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⁹⁰Sr Content in the Stemwood of Forests within Ukrainian Polissya

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Received: 20 January 2020; Accepted: 27 February 2020; Published: 28 February 2020



Abstract: The consequences of the Chernobyl disaster continue to threaten humans and ecosystems across fallout gradient in Northern Ukraine and nearby. Forest ecosystems contain substantial stocks of long-lived radionuclide ⁹⁰Sr which was leached from the fuel matrix during the disaster. Nowadays, there is a lack of information about current transfer factors (TF) of this radionuclide from soil to the stemwood of native tree species. We have estimated ⁹⁰Sr content in the forest stemwood of three tree species utilizing models of their growth and yield and collected woody samplings. TFs provided here vary greatly across studied tree species ($18.0 \times 2.1^{\pm 1}$, $8.7 \times 2.8^{\pm 1}$, and $10.4 \times 6.0^{\pm 1} n \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$ (geometrical mean (GM) \pm geometrical standard deviation, GSD) for the above species, respectively) and together with indicators of soil contamination allow us to reliably assess local stocks in the stemwood. Silver birch stands are estimated to deposit the highest ⁹⁰Sr stocks. Herewith, at 25 years old Black alder stands could accumulate higher stocks (up to 35 MBq·ha⁻¹) under rich growth conditions. TFs obtained in this study substantially exceed values provided by the International Atomic Energy Agency for studied tree species and thus could entail respective restrictions on use of firewood across large areas in Ukrainian Polissya. Data provided here may be harnessed to support decisions of respective stakeholders to provide credibly safe management of the contaminated forest ecosystems.

Keywords: Chernobyl exclusion zone; forest growth models; long-lived radionuclides; radioactive contamination

1. Introduction

Radioactive contamination of forests remains one of the main ecological consequences of the Chernobyl and Fukushima Daiichi nuclear power plant (NPP) accidents [1]. Currently, only long-lived radionuclides (⁹⁰Sr, ¹³⁷Cs, and also transuranium elements) pose a radiological hazard in Ukraine [2]. In total, ¹³⁷Cs deposition exceeded 37 kBq m⁻² at the forest area of approximately 1230.7 thousand ha (38.6% total forest land of Ukrainian Polissya as of 1993) [3]. Spatially distributed high-resolution data on levels of radioactive contamination ⁹⁰Sr in forest are absent currently in Ukraine.

The most perspective (in terms of sanitary) types of use of abandoned contaminated lands are either natural afforestation (or closed to nature silviculture) or bioenergy production for local needs [4].

Nowadays, forest management based on native tree species is likewise considered as an efficient way to use respective areas [5]. Hence, studies focused on patterns of radionuclide migration and accumulation in forests will remain at a high level of significance for contaminated areas.

To date, ^{90}Sr activity due to its physical half-life (~ 30 years) has been decreased twice. However, substantial areas will persist as highly contaminated for at least a century more [6]. Consequently, the risk of contaminated wood being occasionally used by the people remains. Special consideration must be given for the firewood, since local inhabitants in rural areas typically use ash after firewood utilization as a fertilizer thus leading to the secondary contamination of soil and agricultural products as well. Despite all the villages in the Ukrainian Polissya region being electrified, settlers there hitherto prefer to use fuelwood to heat their homes [1].

Nowadays, restrictions of the activity concentration of ^{90}Sr in Ukraine forest are met only for the requirements of firewood and fuel bunches [7]. Fuel bunches are the only forest products which hygienic standards set for them. The regulations to ^{90}Sr activity concentration in timber are introduced in Russia [8], whereas there is no any statutory restriction for ^{90}Sr content of contaminated wood in Belarus (Table 1) the territory of which was heavily contaminated after the Chernobyl disaster as well.

Table 1. Existing restrictions for forest products use according to ^{90}Sr contamination.

Group of Products	^{90}Sr Activity Concentration, $\text{Bq}\cdot\text{kg}^{-1}$	
	Russia (1997), [7]	Ukraine (2005), [6]
Round timber for constructions of residential buildings	5200	–
Other round timber	5200	–
Pulpwood	2300	–
Firewood	370	60
Lumber, products made out of wood and woody materials for constructions of residential buildings	5200	–
Lumber and other wood products	520	–
Other non-food forest products	520–2300	–

Biogeochemical ^{90}Sr cycling in forest ecosystems is strongly dependent on the soil type (including fertility and water supply conditions), tree species, features of their growth and development, tree mortality patterns and dead organic matter (including litter) decomposition. While radionuclide fluxes in each ecosystem have certain features, and generalization of ^{90}Sr migration and accumulation patterns will allow researchers to assess and simulate dynamics of concentration activity in ecosystem compartments including forest live biomass [9]. Another important factor determining the magnitude of its root uptake is a content of exchangeable calcium in soil. Being the chemical analogue of Ca, strontium is absorbed from soil, translocated and accumulated in the tree organs, and is removed from the aboveground biomass by the same mechanisms of the Ca cycle. ^{90}Sr soil-to-plant transfer factor (TF) declines with increase of the exchangeable forms of Ca in soil [10].

