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Transfer of radionuclides from soil to *Acacia auriculiformis* trees in high radioactive background areas in North Vietnam

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ABSTRACT

The *Acacia auriculiformis* is a tree common in tropical Asian countries, capable of growing in many different soil types, so it could be used for biomonitoring for high natural radionuclide areas in tropical and subtropical climates. The transfer factor (TF) of radionuclides from soil to *A. auriculiformis* in eight uranium and rare earth element (REE) mining areas of North Vietnam was investigated. The activity concentrations ^{226}Ra, ^{238}U, ^{137}Cs, ^{228}Ra, and ^{40}K in both soil and *A. auriculiformis* showed considerable variation. The TFs of these radionuclides also varied in a wide range. In most of the eight areas, the highest TF was observed for ^{137}Cs and ^{228}Ra. While the TFs for ^{226}Ra and ^{238}U were smallest. In addition, the TFs for radionuclides near REE mines were similar to those observed near uranium mines. The TFs for *A. auriculiformis* were within the ranges of TF reported for other plants, except for ^{137}Cs.

1. Introduction

Soil-to-plant transfer factors (TF) are one of the important parameters to evaluate the uptake of radionuclides from soil to plants. It is the ratio of radionuclide concentration in the dry plant to the concentration of radionuclides in dry soil per unit mass.

$$TF = \frac{\textit{Activity concentration of nuclide of interest per kg dry plant mass}}{\textit{Activity concentration of that nuclide in dry soil within the rooting area}}$$

TF have been widely investigated for different plants in different countries (e.g., Al-Masri et al., 2008; Azeez et al., 2019; Cengiz, 2019; Tuo et al., 2017; Van et al., 2020). In general, these investigations showed that the TF has significant variation and it is strongly dependent on many parameters, such as plant type, climate, and geographical conditions.

The various *Acacia* species are present in a large portion of the world, including the tropical, subtropical, arid and semi-arid climates. In 2005 the *Vachellia* genus was distinguished from the *Acacia* genus, previously both of them were categorized as *Acacia*. The various species belonging to the *Acacia* and *Vachellia* genus are significant for their economic value (Blackburn et al., 2020; Thabethe et al., 2018). They are utilized for numerous purposes including building material (Blackburn et al., 2020), fuel (Ngorima and Shackleton 2019), food (Welcome and Van Wyk 2019), medicine (Namasivayam et al., 2020), land reclamation (Nigussie et al., 2021), production of gum arabic (Welcome and Van Wyk 2019), paper production (Haque et al., 2019) and more. *Robinia pseudoacacia*, which looks similar, and is also often sold as *Acacia* wood, is in the same family but in a different clade. It also has good economic value, but it can live in colder climates.

The *A. auriculiformis* has its natural distribution in tropical Asian countries such as Indonesia, Australia, and Papua New Guinea (Schmerbeck and Naudiyal, 2014). This plant can thrive in different types of soil, including clay, sandy soils, saline soil, acid and alkaline soil (Schmerbeck and Naudiyal, 2014). This species has a wide of range of application. The good-quality durable heartwood can be used for construction and making furniture (Schmerbeck and Naudiyal, 2014). This plant is one of the main sources of pulp for the paper industry and a source of charcoal (Schmerbeck and Naudiyal, 2014). The wide superficial and dense root system of this plant can be useful for controlling soil erosion, restoration of mining sites, and soil improvement (Schmerbeck and Naudiyal, 2014). In Vietnam, the *A. auriculiformis* is commonly planted in many areas (Blackburn et al., 2020). In the mountainous areas and mining sites in the North of Vietnam, it is planted with the main purposes of land restoration, soil erosion control, pulp for paper

