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Effects of Saline Water Intrusion and Age of Upland Soils on Morphology and Chemistry of Soil Cultivating Pomelo in Vietnam

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ABSTRACT

Saline water intrusion and long-term upland soils are the main difficulties in pomelo cultivation today. Thus, this study aimed to evaluate the influences of salinization and the age of upland soil on the morphological and chemical characteristics of soil in pomelo orchards. The upland soils from 5 years to 10 years were classified as Hapli Gleyic Fluvisols. Moreover, after 8 years of saline water intrusion, the salinity did not affect soil pH and EC any longer, but still reduced soluble P content and cation exchange capacity. For toxins, the salinization reduced Fe^{2+} but increased Al^{3+} concentration. The pH_{KCl} decreased according to the age of upland soil in Giong Trom, while the contents of organic matter, NH_4^+, and Fe^{2+} toxicity reduced according to the age of upland soil in Chau Thanh and Giong Trom. Although after 8 years of salinization, the soil properties did not significantly change compared to the non-salinized case, prevention from salinization to pomelo orchards to ensure pomelo yield was an essential priority.

Keywords: Pomelo, salinization, soil chemistry, soil morphology, upland soil age

INTRODUCTION

Ben Tre Province, Vietnam is heavily affected by salinization. The seawater intrudes into the agricultural regions via three big rivers, including Ham Luong, Co Chien, and Cuu Dai, damaging 20,300 ha of rice, 458 ha of vegetables, and 5,200 ha of fruits, roughly 70% in 2016 (Diep *et al.*, 2022). Ben Tre Province is divided into 3 basic ecosystems, 37% of freshwater, 27% for brackish water, and 36% for salt water. The salinization often occurs in March-April with the greatest salinity of 38.6‰ (Can, 2015). Salinization affects the available fresh water, and many crops are vulnerable to salinity and salt concentrations in soil and water (Bayabil *et al.*, 2021). Citrus is affected when the salinity in water exceeds 3 dS m^{-1} (García-Sánchez *et al.*, 2002; Darshan *et al.*, 2022).

Pomelo is a favorite kind of fruit in the Mekong Delta, widely grown and consumed in Ben Tre Province (Long *et al.*, 2023). It is highly economical with abundant minerals, vitamin C, and polyphenol compounds (Tripoli *et al.*, 2007; Dang *et al.*, 2022a). It can also improve the liver by reducing fat accumulation (Gliozzi *et al.*, 2014). Some studies claim that citrus in salinized soil accumulates more Cl^- than Na^+ in leaves, and Cl^- is reported to involve physiological defoliation (Hussain *et al.*, 2012; Etehadpour *et al.*, 2020). Salinization happens in freshwater ecosystems and affects soil physical and chemical processes (Ury *et al.*, 2022). Salinized soil has low fertility and inhibits plant nutrient uptake (Alam *et al.*, 2017; Xian *et al.*, 2019; Ashrafuzzaman *et al.*, 2022). Using salt water for irrigation can lead to great damage to plants and soil fertility. Na saturation and soil salt concentration decide the positions of clay particles in the soil, which interrupts soil vacancies and reduces osmosis and porosity (Tedeschi and Dell'Aquila, 2005). Furthermore, high soil salinity results in Na saturation which interferes with growth, water uptake, and mineral uptake in plants (Tan and Thanh, 2021). Hence, the soil in fruit orchards in the Mekong Delta is becoming more and more degraded (Dang *et al.,* 2021).

Apart from salinity, there have been many studies investigating the influences of soil features on the growth, yield, and quality of pomelo. For instance, high soil pH leads to better pomelo yield and nutrition, while the lower one results in poor flavor quality (Wu *et al.*, 2024). Meanwhile, the greater the soil organic matter is, the better pomelo flavor quality (Wu *et al.,* 2024). This could be because soil nutrient availability relies on the soil pH (Hartemink and Barrow, 2023). Thus, it is important to determine the soil properties so as to find out what are suitable approaches to improving pomelo performance in a certain type of soil. For example, in acidic soil, the use of lime and Mg improved soil nutrient availability by increasing the soil pH, which thereby increased the yield of pomelo (Zhang *et al*., 2021). An optimized fertilizer formula (550 kg N ha^{-1}, 295 kg P_2O_5 ha^{-1}, 498 kg K_2O ha^{-1}, and 196 kg MgO ha^{-1}) has shown positive results in acidic soil (Chen *et al.,* 2022). In slightly acidic soil, cover crops and rice straw mulching have been used to improve pomelo yield. Furthermore, in alluvial soil, biochar and compost were used to not only increase pomelo yield but also the production profit by USD 1,672 ha^{-1} after three years of application (Dang *et al*., 2022b). Ultimately, the farming practice should follow a certain soil feature.

In addition, upland planting can improve soil fertility (Govaerts *et al.*, 2007). Plants in upland soil have greater growth, bacterial, and fungal density than plants in flat soils (Zhang *et al.*, 2012). Moreover, upland planting can increase water and nitrogen (N) use efficiency than flat planting (Hashimi *et al.*, 2021). However, the upland planting increases salinity according to the time when there is no plant residue on the bed surface than the flat planting, because of the movement of salt to the bed surface due to capillary action as a response to the evaporation rates (Devkota *et al.*, 2015). Thus, aging of upland planting can decrease yield and quality of citrus (Van Quang and Guong, 2011). Additionally, long-term upland soil leads to poor soil structure with soil vacancies filled by clay particles under salinized irrigation (Tedeschi and Dell'Aquila, 2005). This results in poor water drainage and hard soil bed which reduce the growth and activity of roots and eventually plant yield (Cockroft and Olsson, 2000). These have shown that the age of upland soil partially decides the soil fertility.

From the above, in Vietnam, there is a variety of approaches to improve pomelo yield. However, selecting a suitable approach depends on the soil certain soil characteristics which are heavily affected by salinization and aging of upland soil in the Mekong Delta. Moreover, up to now, there have been no studies investigating the effects of salinization and upland soil age on the chemical properties of the soil in the Vietnamese Mekong Delta. Therefore, the current study aimed at detecting the influences of salinization and upland soil age on soil's morphological and chemical traits in pomelo orchards. Moreover, the outcomes of this study will be a valuable reference for determining an appropriate and sustainable farming practice for pomelo in the Vietnamese Mekong Delta or in other regions where the soil features are similar.

MATERIALS AND METHODS

Study site and sampling

The study occurred from December 2023 to April 2024. There were 12 soil profiles collected from 4 communes (3 profiles in each commune), including Quoi Thanh (QT), Tien Long (TL) of Chau Thanh district, Binh Hoa (BH), and Son Phu (SP) of Giong Trom district, Ben Tre

Province. Therein, the soil profiles of TL and SP were affected by salinization in 2016, while QT and BH were unaffected (**Figure 1**). In particular, the soil was collected randomly in each of 12 pomelo fields with three replications for each field. The pomelo orchard land management practices at the study sites are shown in **Table S1**.

