advances. *Front Plant Sci* 13:881242. <https://doi.org/10.3389/fpls.2022.881242>
- Altuntas E, Erkol M (2010) Physical properties of shelled and kernel walnuts as affected by the moisture content. *Czech J Food Sci* 28:547–556. <https://doi.org/10.17221/194/2008-CJFS>
- Amézquita EJ, Quigley MY, Brown PJ, Munch E, Chitwood DH (2023) The shape and volume of air, kernels, and cracks, in a nut-shell. <https://doi.org/10.22541/essoar.169766227.71123889/v1>
- Amin F, Masoodi FA, Baba WN, Khan AA, Ganie BA (2017) Effect of different ripening stages on walnut kernel quality: antioxidant activities, lipid characterization and antibacterial properties. *J Food Sci Technol* 54:3791–3801. <https://doi.org/10.1007/s13197-017-2776-4>
- AOAC (1999) AOAC 1999 Official Methods of Analysis
- Aryapak S, Ziarati P (2014) Nutritive value of persian walnut (*Juglans regia* L.) Orchards. *Am Eurasian J Agric Environ Sci* 14:1228–1235. <https://doi.org/10.5829/idosi.ajeaes.2014.14.11.12438>
- Arzani K, Mansouri-Ardakan H, Vezvaei A, Roozban MR (2008) Morphological variation among persian walnut (*Juglans regia*) genotypes from central Iran. *N Z J Crop Hort Sci* 36:159–168. <https://doi.org/10.1016/j.scienta.2018.07.018>
- Bernard A, Lheureux F, Dirlwanger E (2017) Walnut: past and future of genetic improvement. *Tree Genet Genomes* 14:1. <https://doi.org/10.1007/s11295-017-1214-0>
- Beyhan N, Demir T (2006) Selection of promising walnut genotypes in Samsun province in Turkey. *J Agron* 5:435–439. <https://doi.org/10.3923/ja.2006.435.439>
- Blatt MR (2000) Ca^{2+} signalling and control of guard-cell volume in stomatal movements. *Curr Opin Plant Biol* 3:196–204. [https://doi.org/10.1016/S1369-5266\(00\)80065-5](https://doi.org/10.1016/S1369-5266(00)80065-5)
- Brevik EC (2013) The potential impact of Climate Change on Soil Properties and processes and corresponding influence on Food Security. *Agriculture* 3:398–417. <https://doi.org/10.3390/agriculture3030398>
- Burley J (2004) Encyclopedia of forest sciences. Academic
- Büyüksolak ZN, Aşkın MA, Kahramanoğlu İ, Okatan V (2020) Effects of altitude on the pomological characteristics and chemical properties of ‘chandler’ walnuts: a case study in Uşak province. *Acta Agrobot* 73:1. <https://doi.org/10.5586/aa.7333>
- Cantarello E, Lovegrove A, Orozumbekov A, Birch J, Brouwers N, Newton AC (2014) Human impacts on forest biodiversity in protected walnut-fruit forests in Kyrgyzstan. *J Sustain* 33:454–481. <https://doi.org/10.1080/10549811.2014.901918>
- Chontoev DT, Bazhanova LV (2021) Climate change forecast in Kyrgyzstan for 2050 and 2100. In: Kulenbekov ZE, Asanov BD (eds) *Water Resource Management in Central Asia and Afghanistan: current and future environmental and Water issues*. Springer International Publishing, Cham, pp 37–50. https://doi.org/10.1007/978-3-030-68337-5_5
- Christopoulos M, Ouzounidou G (2021) Climate change effects on the perceived and nutritional quality of fruit and vegetables. *J Innov Econ Manag* 34:79–99. <https://doi.org/10.3917/jie.034.0079>
- Cosmulescu SN, Baci A, Achim G, Mihai B, Trandafir I (2009) Mineral composition of fruits in different walnut (*Juglans regia* L.) cultivars. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 37:156–160. <https://doi.org/10.15835/nbha3723169>