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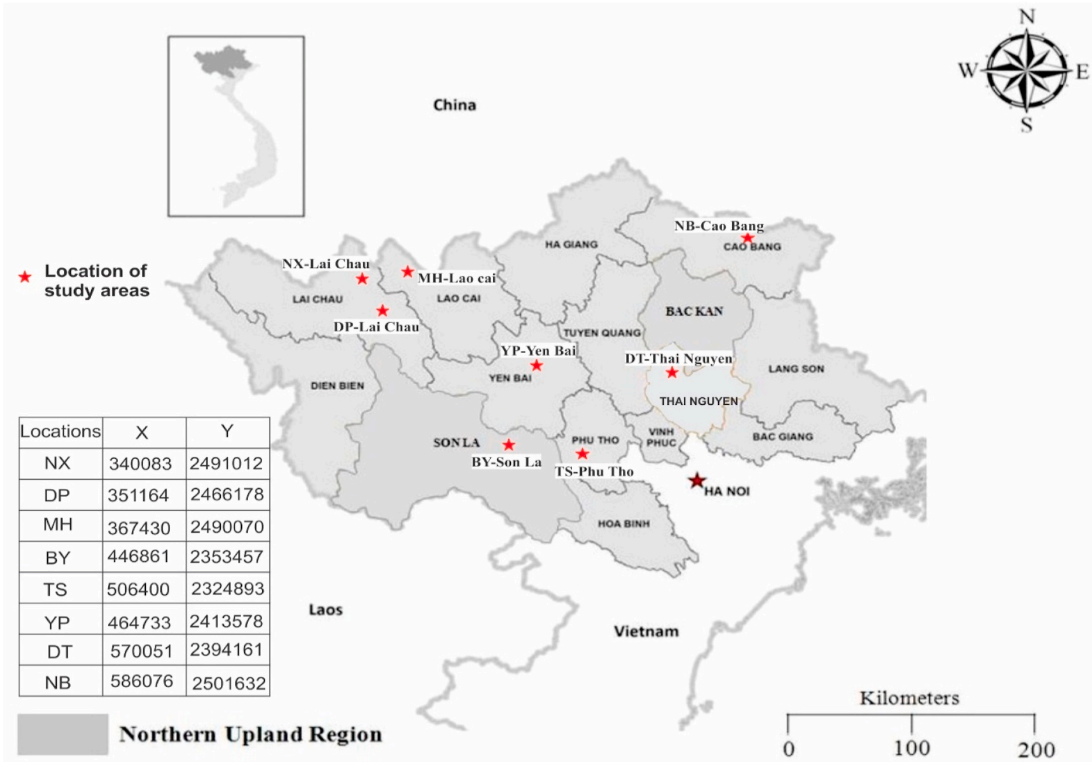

Fig. 1. Location of study areas (modified from Hung et al., 2016).

manufacturing, and making home furniture and building materials. In North Vietnam, there is a distribution of many mines such as rare earth element (REE) mines in NX, DP (located at Lai Chau province), MH (Lao Cai), and YP (Yen Bai); a polymetallic mine (with high uranium concentration) in DT (Thai Nguyen); uranium ore in BY (Son La); TS (Phu Tho), and NB (Cao Bang). These mines were recently reported to have a high radioactive background (unpublished data, Geological Division for Radioactive and Rare Minerals belonging to the General Department of Geology and Minerals of Vietnam). Therefore, the TF of radionuclides in soil in these areas became important in order to be able to monitor the effects of mining activity for the currently operating and for the planned mines as well. *A. auriculiformis*, because it is useful and widespread, might be a good bio-indicator of the effect of these mines. In this study, the TFs of radionuclides (^{226}Ra, ^{238}U, ^{228}Ra, ^{137}Cs, and ^{40}K) from soil to *A. auriculiformis* in these areas was investigated.

2. Study areas, materials, and methods

2.1. Study areas

The study areas cover a wide area in Northern Vietnam, including NX- Lai Chau, DP-Lai Chau, MH-Lao Cai, BY-Son La, TS-Phu Tho, YP-Yen Bai, DT-Thai Nguyen, and NB-Cao Bang (Fig. 1). NX mine is one of the largest REE mines in Vietnam with probable reserves of about 7.7 million tons. The DP mine ranks second with probable reserves of about 3.7 million tons and followed by MH with approximately 400000 tons, YP with about 5000 tons (Moody, 2013). BY (Son La), TS (Phu Tho), and NB (Cao Bang) are uranium ores while DT (Thai Nguyen) is the largest working polymetallic mine in Vietnam which is known having high uranium concentration. With the exception of DT (Thai Nguyen) the mines in question are ore reserves under prospection, with mines being planned in the area.