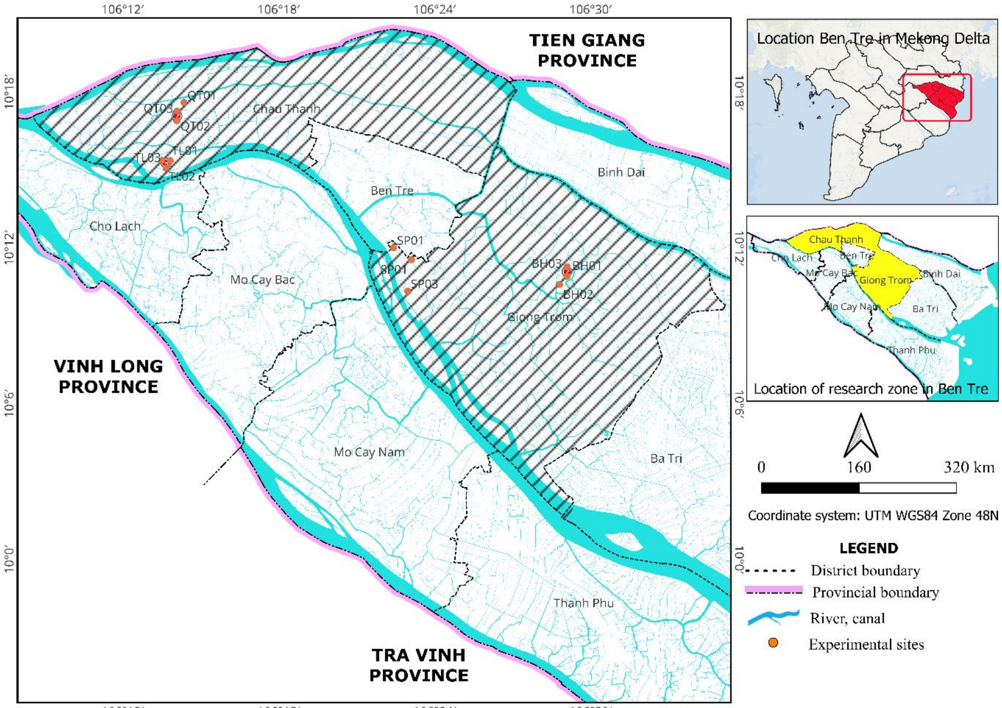

Figure 1. Sampling locations in Chau Thanh and Giong Trom districts

The age of plants and upland soils (years) in the soil profiles were QT (6, 25), TL (10, 50), BH (12, 12), and SP (14, 30). It can be classified that QT was unsalinized 25-year-upland soil, TL was salinized 50-year-upland soil, BH was unsalinized 12-year-upland soil, and SP was salinized 30-year-upland soil.

Analyses

Soils were sampled according to horizons. At each horizon, 500.0 g of soil was collected. The soil was dried naturally and ground via a 0.5- and 2.0-mm sieve. The collected soil was classified according to FAO (2006b) for the diagnostic horizon and characteristics. The soil profile was described according to FAO (2006a) by using the soil at a depth of 2 m, and measuring by Munsell soil color chart.

The soil chemistry was analyzed according to methods summarized by Sparks *et al*. (2020) as follows: for pH_{H2O}, pH_{KCl}, and electrical conductivity (EC), the soil was extracted by distilled water or 1.0 M KCl solution with ratios of 1:2.5 or 1:5, respectively. The extract by distilled water was used to measure pH_{H2O} and EC with a pH meter and an EC meter, respectively. The extract of 1.0 M KCl was used to measure pH_{KCl} by the pH meter. For the total N, the soil sample was digested by the mixture of sulfuric-salicylic acids catalyzed by $CuSO_4$: Na_2SO_4: Se. The total N was determined by the Kjeldahl method and titrated by 0.01 N H_2SO_4. The NH_4^+ was extracted from the soil by 2.0 M KCl. Subsequently, the NH_4^+ was measured by spectrophotometry at 650 nm wavelength. For the total P, the soil sample was digested by the mixture of H_2SO_4 saturated-$HClO_4$. The soluble P was determined by the Bray II method (extracted by 0.03 N NH_4F in 0.1 N HCl with the soil: solvent ratio of 1: 7). The soil was extracted by 0.5 M NH_4F (pH=8.2) to determine Al-P, extracted by NaOH 0.1 M to determine Fe-P, and extracted by 2.5 M H_2SO_4 to determine Ca-P. The three insoluble P compounds were rinsed with saturated NaCl twice. All the five P fractions were measured by spectrophotometry at 880.0 nm wavelength. For the Fe_2O_3, the soil was extracted by sodium dithionite to form a complex with EDTA. Fe_2O_3 was measured by atomic absorption spectrophotometry at 248.0 nm wavelength. Dissolved Fe and Fe^{2+} were extracted by 1.0 N KCl (pH=5.6-6.0). To measure Fe^{2+}, Fe^{3+} needed to be covered by 3,5% NaF, then dissolved Fe and Fe^{2+} were measured by spectrophotometry at 520 nm wavelength. For the organic matter (OM), it was measured according to the Walkley-Black method in which $K_2Cr_2O_7$ was used to oxidize OM in saturated H_2SO_4, then OM was titrated by 0.5 N $FeSO_4$. The titratable acidity in the soil was extracted by 1.0 N KCl and titrated by 0.01 N NaOH. The Al^{3+} was extracted by 1.0 N KCl and measured by spectrophotometry at 395 nm wavelength. The cations K^+, Na^+, Ca^{2+}, and Mg^{2+}, were extracted by 0.1 M $BaCl_2$, measured by atomic absorption spectrophotometry at 766.5, 589.0, 422.7, and 285.2 nm wavelengths, respectively. CEC was extracted by 0.02 M $MgSO_4$ and titrated by 0.01 M EDTA. The data were analyzed by using Microsoft Excel.

RESULTS AND DISCUSSION

Morphology of soil profiles in pomelo orchards

In soil profiles in QT, the first horizon was silty clay with low to moderate OM contents in the semi-decomposed form (**Table 1**). Three soil profiles in QT considered as acid sulfate soils (ASSs) with pyrite at the 80-200 cm depth. Thus, the soil classifications of soil profiles in QT, including deep potential ASS (QT02) to extremely deep potential ASS (QT01 and QT03), were Hapli Gleyic Fluvisols (Endo ProtoThionic, Dystric) and Hapli Gleyic Fluvisols (Bathi ProtoThionic, Dystric), respectively, according to FAO (2006b).

Table 1. Morphology of soil profiles in pomelo orchards in Quoi Thanh commune

Horizon	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color
		QT01			QT02			QT03	
Ah	0-35	2.5YR 6/3	-	0-50	5YR 4/2	-	0-30	7.5YR 7/4	-
Bg1	35-70	2.5YR 7/2	7.5YR 5/8 2.5YR 2.5/1	50-80	10YR 7/1	10YR 3/6	30-50	Gley 1 7/N	5YR 5/6
Bg2	70-100	Gley 1 7/1	7.5YR 6/8	80-120	Gley 1 4/N	-	50-110	5Y 2.5/1	-
Cr1	100-130	2.5YR 5/1	-	-	-	-	-	-	-
Cr2	>130	5YR 4/1	-	>120	10R 5/1	-	>110	Gley 2 4/5PB	-

Likewise, the soil profiles in TL were clayey silt, humid, and semi-mature with moderate OM contents (**Table 2**). The soils were classified as deposited alluvial soil, also called Hapli Gleyic Fluvisols (Dystric) according to FAO (2006b).