- Cowles J, Boldgiv B, Liancourt P, Petraitis PS, Casper BB (2018) Effects of increased temperature on plant communities depend on landscape location and precipitation. *Ecol Evol* 8:5267–5278. <https://doi.org/10.1002/ece3.3995>
- Devin SR, Bujdoso G (2022) Walnut genotypes for high density orchards. *Horticulturae* 8:490. <https://doi.org/10.3390/horticulturae8060490>
- Drollinger S, Müller M, Kobl T, Schwab N, Böhner J, Schickhoff U, Scholten T (2017) Decreasing nutrient concentrations in soils and trees with increasing elevation across a treeline ecotone in Rolwaling Himal, Nepal. *J Mt Sci* 14:843–858. <https://doi.org/10.1007/s11629-016-4228-4>
- Eijkelkamp (2012) 08.53 Calcmeter Operating Instructions, Griesbeek, The Netherlands, pp.12
- FFAlae-Carew C, Nicoleau S, Bird FA, Hawkins P, Tuomisto HL, Haines A, Dangour AD, Scheelbeek PF (2020) The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. *Environ Res Lett* 15:023002. <https://doi.org/10.1088/1748-9326/ab5cc0>
- Fortier J, Truax B, Gagnon D, Lambert F (2020) Soil nutrient availability and microclimate are influenced more by genotype than by planting stock type in hybrid poplar bioenergy buffers on farmland. *Ecol Eng* 157:105995. <https://doi.org/10.1016/j.ecoleng.2020.105995>

- Gee GW, Or D (2018) 2.4 Particle-Size Analysis. Methods of soil analysis: Part 4 physical methods 5:255–293. <https://doi.org/10.2136/sssabookser5.4.c12>
- Grubb P (2003) Control of forest growth and distribution on wet tropical mountains: with special reference to mineral nutrition. *Annu Rev Ecol Evol Syst* 8:83–107. <https://doi.org/10.1146/annurev.es.08.110177.000503>
- Guney M, Kafkas S, Keles H, Zarifikhosroshahi M, Gundesli MA, Ercisli S, Necas T, Bujdosó G (2021) Genetic diversity among some Walnut (*Juglans regia* L.) genotypes by SSR markers. *Sustainability* 13:6830. <https://doi.org/10.3390/su13126830>
- Haag I, Jones PD, Samimi C (2019) Central Asia's changing climate: how temperature and precipitation have changed across time, space, and altitude. *Climate* 7:123. <https://doi.org/10.3390/cli7100123>
- Hamzah Saleem M, Usman K, Rizwan M, Al Jabri H, Alsafran M (2022) Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Front Plant Sci* 13:1033092. <https://doi.org/10.3389/fpls.2022.1033092>
- He X, Hou E, Liu Y, Wen D (2016) Altitudinal patterns and controls of plant and soil nutrient concentrations and stoichiometry in subtropical China. *Sci Rep* 6:24261. <https://doi.org/10.1038/srep24261>
- Hu Z, Zhang C, Hu Q, Tian H (2014) Temperature changes in Central Asia from 1979 to 2011 based on multiple datasets. *J Clim* 27:1143–1167. <https://doi.org/10.1175/JCLI-D-13-00064.1>
- Jiang J, Zhou T (2023) Agricultural drought over water-scarce Central Asia aggravated by internal climate variability. *Nat Geosci* 16:154–161. <https://doi.org/10.1038/s41561-022-01111-0>
- Jiang Y, Gao WW, Zhao JL, Chen Q, Liang D, Xu C, Huang LS, Ruan LM (2018) Analysis of influencing factors on soil Zn content using generalized additive model. *Sci Rep* 8:15567. <https://doi.org/10.1038/s41598-018-33745-9>
- Jobbágy EG, Jackson RB (2001) The distribution of soil nutrients with depth: global patterns and the imprint of plants. *Biogeochemistry* 53:51–77. <https://doi.org/10.1023/A:1010760720215>
- Juranović Cindrić I, Zeiner M, Hlebec D (2018) Mineral composition of elements in Walnuts and Walnut oils. *Int J Environ Res Public Health* 15:2674. <https://doi.org/10.3390/ijerph15122674>