2.2. Materials

2.2.1. Collecting samples and pre-processing

A total of 88 pairs of samples of soil and *A. auriculiformis* were collected for this study. One-kilogram soil samples were collected from each mining area at eleven locations. The locations were close to, related to, or stood in the REE or uranium mine area. Corresponding to the soil samples, the *A. auriculiformis* samples (trunk and branches of the tree) were also collected, with 10 kg each, at the same time and position. The soil samples were collected within the area the *A. auriculiformis* roots can reach (the area was estimated to be about 4 m^2 –subsample were taken at the four corners and at the center of a 2 m by 2 m square) and reaching to more than 1m depth by a hand core sampling tool. The depth depended on how deep the tree roots were in the different study areas, but sampling did not exceed 1.5m in depth. The depth of soil sampled is deeper than other studies (the IAEA TRS472 recommends sampling to 20 cm), which can be a problem for later comparison of our data with IAEA compilations. The *A. auriculiformis* has been known to have deep roots that can reach underground water, because the tree is adapted to survive in an environment with little water. Foreign objects, such as stones or tree roots were removed from the soil subsamples. The soil samples were homogenized thoroughly from the five subsamples, then a 1 kg representative sample was produced by coning and quartering for the measurement of radioisotopes. For trunk and branches of the tree samples were cleaned from dust, and then they were put into plastic boxes. The bark was removed and only the bole was measured, the trunk and branches thicker than 5 cm diameter were used in the experiment.

The tree samples were converted to charcoal form. Then charcoal samples were then milled into small pieces and dried in an electric oven at 85 °C to a constant dry weight. The soil samples were dried at 110 °C to a constant weight, then milled into powder and sieved through a 2 mm mesh sieve. The powder was weighed and hermetically sealed in plastic containers for 30 days to reach a secular equilibrium between the radium and its daughter radionuclides.

Table 1
Radionuclides concentration in soil in North Vietnam (Bq/kg dry weight).

Location	Value	^{226}Ra	^{238}U	^{228}Ra	^{137}Cs[a]	^{40}K
NX-Lai Chau	*Average*	**655**	**643**	**886**	**2.15–2.63**	**254**
	Median	**645**	**628**	**894**	**0.70–1.57**	**233**
	Range	*543–787*	*520–740*	*746–994*	*BDL-6.71*	*214–360*
DP-Lai Chau	*Average*	**180**	**175**	**217**	**1.49–1.64**	**745**
	Median	**175**	**174**	**224**	**1.35–1.73**	**762**
	Range	*150–213*	*151–204*	*177–270*	*BDL-2.81*	*413–1252*
MH-Lao Cai	*Average*	**428**	**436**	**848**	**1.54–2.41**	**601**
	Median	**428**	**428**	**863**	**1.84–2.24**	**601**
	Range	*359–492*	*347–555*	*553–1348*	*BDL-4.03*	*440–675*
BY-Son La	*Average*	**60**	**59**	**114**	**1.24–1.37**	**528**
	Median	**67**	**65**	**147**	**0.51–1.05**	**730**
	Range	*12–155*	*17–148*	*21–253*	*BDL-2.82*	*54–986*
TS-Phu Tho	*Average*	**154**	**159**	**387**	**1.17–1.43**	**252**
	Median	**150**	**155**	**387**	**1.34–1.37**	**246**
	Range	*125–193*	*121–195*	*330–477*	*BDL-2.07*	*209–291*
YP-Yen Bai	*Average*	**76**	**78**	**144**	**1.86–2.05**	**357**
	Median	**95**	**98**	**195**	**1.52–1.88**	**284**
	Range	*25–148*	*23–139*	*53–229*	*BDL-3.50*	*209–551*
DT-Thai Nguyen	*Average*	**101**	**104**	**72**	**0.32–1.74**	**303**
	Median	**104**	**96**	**73**	**0–1.73**	**289**
	Range	*54–132*	*59–146*	*53–100*	*BDL-1.79*	*122–393*
NB-Cao Bang	*Average*	**594**	**636**	**103**	**1.16–1.42**	**724**
	Median	**612**	**613**	**103**	**1.33–1.37**	**794**
	Range	*403–737*	*404–851*	*84–128*	*BDL-1.99*	*468–909*
Maximum value		**787**	**851**	**1348**	**6.71**	**1252**
Minimum value		**12**	**17**	**21**	**BDL**	**54**

[a] Due to the many values below the detection limit (BDL) a range is given for the average, where the lower value is where BDL values are treated as 0 as a lower estimate, and the upper value is the average without considering BDL values as a higher estimate.