Furthermore, soil profiles in BH were similar to those in QT and TL but had many horizons (**Table S2-S13**), more visible transformations between horizons, and rusty spots in the soil colors of 5YR 5/2 and 10YR 4/2 (**Table 3**). The soils were classified as deposited alluvial soil, also called Hapli Gleyic Fluvisols (Dystric) according to FAO (2006b).

Table 2. Morphology of soil profiles in pomelo orchards in Tien Long commune

Horizon	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color
		TL01			TL02			TL03	
Ah	0-30	7.5YR 4/6	-	Ah	0-30	7.5YR 4/6	-	Ah	0-30
Bg	30-50	10R/3	2.5YR 3/6	Bg	30-50	10R/3	2.5YR 3/6	Bg	30-50
Cr	> 50	5YR	2.5/1	Cr	> 50	5YR	2.5/1	Cr	> 50

Table 3. Morphology of soil profiles in pomelo orchards in Binh Hoa commune

Horizon	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color
		BH01			BH02			BH03	
Ah	0-30	-	-	0-20	10YR 4/2	-	0-35	10YR 4/2	-
Bg1	30-60	7.5YR 5/8	2.5YR 5/2	20-60	5YR 4/4	-	35-65	5YR 6/2	5YR 3/4
Bg2	60-80	7.5YR 7/8	Gley 1 6/N	60-90	5YR 5/1	5YR 5/6	65-80	10YR 5/1	5YR 5/8
Bg3	80-120	2.5YR 3/6	5Y 2.5/1	90-120	7.5YR 5/8	-	80-120	Gley 1 5/N	2.5Y 3/3
Bg4	120-160	10YR 3/4	Gley2 5/5B	-	-	-	-	-	-
Cr	>160	-	Gley1 4/N	>120	5Y 2.5/1	-	>120	5Y 4/1	-

The soil profiles in SP had colors of 7.5YR 3/3, 7.5YR 7/1, and 5YR 5/3 (**Table 4**). The soil in SP01 and SP02 profiles was classified as deposited alluvial soil with the name according to FAO (2006b) as Hapli Gleyic Fluvisols (Bathi Proto Thionic, Dystric), while that of the SP03 soil profile was Hapli Gleyic Fluvisols (Dystric).

Table 4. Morphology of soil profiles in pomelo orchards in Son Phu commune

Horizon	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color	Depth (cm)	Color	Rusty color
		SP01			SP02			SP03	
Ah	0-25	7.5YR 4/3	10R 3/6	0-40	7.5YR 3/3	5YR 3/4	0-40	5YR 5/3	5YR 4/6
Bg1	25-50	7YR 4/2	2.5YR 3/6	40-80	10YR 5/2	5YR 3/4	40-90	7.5YR 7/1	2.5YR 3/6
Bg2	50-80	5Y 4/1	2.5YR 2.5/4	80-110	5Y 5/1	-	90-110	Gley 1 7/10Y	7.5YR 5/8
Bg3	80-160	2.5Y 4/1	2.5Y 3/2	110-140	2.5Y 5/1	-	110-140	7.5YR 5/1	-
Cr	>160	5Y 2.5/1	-	>140	5Y 2.5/1	-	>140	5Y 4/1	-

Impacts of salinization and upland soil age on the chemistry of soil for pomelo farming in Ben Tre

Referring to **Figure 1**, TL and SP are nearer to the river than QT and BH. The variation of pH_{H2O} was large in QT and SP but narrow in TL and BH. In particular, QT and BH were the two communes that were not affected by salinization, while TL and SP were the two salinized communes. The pH_{H2O} among horizons of soil profiles in QT and SP dramatically varied, ranging from 3.37-5.27 and 2.51-5.11, respectively (**Figure 2a**, **2d**). On the contrary, the soil profiles in TL and BH had less varied pH_{H2O} among horizons, with 4.75-5.68 in TL (**Figure 2b**) and 4.60-5.40 in BH (**Figure 2c**). This showed that the salinization did not affect the pH_{H2O}

in the four locations. However, a study by Jesus *et al.* (2015), pH_{H2O} decreased under salinization. This could be due to different soil types and different salts. Therefore, the salts in the soil profiles should be further investigated in the followings studies. Furthermore, pH_{KCl} in soil profiles in the four communes were 3.87, 4.29, 4.39, and 3.60 corresponding to QT, TL, BH, and SP because the long-term upland soil had less varied pH values. Moreover, the pH_{KCl} decreased in 30-year-old upland soil as compared with that in 12-year-old one in the surface horizon, with 3.49 compared with 4.58 in the Giong Trom district. This is in accordance with the study by Dang and Hung (2023) where older upland soil had lower pH than the younger one. However, the pH_{KCl} was equivalent in Chau Thanh district (**Figure 2e**, **2f**, **2g**, **2h**). The titratable acidity in QT, TL, and SP was greater than that in BH (**Figure 2i**, **2j**, **2k**, **2l**).