- Kamal A, Mian I, Akbar W, Rahim H, Irfan M, Ali S, Alrefael A, Zaman W (2023) Effects of soil depth and altitude on soil texture and soil quality index. *Appl Ecol Environ Res* 21:4135–4154. https://doi.org/10.15666/aer%2F2105_41354154
- Körner C (1989) The nutritional status of plants from high altitudes: a worldwide comparison. *Oecologia* 81:379–391. <https://doi.org/10.1007/BF00377088>
- Li Y, Gong J, Liu J, Hou W, Moroonyane I, Liu Y, Jin J, Liu J, Xiong H, Cheng C, Malik K, Wang J, Yi Y (2022) Effects of different land use types and soil depth on soil nutrients and soil bacterial communities in a Karst Area, Southwest China. *Soil Sys* 6:20. <https://doi.org/10.3390/soilsystems6010020>
- Lioubimtseva E, Cole R (2006) Uncertainties of climate change in arid environments of Central Asia. *Rev Fish Sci* 14:29–49. <https://doi.org/10.1080/10641260500340603>
- Liu Y, Geng X, Hao Z, Zheng J (2020) Changes in climate extremes in Central Asia under 1.5 and 2°C global warming and their impacts on agricultural productions. *Atmosphere* 11:1076. <https://doi.org/10.3390/atmos11101076>
- Luedeling E, Girvetz EH, Semenov MA, Brown PH (2011) Climate change affects winter chill for temperate fruit and nut trees. *PLoS ONE* 6:e20155. <https://doi.org/10.1371/journal.pone.0020155>
- Marschner H (1993) Zinc Uptake from Soils. in: Robson, AD (Ed.), *Zinc in Soils and Plants: Proceedings of the International Symposium on 'Zinc in Soils and Plants' held at The University of Western Australia, 27–28 September, 1993*. Springer Netherlands, Dordrecht, pp. 59–77
- Martínez ML, Labuckas DO, Lamarque AL, Maestri DM (2010) Walnut (*Juglans regia* L.): genetic resources, chemistry, by-products. *J Sci Food Agric* 90:1959–1967. <https://doi.org/10.1002/jsfa.4059>
- Massaccesi L, De Feudis M, Leccese A, Agnelli A (2020) Altitude and vegetation affect soil organic carbon, basal respiration and microbial biomass in Apennine forest soils. *Forests* 11:710. <https://doi.org/10.3390/f11060710>
- Meisen SA, Smanalieva J, Oskonbaeva Z, Iskakova J, Darr D, Wichern F (2021) Intraspecific variability overlays abiotic site effects on some quality parameters of walnut (*Juglans regia* L.) fruits from Kyrgyzstan. *Eur Food Res Technol* 247:363–373. <https://doi.org/10.1007/s00217-020-03628-3>
- Mekonnen H, Bazie DZ, Belay A (2018) Effects of climate change on soil and water resources: a review. *J Environ Earth Sci* 8:71–80
- Noulas C, Tziouvalakas M, Karyotis T (2018) Zinc in soils, water and food crops. *J Trace Elem Med Biol* 49:252–260. <https://doi.org/10.1016/j.jtemb.2018.02.009>
- Oskonbaeva Z, Maitykov T, Schwalb SA, Joergensen RG, Wichern F (2023) No evidence of an elevation effect caused by temperature differences on soil microbial properties in a walnut fruit forest in Kyrgyzstan. *J Soil Sci Plant Nut* 23:2663–2672. <https://doi.org/10.1007/s42729-023-01222-6>
- Ozcan MM (2009) Some nutritional characteristics of fruit and oil of walnut (*Juglans regia* L.) growing in Turkey. *Iran J Chem Chem Eng* 28:57–62. <https://doi.org/10.30492/IJCCCE.2009.6915>
- Rabadán A, Pardo JE, Pardo-Giménez A, Álvarez-Orti M (2018) Effect of genotype and crop year on the nutritional value of walnut virgin oil and defatted flour. *Sci Total Environ* 634:1092–1099. <https://doi.org/10.1016/j.scitotenv.2018.04.090>