2.3. Methods

The samples were left to achieve equilibrium status and activity concentration measurements were performed using a high-resolution detector HPGe with a low background of Ortec™. The analysis was performed using Gamma Vision software. The detector energy resolution is 1.9 keV at the 1.33 MeV ^{60}Co gamma-ray peak. To reduce the effect of background radiation at the laboratory, the detector is shielded by a 10-cm thick old-lead cylinder with a 1 mm cadmium and 1 mm copper inner lining. The soil and charcoal samples were counted for two and three days respectively to minimize the statistical counting error and activity calculation were carried out based on standard reference materials (IAEA-375 and IAEA-446). The detector is maintained and calibrated regularly.

The activity concentration of each sample was determined based on its respective gamma lines. The gamma lines of 609.3 keV, 1120.3 keV and 1764.5 keV were used to determine the activity concentration of ^{226}Ra, while the lines of 911.2 keV, 969.0 keV, were used for ^{228}Ra,

Table 2
Radionuclides concentration in *A. auriculiformis* bole wood in North Vietnam (Bq/kg dry weight).

Location	Value	^{226}Ra	^{238}U	^{228}Ra	^{137}Cs[a]	^{40}K
NX-Lai Chau	*Average*	**40.2**	**25.1**	**25.9**	**0.14–0.31**	**273**
	Median	**12.3**	**17.6**	**26.4**	**0–0.22**	**253**
	Range	*7.0–21.4*	*12.1–50.9*	*15.8–37.3*	*BDL-0.61*	*170–500*
DP-Lai Chau	*Average*	**19.4**	**21.4**	**23.4**	**0.05–0.18**	**231**
	Median	**23.1**	**20.0**	**21.7**	**0–0.17**	**233**
	Range	*7.1–28.4*	*5.7–46.8*	*15.9–35.4*	*BDL-0.25*	*139–375*
MH-Lao Cai	*Average*	**15.0**	**11.6**	**48.8**	**0.08–0.44**	**293**
	Median	**16.3**	**13.0**	**46.1**	**0–0.44**	**274**
	Ranges	*8.5–22.7*	*5.3–21.5*	*25.1–85.6*	*BDL-0.54*	*139–375*
BY-Son La	*Average*	**2.8–3.4**[a]	**3.0**	**6.0**	**0.23–0.26**	**192**
	Median	**2.6–2.9**	**2.2**	**7.0**	**0.18–0.25**	**170**
	Range	*BDL-7.7*	*1.3–7.3*	*2.1–10.5*	*BDL-0.44*	*118–332*
TS-Phu Tho	*Average*	**5.2**	**6.0**	**19.2**	**1.64–1.80**	**187**
	Median	**4.9**	**5.0**	**21.2**	**1.42–1.48**	**169**
	Range	*3.1–7.5*	*3.6–11.1*	*8.9–25.6*	*BDL-2.77*	*145–283*
YP-Yen Bai	*Average*	**4.4**	**5.3**	**8.7**	**0.26–0.29**	**221**
	Median	**3.1**	**2.5**	**5.1**	**0.16–0.21**	**219**
	Range	*1.9–8.9*	*0.6–13.3*	*3.5–30.8*	*BDL-1.12*	*112–332*
DT-Thai Nguyen	*Average*	**14.1**	**13.9**	**13.1**	**0.75–0.83**	**443**
	Median	**13.3**	**14.3**	**12.9**	**0.41–0.49**	**450**
	Range	*6.0–21.6*	*10.3–16.0*	*10.9–16.7*	*BDL-3.36*	*307–577*
NB-Cao Bang	*Average*	**21.4**	**22.4**	**39.8**	**0.31–0.43**	**477**
	Median	**18.4**	**17.5**	**38.7**	**0.25–0.39**	**494**
	Range	*12.5–36.8*	*11.1–42.9*	*26.5–58.4*	*BDL-0.74*	*275–614*
Maximum value		**40**	**51**	**86**	**3.36**	**614**
Minimum value		**BDL**	**0.59**	**2.09**	**BDL**	**112**

[a] Due to the values below the detection limit (BDL) a range is given for the average, where the lower value is where BDL values are treated as 0 as a lower estimate, and the upper value is the average without considering BDL values as a higher estimate.