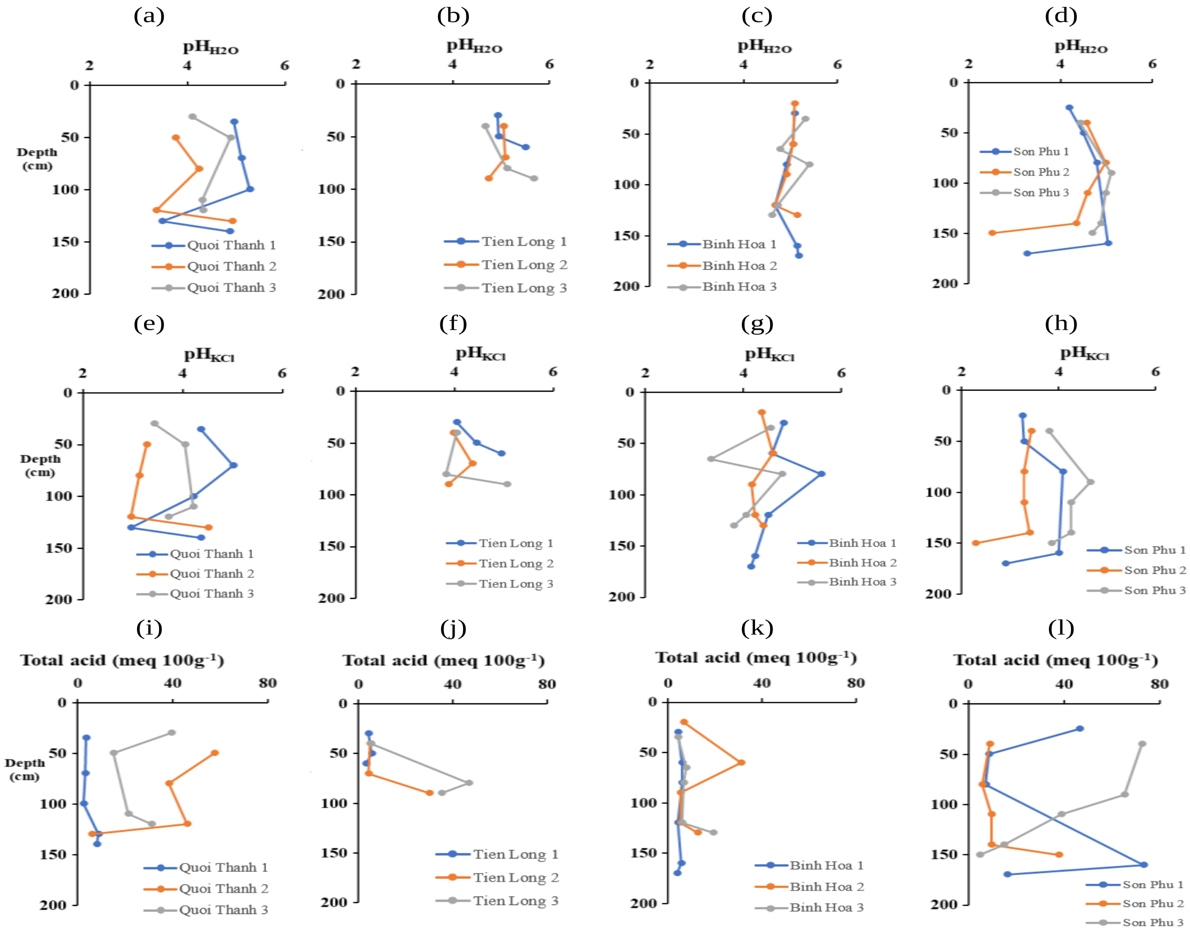

Figure 2. Effects of salinization and upland soil age on (a, b, c, d) pH_{H2O}, (e, f, g, h) pH_{KCl}, and (i, j, k, l) titratable acidity in the soil of pomelo orchards in Quoi Thanh, Tien Long, Binh Hoa, and Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

The soil profiles in the four communes had moderate EC values. Salinized soil profiles in TL and SP (**Figure 3b**, **3d**) had EC of 1.48 and 2.36 mS cm^{-1}. In the meantime, in the unsalinized soil profiles in QT and BH, the EC was 2.97 and 2.54 mS cm^{-1}, respectively (**Figure 3a**, **3c**). This could be because the sampling time was at the harvesting which was less affected by salinization and farmers used freshwater to water crops, leading to not very high EC values. Salinization is considered a basic factor affecting the salinity and water drainage of farming soils (Phankamolsil *et al.*, 2021). High and prolonged salinity in soil can change the water-holding capacity of soil because the salinity represents the total dissolved salt in the soil or the total salt concentration in the soil solution (Tang *et al.*, 2020). Soils with EC $\geq$ 4 dS m^{-1} are considered saline soils (Negacz *et al.*, 2022). The soil salinity degrades the physical, biological, and chemical characteristics of soils, which are the main factors leading to the disability of soil to adapt to the nutrient demands of crops and lower crop yields (Bello *et al.*, 2021). In contrast, the EC was not significantly affected by the upland soil age. This is consistent with the study by Dang and Hung (2023).

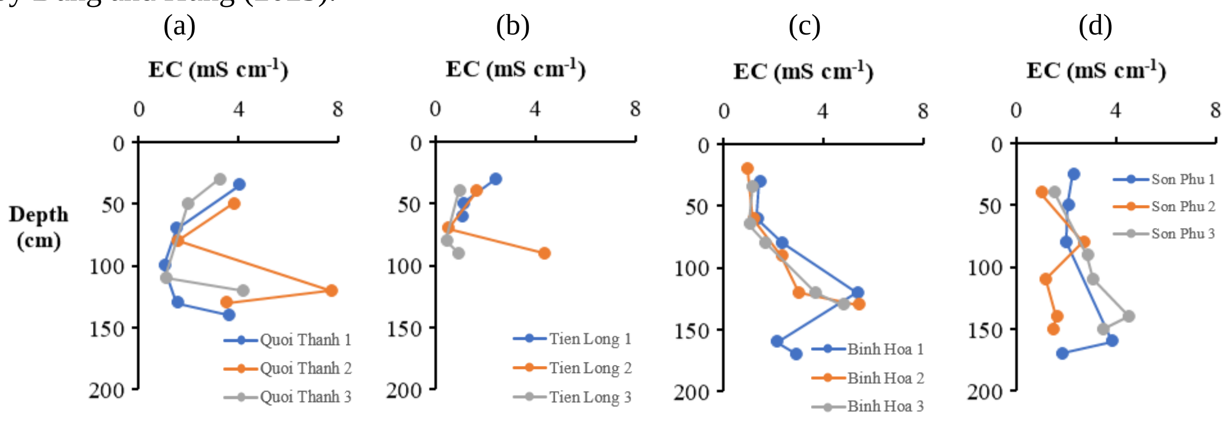

Figure 3. Effects of salinization and upland soil age on EC values in the soil of pomelo orchards in (a) Quoi Thanh, (b) Tien Long, (c) Binh Hoa, and (d) Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

The average total N content between horizons in the same location ranged from 0.131-1.168% which was considered low (**Figure 4a**, **4b**, **4c**, **4d**). The NH_4^+ concentrations in the unsalinized soils were less affected by salinity than in the salinized ones. In particular, the soil profiles in QT had greater NH_4^+ concentrations than those in TL, with 37.0 compared with 27.8 mg kg^{-1} (Figure 4e, 4f). Likewise, the soil profiles in BH had greater NH_4^+ concentration than those in SP, with 27.5 compared with 23.0 mg kg^{-1} (**Figure 4g**, **4h**). This is in accordance with the study by Xian *et al.* (2018), where under salinization, the concentration of NH_4^+ went down. However, the NO_3^- concentration went on the opposite pattern (**Figure 4i**, **4j**, **4k**, **4l**). Moreover, the NH_4^+ concentration in the surface horizon decreased according to the decreasing upland soil age from 50, 30, 25, to 12, with corresponding values of 35.7 > 25.5 > 23.8 > 17.9 mg kg^{-1} in TL, SP, QT, and BH (**Figure 4b**, **4d**, **4a**, **4c**). This is in accordance with the study by Zhang *et al.* (2012), where the NH_4^+ concentration increased by 18% when applying upland farming.