- Rai S, Singh PK, Mankotia S, Swain J, Satbhai SB (2021) Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese. *Plant Stress* 1:100008. <https://doi.org/10.1016/j.stress.2021.100008>
- Raj S, Roodbar S, Brinkley C, Wolfe DW (2022) Food Security and climate change: differences in impacts and adaptation strategies for rural communities in the Global South and North. *Front Sustain Food Syst* 5:691191. <https://doi.org/10.3389/fsufs.2021.691191>
- Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X, Lv Y, Xu J (2019) Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review. *Plants (Basel)*. 8:34. <https://doi.org/10.3390/plants8020034>
- Rodushkin I, Engström E, Sörlin D, Baxter D (2008) Levels of inorganic constituents in raw nuts and seeds on the Swedish market. *Sci Total Environ* 392:290–304. <https://doi.org/10.1016/j.scitotenv.2007.11.024>
- Rumsey DJ (2016) *Statistics for dummies*. John Wiley Sons 2:8–17
- Sakbaeva Z, Schroetter S, Karabaev N, Avazov A, Rogasik J, Schnug E (2013) Soils of nut-fruit forests in southern Kyrgyzstan—important ecosystems worthy of protection. *Appl Agri Res* 63:93–102. <https://doi.org/10.3220/LBF-2013-93-102>
- Simsek T, Bayram CA, Buyuk G, Akca E, Kalkanci N (2023) The effect of altitude on soil organic carbon content in semi-arid Mediterranean climate. <https://doi.org/10.31015/jaefs.2023.1.23>
- Sundqvist MK, Sanders NJ, Wardle DA (2013) Community and ecosystem responses to elevational gradients: processes, mechanisms, and insights for global change. *Annu Rev Ecol Evol Syst* 44:261–280. <https://doi.org/10.1371/journal.pone.0092942>
- Temirbekov A (2010) Facilitating financing for sustainable forest management in small islands developing states and low forest cover countries, an analytical report prepared by Indufor for the United Nations Forum on forests. the Kyrgyz Republic, Country Case Study
- Vincent AG, Sundqvist MK, Wardle DA, Giesler R (2014) Bioavailable soil phosphorus decreases with increasing elevation in a subarctic tundra landscape. *PLoS ONE* 9:e92942. <https://doi.org/10.1371/journal.pone.0092942>

- White PJ, Broadley MR (2003) Calcium in plants. *Ann Bot* 92:487–511. <https://doi.org/10.1093/aob/mcg164>
- Winter MB, Wolff B, Gottschling H, Cherubini P (2009) The impact of climate on radial growth and nut production of persian walnut (*Juglans regia* L.) in Southern Kyrgyzstan. *Eur J Res* 128:531–542. <https://doi.org/10.1007/s10342-009-0295-1>
- WRB IWG (2022) World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps (4th ed.). International Union of Soil Sciences (IUSS). https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf
- Yang M, Li Y, Liu Z, Tian J, Liang L, Qiu Y, Wang G, Du Q, Cheng D, Cai H (2020) A high activity zinc transporter OsZIP9 mediates zinc uptake in rice. *Plant J* 103:1695–1709. <https://doi.org/10.1111/tpj.14855>
- Zeneli G, Kola H, Dida M (2005) Phenotypic variation in native walnut populations of Northern Albania. *Sci Hort* 105:91–100. <https://doi.org/10.1016/j.scienta.2004.11.003>
- Zhao S, Zhao Y, Wang H, Gao Y, Zhang Z, Feng D (2011) Factors affecting nutshell structure of walnut. *Scientia Silvae Sinicae* 47:70–75
- Zhao S, Niu J, Yun L, Liu K, Wang S, Wen J, Wang H, Zhang Z (2019) The relationship among the structural, cellular, and physical properties of walnut shells. *Hort Sci* 54:275–281. <https://doi.org/10.21273/HORTSCI13381-18>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.