Table 3
Transfer factors for radionuclides from soil to the bole wood of *A. auriculiformis*

Location	Value	^{226}Ra	^{238}U	^{228}Ra	^{137}Cs[a]
NX-Lai Chau	*Average*	**0.033**	**0.040**	**0.029**	**0.095–0.261**
	Median	**0.019**	**0.027**	**0.030**	**0–0.299**
	GM (GSD)	**0.026 (2.0)**	**0.035 (1.7)**	**0.028 (1.4)**	**0.217 (2.2)**
	Range	*0.011–0.063*	*0.017–0.085*	*0.017–0.043*	*n.a.-0.381*
DP-Lai Chau	*Average*	**0.109**	**0.123**	**0.110**	**0.023–0.125**
	Median	**0.172**	**0.115**	**0.096**	**0–0.125**
	GM (GSD)	**0.097 (1.7)**	**0.108 (1.8)**	**0.106 (1.3)**	**0.121 (1.4)**
	Range	*0.038–0.172*	*0.037–0.277*	*0.084–0.174*	*n.a.-0.155*
MH-Lao Cai	*Average*	**0.035**	**0.027**	**0.059**	**0.028–0.157**
	Median	**0.033**	**0.024**	**0.059**	**0–0.157**
	GM (GSD)	**0.034 (1.4)**	**0.024 (1.7)**	**0.057 (1.4)**	**0.155 (1.2)**
	Range	*0.021–0.050*	*0.011–0.052*	*0.027–0.085*	*n.a.-0.179*
BY-Son La	*Average*	**0.075–0.092**[a]	**0.087**	**0.105**	**0.171–0.209**
	Median	**0.043–0.046**	**0.049**	**0.050**	**0.191–0.195**
	GM (GSD)	**0.068**[a] **(2.1)**	**0.058 (2.7)**	**0.067 (2.6)**	**0.188 (1.7)**
	Range	*n.a.-0.344*	*0.011–0.271*	*0.017–0.345*	*n.a.-0.349*
TS-Phu Tho	*Average*	**0.035**	**0.038**	**0.050**	**1.208–1.476**
	Median	**0.034**	**0.033**	**0.057**	**0.963–1.007**
	GM (GSD)	**0.032 (1.5)**	**0.035 (1.5)**	**0.048 (1.4)**	**1.300 (1.7)**
	Range	*0.017–0.055*	*0.020–0.072*	*0.023–0.065*	*n.a.-3.433*
YP-Yen Bai	*Average*	**0.108**	**0.133**	**0.105**	**0.164–0.226**
	Median	**0.032**	**0.024**	**0.038**	**0.102–0.125**
	GM (GSD)	**0.057 (1.4)**	**0.043 (6.1)**	**0.056 (2.9)**	**0.157 (2.2)**
	Range	*0.015–0.274*	*0.006–0.380*	*0.020–0.578*	*n.a.-0.896*
DT-Thai Nguyen	*Average*	**0.146**	**0.147**	**0.187**	**0.047–0.515**
	Median	**0.135**	**0.147**	**0.182**	**0–0.515**
	GM (GSD)	**0.138 (1.4)**	**0.140 (1.4)**	**0.183 (1.2)**	**0.515 (1.0)**
	Range	*0.072–0.247*	*0.094–0.228*	*0.115–0.275*	*n.a.-0.515*
NB-Cao Bang	*Average*	**0.037**	**0.036**	**0.392**	**0.169–0.270**
	Median	**0.038**	**0.026**	**0.375**	**0.168–0.250**
	GM (GSD)	**0.035 (1.5)**	**0.032 (1.7)**	**0.380 (1.3)**	**0.255 (1.4)**
	Range	*0.017–0.066*	*0.017–0.069*	*0.248–0.655*	*n.a.-0.372*
Maximum value		**0.344**	**0.380**	**0.655**	**3.433**
Minimum value		**n.a.**	**0.006**	**0.017**	**n.a.**

[a] Due to the values below the detection limit a range is given for the average, where the lower value is where BDL values are treated as 0 as a lower estimate, and the upper value is the average without considering BDL values as a higher estimate. In these cases the minimum TF is given as n.a. (not available). For GM (geometric mean) and GSD (geometric standard deviation) BDL values were left out as a higher estimate.