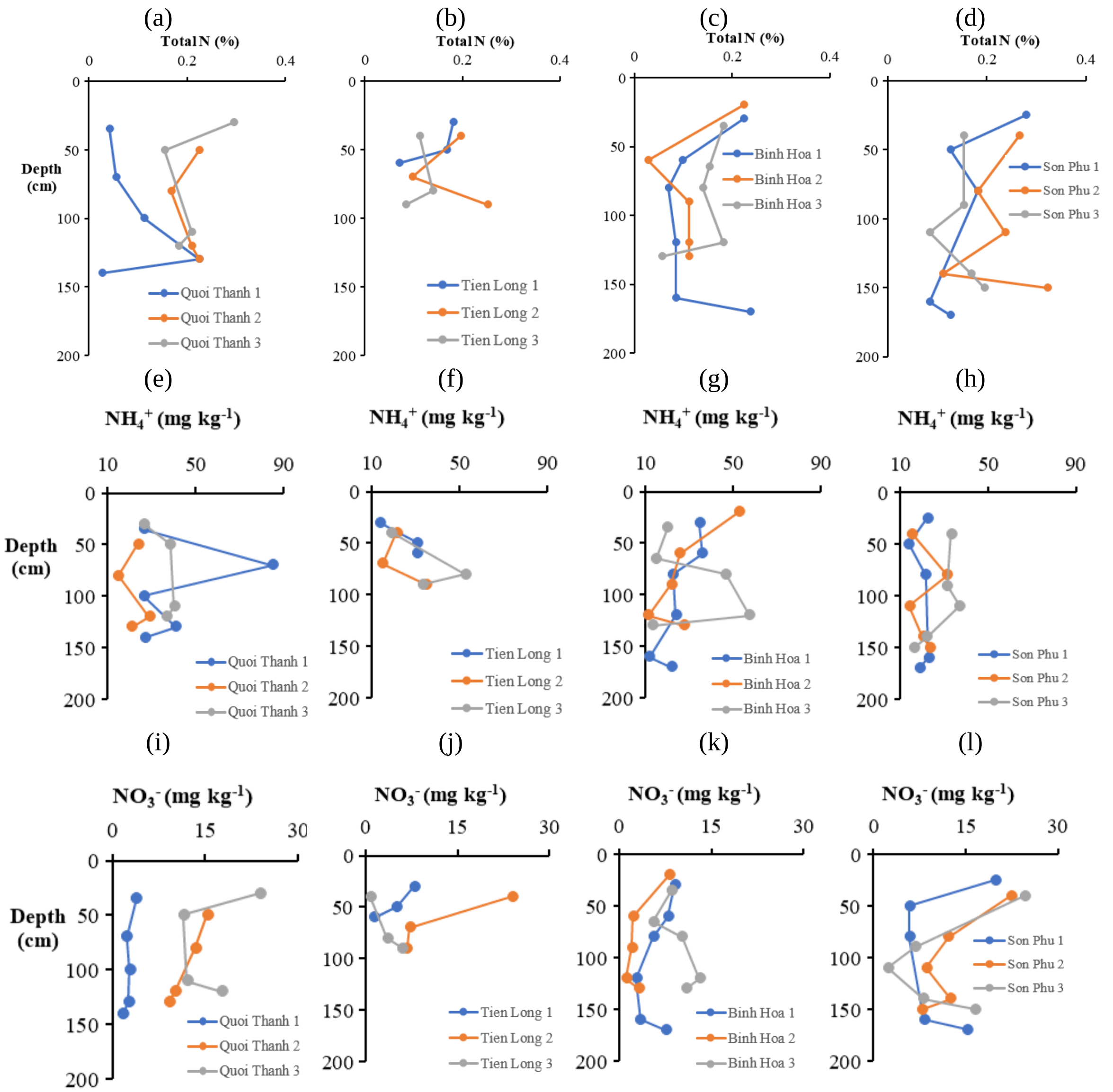

Figure 4. Effects of salinization and upland soil age on (a, b, c, d) total N content, (e, f, g, h) NH_4^+ concentration, and (i, j, k, l) NO_3^- concentration in soil of pomelo orchards in Quoi Thanh, Tien Long, Binh Hoa, and Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

The total P content was low with the average values lower than 0.06% (**Figure 5a**, **5b**, **4c**, **4d**). The soluble P content was high in the unsalinized soil profiles in QT and low in the salinized soil profiles in TL, with 77.5 compared with 54.8 mg kg^{-1}. This follows the study of Xian *et al.* (2018) showing a decrease in soluble P content under saltwater intrusion. However, the soluble P content in BH and SP was equivalent values (**Figure 5e**, **5f**, **5g**, **5h**). Furthermore, the contents of Al-P and Fe-P were not affected by salinization, with 306.9 mg kg^{-1} (Figure 5i) and 164.5 mg kg^{-1} (**Figure 5m**) in QT, 338.3 mg kg^{-1} (**Figure 5k**) and 176.2 mg kg^{-1} (**Figure 5o**) in BH. Moreover, the Ca-P content in unsalinized soil in QT was lower than the salinized soil in TL (**Figure 5q**, **5r**, **5s**, **5t**). In addition, high upland soil age led to low soluble P content in the top horizon. In particular, the soluble P contents in the soil profiles in TL and SP were lower than in those in QT and BH with 71.9 and 77.3 mg kg^{-1} (**Figure 5e**, **5g**) compared with 168.6 and 205.1 mg kg^{-1} (**Figure 5f**, **5h**), respectively.