1460 keV was used for ^{40}K, and 1001 keV was used for ^{238}U (which was verified by ^{235}U measurement with 186 keV line).

It is important to note that in the literature, it is usual to report ^{232}Th activity concentrations even in plants measured by gamma-spectroscopy through its daughter radionuclides, and calculate TFs based on this value (Al-Masri et al., 2008; Azeez et al., 2019; Cengiz, 2019; Tuo et al., 2017; Van et al., 2020), however the equilibrium between ^{232}Th and ^{228}Ra might not be present (Sathyapria et al., 2017), in such cases ^{232}Th concentrations should be measured directly by a different method (for example ICP-MS, neutron activation analysis or alpha-spectroscopy).

3. Results and discussions

The range and average activity concentrations of ^{226}Ra, ^{238}U, ^{228}Ra, ^{137}Cs, and ^{40}K in soil around the root of *A. auriculiformis* are listed in Table 1 For REE mines such as NX-Lai Chau, DP-Lai Chau, MH-Lao Cai, the concentrations of ^{228}Ra are rather high, probably being correlated to ^{228}Ra being present in larger amounts in the ore mined in these REE mines. For the uranium mines the ^{226}Ra and ^{238}U activity concentrations were not markedly higher than that concentration in REE mines, in fact in multiple cases the concentrations of these radionuclides were lower.

Table 2 presents the activity concentrations of ^{226}Ra, ^{238}U, ^{228}Ra,

Table 4
Spearman's Rho correlation coefficient between the variables.

	Acacia Ra-226	Soil U-238	Acacia U-238	Soil Ra-228	Acacia Ra-228	Soil Cs-137	Acacia Cs-137	Soil K-40	Acacia K-40
Soil Ra-226	0.58 $p = 0.00$	0.98 $p = 0.00$	0.58 $p = 0.00$	0.64 $p = 0.00$	0.76 $p = 0.00$	0.07 $p = 0.56$	0.16 $p = 0.24$	0.21 $p = 0.05$	0.32 $p = 0.00$
Acacia Ra-226		0.58 $p = 0.00$	0.82 $p = 0.00$	0.15 $p = 0.16$	0.69 $p = 0.00$	−0.03 $p = 0.79$	0.03 $p = 0.84$	0.36 $p = 0.001$	0.50 $p = 0.00$
Soil U-238			0.57 $p = 0.00$	0.62 $p = 0.00$	0.77 $p = 0.00$	0.06 $p = 0.65$	0.14 $p = 0.29$	0.20 $p = 0.06$	0.34 $p = 0.001$
Acacia U-238				0.13 $p = 0.22$	0.57 $p = 0.00$	0.20 $p = 0.11$	0.21 $p = 0.12$	0.22 $p = 0.04$	0.41 $p = 0.00$
Soil Ra-228					0.47 $p = 0.00$	0.08 $p = 0.50$	0.15 $p = 0.27$	−0.003 $p = 0.98$	−0.14 $p = 0.18$
Acacia Ra-228						−0.007 $p = 0.96$	0.22 $p = 0.11$	0.38 $p = 0.00$	0.40 $p = 0.00$
Soil Cs-137							0.36 $p = 0.02$	−0.16 $p = 0.19$	−0.18 $p = 0.14$
Acacia Cs-137								−0.26 $p = 0.05$	0.07 $p = 0.58$
Soil K-40									0.21 $p = 0.05$
Acacia K-40									

Table 5
Comparison of soil to plant transfer factors obtained in this study with literature studies.

Country	Type of sample	^{226}Ra	^{238}U	^{232}Th/^{228}Ra	^{137}Cs	Reference
Vietnam	*A. auriculiformis*	n.a.[a]-0.344	0.006–0.380	0.017–0.655	n.a.[a]-3.433	This study
China	Mushroom	0.01–0.05	0.06–0.13	–	0.1–0.7	Tuo et al. (2017)
Iraq	Plant crops	0.02–0.053	–	0.011–0.035	–	Azeez et al. (2019)
China (Uranium mine)	Plants	0.006–0.034	0.005–0.037	0.00013–0.00214	–	Chen et al. (2005)
Nigeria (mining areas)	Cassava plant	–	0.01–0.90	0.006–1.54	–	Adesiji and Ademola (2019)
Syria	Plants	–	0.003–0.12	–	–	Al-Masri et al. (2008)
Thailand	Medicinal plants	0.02–0.63	–	–	–	(Saenboonruang et al., 2018))
Bangladesh	Grass	0.038–0.078	–	0.067–0.122	0.034–0.075	(Chakraborty et al., 2013)
	Plants	0.045–0.070	–	0.064–0.108	0.04–0.075	
Serbia	Wheat	–	–	–	0.01–0.43	Sarap et al. (2015)
Bulgaria	Oak tree				0.006–0.009	Zhiyanski et al. (2010)

[a] Due to the values below the detection limit a range is given for the average, where the lower value is where BDL values are treated as 0 as a lower estimate, and the upper value is the average without considering BDL values as a higher estimate. In these cases the minimum TF is given as n.a. (not available).

^{137}Cs, and ^{40}K in the wood of *A. auriculiformis* in different areas. It can be seen that some locations had the highest concentration of radionuclides in soil, but the trees in these areas might not have the highest concentration of these radionuclides. This confirms that the concentration of radionuclides in soil might not be the single determining factor of the concentration in plants (Azeez et al., 2019).

Finding comparable values in the literature is not easy, however there is some information available on *Robinia pseudo Acacia*, in a recultivated mining area in Hungary, the two *Acacia* trees sampled were reported to have 407 ± 18 and 243 ± 6 ng g^{-1} U (5.0 ± 0.2 and 3.0 ± 0.1 Bq/kg ^{238}U) and 2.62 ± 0.32 and 8.53 ± 0.20 ng g^{-1} Th (0.011 ± 0.001 and 0.035 ± 0.001 Bq/kg ^{232}Th) in their leaves (Mihucz et al., 2008) and *Acacia* trees in Portugal in a non-contaminated area were reported to have 0.020 ± 0.001 Bq kg$^{-1}{}_{dry}$ ^{238}U, 1.5 ± 0.1 Bq kg$^{-1}{}_{dry}$ ^{226}Ra, and 0.008 ± 0.001 Bq kg$^{-1}{}_{dry}$ ^{232}Th in their trunk and Bq 13.0 ± 0.3 kg$^{-1}{}_{dry}$ ^{238}U, 30.8 ± 1.6 Bq kg$^{-1}{}_{dry}$ ^{226}Ra, and 0.16 ± 0.02 Bq kg$^{-1}{}_{dry}$ ^{232}Th in their leaves, respectively (Carvalho et al., 2014). The values observed in the bole of *A. auriculiformis* in the REE and uranium mining areas of Vietnam are orders of magnitude higher than those observed in the trunks of *Acacia* trees (unspecified species) in Portugal. This might not be a perfect basis for comparison, since the exact species of the *Acacia* tree was not specified in the Portuguese article, tree species showed higher activity concentrations in their trunks in Portugal and it is an uncontaminated area (Carvalho et al., 2014).

Due to the relatively low activity concentrations present in wood compared to other building materials, all samples presented in Table 2 could be used in unlimited amounts according to the various radiological hazard indices (for example radium equivalent $Ra_{eq}<370$, gamma-index $I < 1$, internal hazard index $H_{in}<1$ and external hazard index $H_{ex}<1$).