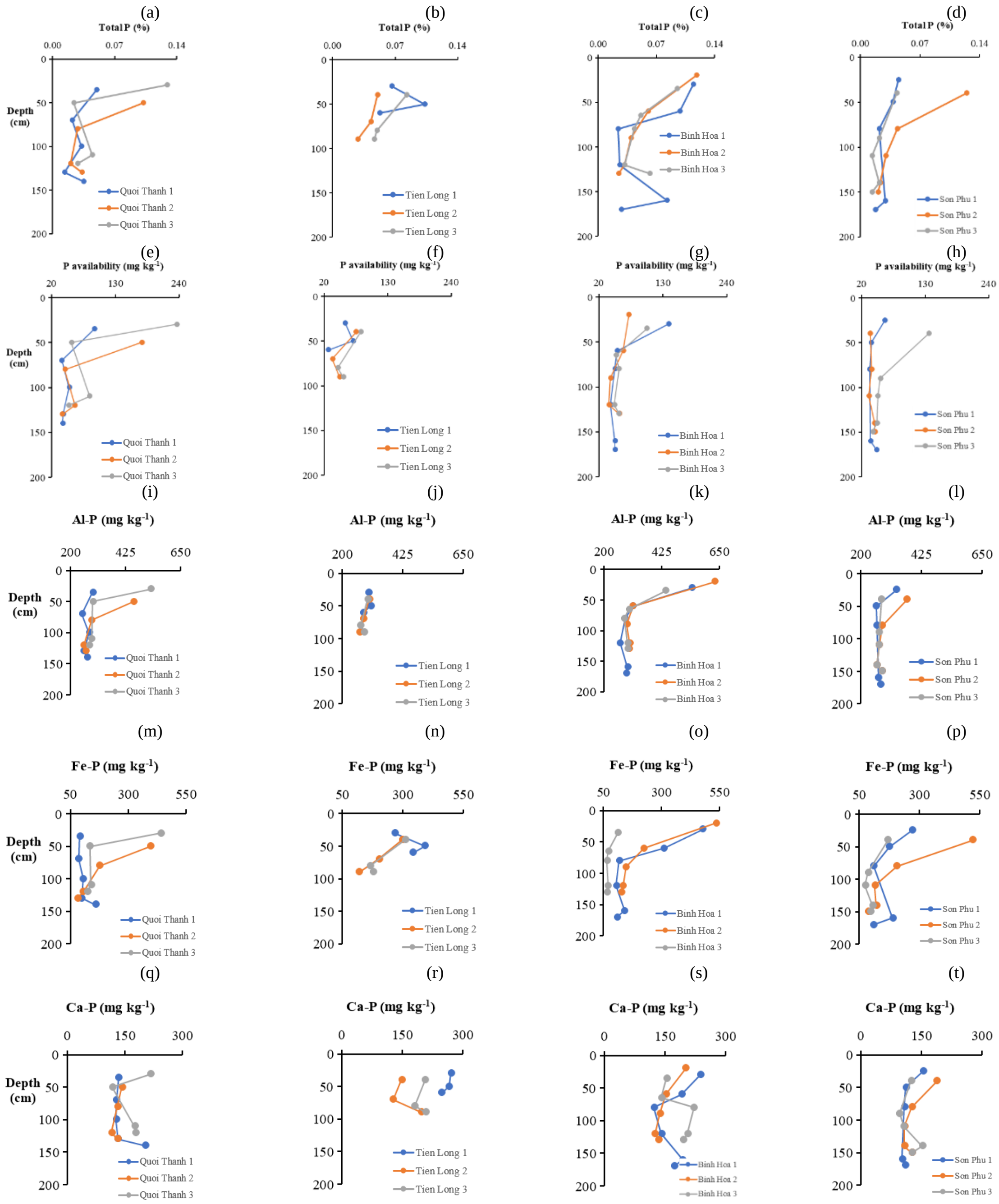

Figure 5. Effects of salinization and upland soil age on (a, b, c, d) total P content, (e, f, g, h) soluble P content, (i, j, k, l) Al-P, (m, n, o, p) Fe-P, and (q, r, s, t) Ca-P in soil of pomelo orchards in Quoi Thanh, Tien Long, Binh Hoa, and Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

Simultaneously, the older the upland soil age was, the lower the OM content in the soil was. In particular, the soil OM content in profiles in QT was 1.80 %C (**Figure 6a**) and lower than that in TL (2.06 %C) (**Figure 6b**), but equivalent to those in BH and SP (**Figure 6c**, **6d**). This indicated that salinization affected the soil OM, i.e. salinized soil profiles had greater OM than those without salinization. This follows the study by Ury *et al.* (2022), where OM increased under addition of marine water. The OM also went down in the study by Xian *et al.* (2018) under the salinization. Furthermore, the long-term upland soil had lower OM content in the surface horizon, i.e. the OM in TL and SP was lower than in QT and BH (1.68 and 1.84 compared with 2.31 and 2.36 %C) (**Figure 6**). A previous study proved that soils in perennial fruit orchards have their fertility decreased (Dang and Hung, 2023). According to Dung *et al.* (2022), using legumes can improve soil compaction and degradation in pomelo orchards. Furthermore, Dung *et al.* (2023) claim that the OM content in pomelo orchards can be improved by using straw or legumes. Using organic fertilizer can improve soil OM and the availability of Ca^{2+} and Mg^{2+} (Dang *et al.*, 2022b). The soil OM in pomelo orchards can be ameliorated by poultry and cattle manure (Dang *et al.*, 2021). Therefore, there are many promising approaches suggested for the pomelo farming region to obtain sustainable cultivation.

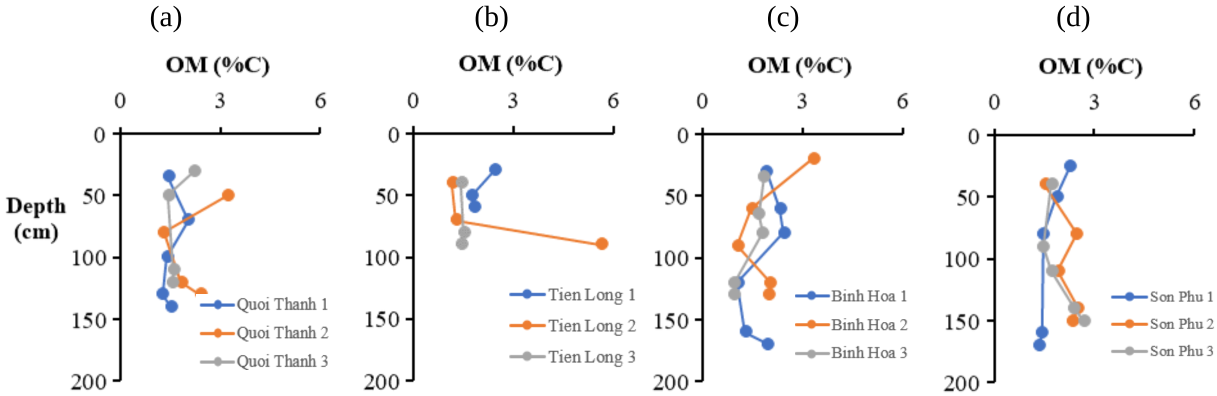

Figure 6. Effects of salinization and upland soil age on organic matter content in soil of pomelo orchards in (a) Quoi Thanh, (b) Tien Long, (c) Binh Hoa, and (d) Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

The soil CEC fluctuated from 7.95-9.11 meq 100 g^{-1} among the four locations (**Figure 7a**, **7b**, **7c**, **7d**). However, the CEC of a district was greater when no salinization was affected. Particularly, the CEC in the soil profiles in QT (9.25 meq 100 g^{-1}) was greater than in TL (7.84 meq 100 g^{-1}). The CEC in the soil profiles in BH (11.7 meq 100 g^{-1}) was also greater than in SP (7.31 meq 100 g^{-1}). The K^+ concentration in salinized soil in TL (1.25 meq 100 g^{-1}) was lower than in QT (2.41 meq 100 g^{-1}) (**Figure 7e**, **7f**); while that in BH (1.51 meq 100 g^{-1}) was lower than in SP (4.73 meq 100 g^{-1}) in the surface horizon (Figure 7g, 7h). Moreover, the concentrations of Na^+ and Ca^{2+} were not affected by salinization, with equivalent concentrations ranging from 0.30-0.41 meq 100 g^{-1} (**Figure 7i**, **7j**, **7k**, **7l**) and from 0.47-0.66 meq 100 g^{-1} (**Figure 7m**, **7n**, **7o**, **7p**), respectively. Furthermore, the soil profiles in QT had greater Mg^{2+} concentrations than in TL, with 9.38 compared with 4.54 meq 100 g^{-1} (meq 100 g^{-1}) (**Figure 7q**, **7r**, **7s**, **7t**). The upland soil age did not affect the CEC and exchangeable cations concentrations. However, in the study by Dang and Hung (2023), only K^+ remained under the influence of upland soil age, while CEC, Ca^{2+}, Mg^{2+}, and Na^+ changed. Nevertheless, in the study by Govaerts *et al.* (2007), upland farming changed K^+ but maintained CEC, Ca^{2+}, Mg^{2+}, and Na^+. This could be due to different soil types leading to different upland soil characteristics. Salinization can lead to eutrophication since at 5-15‰ salinity the soluble P content and NH_4^+ concentration increase due to the stimulated mineralization of soil OM leading to NH_4^+ release (Bayabil *et al.*, 2021). Furthermore, salinity can change osmosis by reducing the water potential in the environment and the one in the plant roots, and salt can reduce germination rate by ionic stress and interfering with enzyme functions and metabolism (de la Reguera *et al.*, 2020). Saline stress can alter plant growth by reducing or terminating metabolisms, respirations, N fixations (Kasim *et al.*, 2016), and water uptake of crops (Safdar *et al.*, 2019). Salinity can also affect photosynthesis by reducing leaf area, chlorophyll content, stomatal conductance, and efficiency of photosystem II (Saddiq *et al.*, 2021).

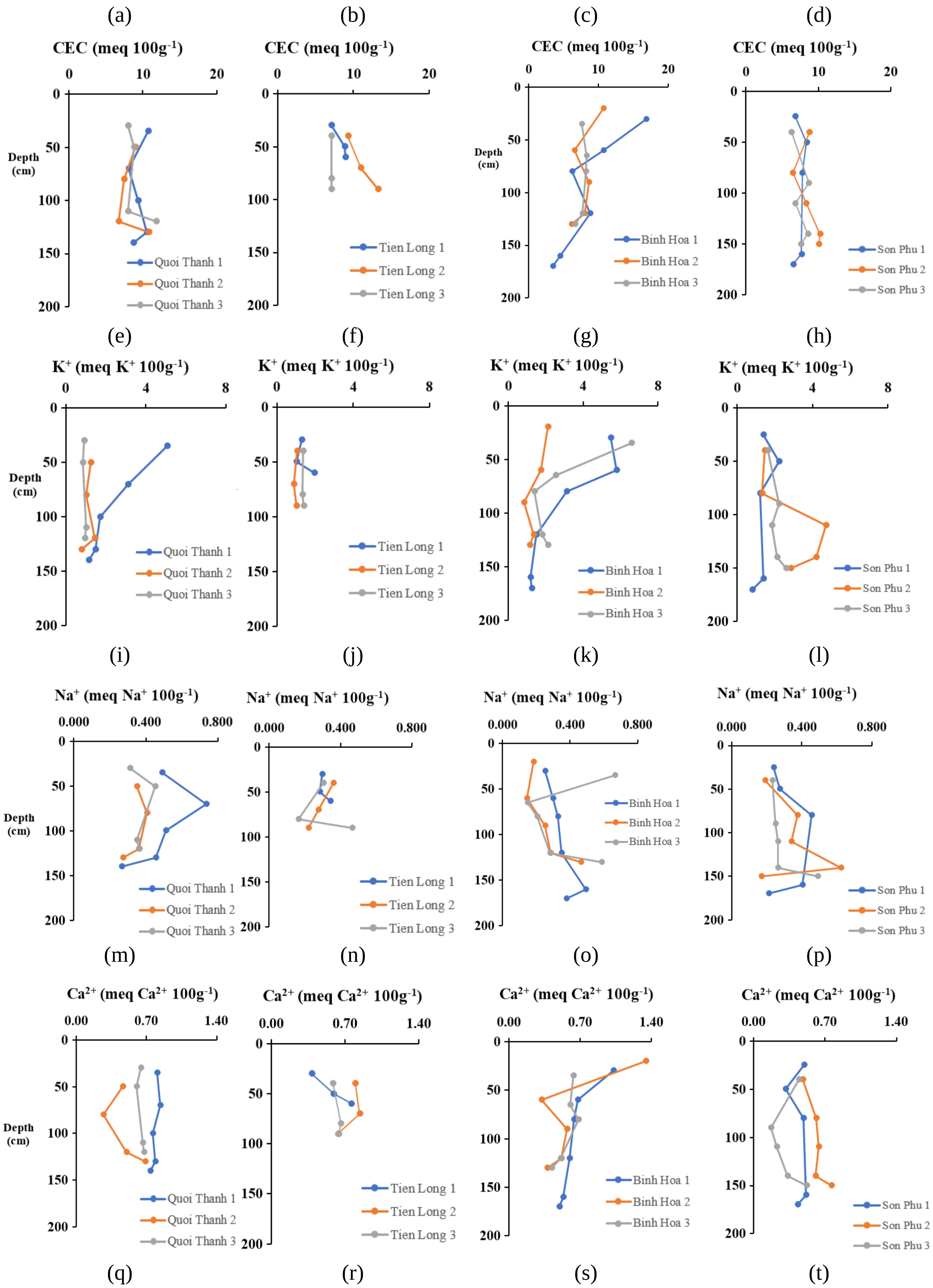

Figure 7. Effects of salinization and upland soil age on (a, b, c, d) cation exchange capacity, (e, f, g, h) Na^+ concentration, (i, j, k, l) K^+ concentration, (m, n, o, p) Ca^{2+} concentration, and (q, r, s, t) Mg^{2+} concentration in soil of pomelo orchards in Quoi Thanh, Tien Long, Binh Hoa, and Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

The concentrations of Fe^{2+} and dissolved Fe followed the same pattern. Therein, the concentrations of Fe^{2+} and dissolved Fe in soil profiles in QT were greater than those in TL, with 32.0 compared with 17.7 mg kg^{-1} (**Figure 8a**, **8b**) and 31.2 compared with 17.1 mg kg^{-1} (**Figure 8e**, **8f**), respectively. These results in BH were also greater than those in SP, with 27.3 compared with 18.3 mg kg^{-1} (**Figure 8c**, **8d**) and 28.4 compared with 18.4 mg kg^{-1} (**Figure 8g**, **8h**), respectively. In addition, the Fe_2O_3 content ranged from 0.61-0.91% among the four locations (**Figure 8i**, **8j**, **8k**, **8l**). Moreover, the greater the upland soil age was, the lower Fe^{2+} toxicity was, in the surface horizon (**Figure 8a**, **8b**, **8c**, **8d**) because during the cultivation, farmers used limes as well as leaching by irrigation in upland soils. The soil profiles belonging to 30-50-year-old upland soil had lower Fe^{2+} concentration than those of 12-25-year-old upland soil, with 4.69-9.05 mg kg^{-1} compared with 14.5-25.8 mg kg^{-1} in the surface horizon.