TFs were calculated for all soil/plant pairings and are shown in Table 3. The TFs for ^{226}Ra, ^{238}U, ^{228}Ra, ^{137}Cs, and ^{40}K ranged from 0.03 to 0.14, from 0.03 to 0.13, from 0.03 to 0.38, from 0.11 to 1.26, and from 0.31 to 1.46 in respective (Table 2). The TFs for ^{226}Ra, ^{238}U, and ^{228}Ra are numerically small and somewhat similar in almost all studied areas, except for NB-Cao Bang. These radionuclides are heavy elements and most chemical species are highly insoluble in water (IAEA, 2014). These features will lower the TF for these radionuclides. In NB-Cao Bang, the TF for ^{228}Ra is rather high compared to that for ^{226}Ra and ^{238}U. Generally, the level of soil-to- *A. auriculiformis* TF was highest ^{137}Cs and ^{228}Ra. The TFs for ^{238}U and ^{226}Ra were similar. There is little difference of TF for studied radionuclides between REE mines (NX-Lai Chau, MH-Lao Cai, DP-Lai Chau, BY-Son La) and uranium mines (TS-Phu Tho, YP-Yen Bai, DT-Thai Nguyen, NB-Cao Bang). However, it should be noted that in REE areas such as NX-Lai Chau, DP-Lai Chau, MH-Lao Cai, although the activity concentration of ^{228}Ra in soil in these areas was higher than that in uranium mines, the TF for this radionuclide was rather low. It is lower than that in NB-Cao Bang and DT-Thai Nguyen. NB-Cao Bang had an especially high TF for ^{228}Ra. In general, the TFs were different for different locations (see Table 4).

The TFs presented in Table 3 have a lognormal distribution according to the Kolmogorov-Smirnov test of normality.

The Spearman's Rho correlation coefficients between ^{226}Ra and ^{238}U activity concentration in soil indicate a strong positive correlation. The activity concentration ratios in soil were between 0.81 and 1.34 for ^{226}Ra/^{238}U. The correlation coefficients between ^{226}Ra and ^{228}Ra and ^{238}U and ^{228}Ra were worse, but still indicate a moderate positive correlation. The Spearman correlation coefficients indicate a moderate positive correlation between ^{226}Ra and ^{238}U in *A. auriculiformis* trunks and soil in all combinations. This might not be the case in other locations, but in this specific case this makes measuring either radionuclide in *A. auriculiformis* a possibly good indicator of ^{238}U concentration in soil. A general assumption like that cannot be made for all plants, however in this particular case, for the soil chemistry and the plant combination in question this was observed. For different soils these correlations might or might not be correct, depending on the soil chemistry and environmental conditions (Mitchell et al., 2013).

It would be interesting in the future to investigate the suitability of different *Acacia* and *Vachellia* species and *Robinia pseudoacacia* for bio-indication or biomonitoring.

The comparison of TFs observed in this study with TFs in literature is shown in Table 5. There was no previous published data with TF for *A. auriculiformis* available in the literature. However, it can be seen that TFs for most studied radionuclides for *A. auriculiformis* are within the range of TFs for other plants. The TF for ^{137}Cs for *A. auriculiformis* is similar to those for other plants with the exception of TS-Phu Tho, where despite the activity concentrations in soil being similar, the activity concentrations measured in the tree trunks are consistently higher than in other locations yielding unusually high TFs compared to the other locations. The IAEA TRS 472 offers limited information on trees, for ^{137}Cs the aggregate transfer factors (T_{ag}) for various woods other than *Acacia* ranges from 0.000010 to 0.02 T_{ag}, m^2 kg^{-1}, dry weight (IAEA, 2010).

4. Conclusions

In this study, the activity concentrations and TFs for ^{226}Ra, ^{238}U, ^{228}Ra, ^{137}Cs, and ^{40}K for the *A. auriculiformis* in different locations with high natural radioactive background in North Vietnam have been investigated. Based on the analysis of research results, some conclusions are drawn as follows:

The activity concentrations of radionuclides in both soil and *A. auriculiformis* varied in a wide range. The activity concentrations for ^{226}Ra, ^{238}U, ^{228}Ra (often seen as ^{232}Th in the currently available literature) soil and *A. auriculiformis* trunks showed a moderate positive correlation confirming the possibility of the use of said plant for biomonitoring. Based on the work of Carvalho and colleagues the leaves of the *Acacia* trees might contain higher activity concentrations than the trunk, thus it would be interesting to investigate the possibility of using leaves instead of wood (Carvalho et al., 2014).

In all areas, the TFs for different radionuclides also showed a large variation. As reported by most researchers, TFs were affected by factors other than the concentration of radionuclides in soil. The TFs for *A. auriculiformis* were within the TF ranges in the literature for other plants, except for ^{137}Cs, where one location, TS-Phu Tho, showed unusually high TFs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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