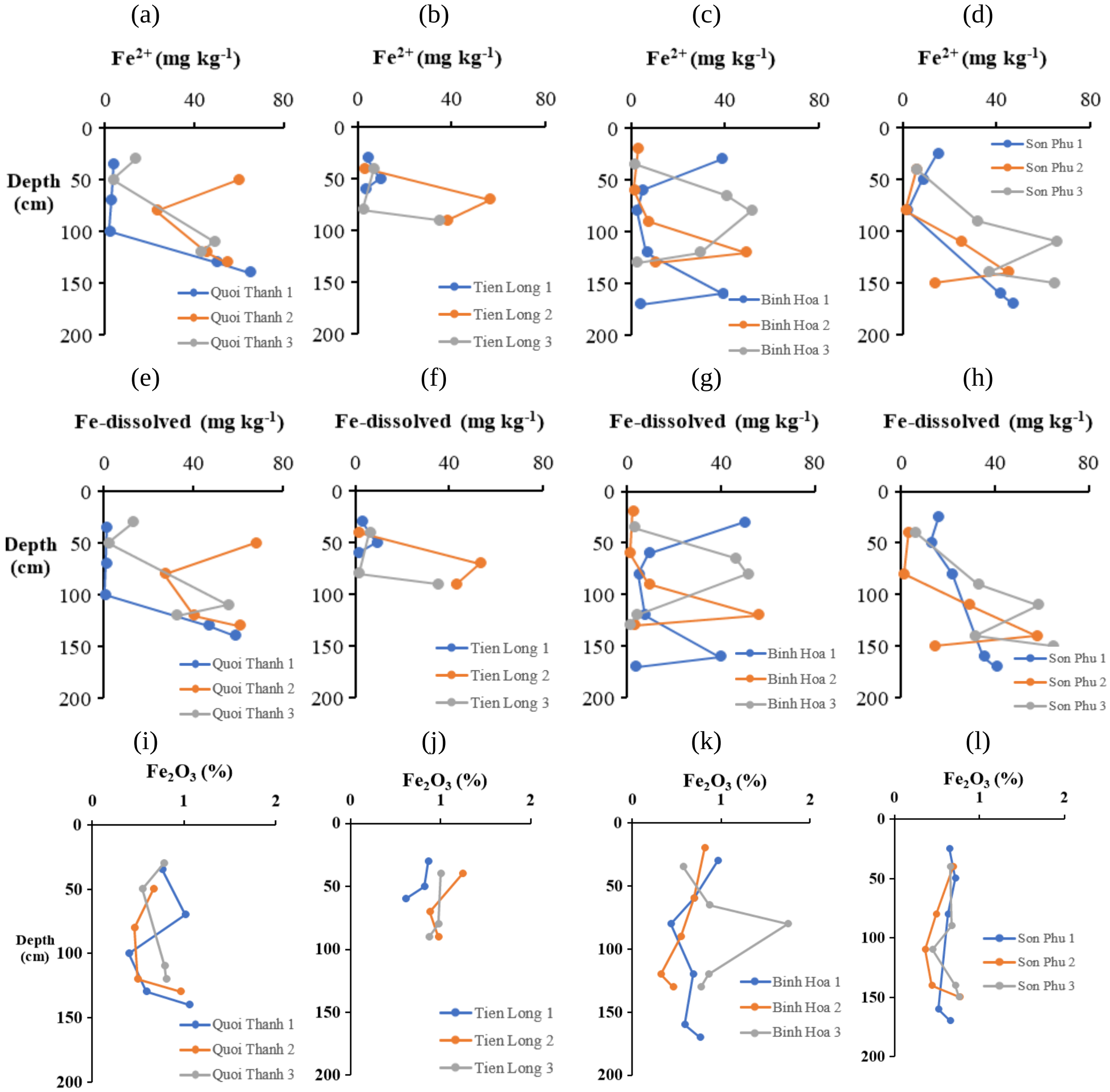

Figure 8. Effects of salinization and upland soil age on (a, b, c, d) Fe^{2+} concentration, (e, f, g, h) dissolved Fe concentration, and (i, j, k, l) Fe_2O_3 content in soil of pomelo orchards in Quoi Thanh, Tien Long, Binh Hoa, and Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

Figure 9 illustrated that the Al^{3+} concentrations in the salinized soil profiles were greater than those in the unsalinized soil with greater Al^{3+} concentration in TL (3.63 meq 100 g^{-1}) (**Figure 9b**) than in QT (3.21 meq 100g^{-1}) (**Figure 9a**). However, the Al^{3+} concentrations in Chau Thanh district showed the opposite pattern with 3.66 meq 100 g^{-1} in SP (**Figure 9d**) and 5.56 meq 100 g^{-1} in BH (**Figure 9c**). The upland soil age did not affect the Al^{3+} concentration.

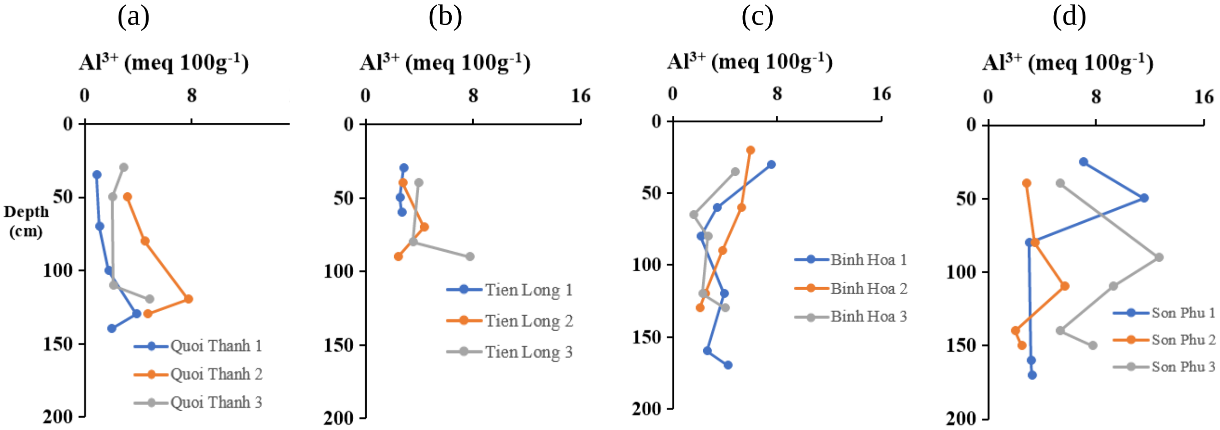

Figure 9. Effects of salinization and upland soil age on Al^{3+} concentration in soil of pomelo orchards in (a) Quoi Thanh, (b) Tien Long, (c) Binh Hoa, and (d) Son Phu. Note: Crop age and upland soil age in QT-(6 and 25), TL-(10 and 50), BH-(12 and 12), SP-(14 and 30).

CONCLUSION

Based on the soil morphology, the soil was classified as Hapli Gleyic Fluvisols. Salinization changed the horizon separation, decreased soluble P content, and increased Fe^{2+} salinity. The upland soil age had impact on soil colors. However, the pH_{KCl}, organic matter content, and Fe^{2+} toxicity decreased, while NH_4^+ concentration increased, along the increasing upland soil age. It is necessary to prevent saline water intrusion in upland soils for pomelo cultivation. Therefore, measures should be taken place. Salinization can be reduced by lime and Mg^{2+} fertilization or some beneficial microorganisms that can be used to lessen the effects of high salinity. The degradation of soil fertility in old upland soil can be aided by proper site-specific nutrient management or some beneficial microorganisms to maintain sustainable agriculture.

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