Patterns of ^{90}Sr migration due to root uptake, transferring into tree live biomass and returning through litterfall, rainfall and stem fluxes, is commonly shown by respective aggregated TF. Aggregated TF is the ratio of the mass activity concentration of radionuclide ($\text{Bq}\cdot\text{kg}^{-1}$) in a specified object to the unit area of its activity density (for terrestrial surfaces, usually: $\text{kBq}\cdot\text{m}^{-2}$). Compared to information on TF for ^{137}Cs , there are a lack of such data for ^{90}Sr and existing TF differ greatly. TF were estimated for ^{90}Sr from soil in wood of Scots pine (*Pinus sylvestris* L., arithmetical mean and standard deviation (AM \pm SD): $39.1 \pm 5.9 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$), Norway spruce (*Picea abies* (L.) H. Karst., $9.0 \pm 2.0 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$), European oak (*Quercus robur* L., $1.92 \pm 0.46 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$), Silver birch (*Betula pendula* Roth., $16.9 \pm 3.1 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$), Black alder (*Alnus glutinosa* (L.) Gaertn., $1.91 \pm 0.35 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$) and Common aspen (*Populus tremula* L., $1.91 \pm 0.35 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$) depending on forest type conditions, as well as TF expansion series for timber wood [11].

Information on ^{90}Sr TF for the stem wood of Scots pine ($11.2\text{--}17.9 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$) and Silver birch ($15.4\text{--}27.3 \times 10^{-3} \text{ m}^2\cdot\text{kg}^{-1}$) published by Davydov et al. [12], are rather consistent with data of

Perevolotskiy [10] for timber, but additionally contain TF for branches and foliage live biomass of these tree species.

Guidelines of the International Atomic Energy Agency (IAEA) for use of ^{90}Sr TF from soil to stem biomass of Black alder (geometrical mean—GM: $0.95 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$), Silver fir (*Abies alba* L., GM: $4.4 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$), Scots pine (GM: $1.6 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$), Common oak (GM: $1.3 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$), Common aspen (GM: $2.1 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$) and Silver birch (GM: $2.4 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$) are based on data from the Kyshtym [13] accident and early studies by Scheglov (1986–1992), that substantially differ from the data of the majority of subsequent researchers [9,11,12].

Estimation of concentration dynamics of ^{90}Sr in forest live biomass compartments allows us not only to expand understanding of biogeochemical fluxes in forest ecosystems, but rather to develop information-support materials for decision-making in planning, organization and management of timber production, including wood for energy purposes. Such materials should sustain reasonable restrictions of wood utilization. Together with fostering the establishment of new naturally regrown mixed forests which are more resilient in terms of radiological sanitary, these are only reliable approaches to maintain contamination levels stable [1].

According to accumulation of the highest dose rates that cause impact on humans due to external and internal exposure, forest ecosystems are especially significant, being characterized fundamentally another radionuclides' behavior compared to agricultural, meadow and peatland ecosystems [14]. Functioning of forests causes biogeochemical radionuclide cycling that define respective concentration in the soil, mushrooms, forest berries, live biomass of the trees, understory, forest litter (foliage and branches up to 1 cm in diameter), coarse woody debris (CWD: branches with $d > 1$ cm) and other ecosystem compartments. Although there are several studies devoted to the migration of ^{137}Cs and ^{90}Sr [15,16], experimental assessment of their biogeochemical fluxes in forest ecosystems hitherto has crucial importance. We are hypothesizing that combining data on the growth and productivity of forest stands with patterns of radionuclide transfer from soil to the stemwood, it is possible to provide sufficient information on the accumulation of ^{90}Sr in birch, alder and aspen wood. That is, the aim of such assessment is thus to predict forest ecosystem contamination in more credible manner and with perspectives to adjust respective knowledge for planning local management decisions and silviculture activities not exceeding implemented hygienic standards for ^{90}Sr and ^{137}Cs content in products.

2. Materials and Methods

2.1. Forest Growth Modelling

This study focuses on the most abundant deciduous tree species within Ukrainian Polissya. Forests of Silver birch, Black alder and Common aspen cover one third of forested area within this zone. Such a ratio is slightly increasing due to the natural succession on abandoned agricultural lands [17,18]. Deciduous forests have crucial importance, provisioning ecosystem services such as biomass accumulation, carbon sequestration, oxygen production, biodiversity maintaining, sustaining conditions for hunting and providing other goods for human well-being [19].

Computations of growth and yield at stand level were carried out using height-based allometric models for Silver birch (seed origin), Black alder (vegetative origin) and Common aspen (vegetative origin) forests, based on the set of inventory units ($n = 175,000$ (Silver birch), $n = 124,000$ (Black alder), and $n = 17,000$ for Common aspen) from data in the aggregated nationwide database of forest planning and management (FPAM).

Models of biophysical parameters dynamics were developed for deciduous tree species examined in this study. Those include models of mean height (H) and diameter (D), growing stock volume (GSV). Dynamics of parameters mentioned above was harmonized using the Chapman–Richards non-linear model [20]. Differential and integral equations of this function are given as:

$$\frac{dX_i}{dt} = c_3 c_2 c_1^{1/c_3} - c_3 c_2 X_i \quad (1)$$

$$X_i = c_1[1 - \exp(-c_2A)]^{c_3} \tag{2}$$

For a given site index, this model (1–2) reflects increment and accumulated value of the certain biophysical parameter as a function of the stand age. Such differential equation generally describes growth patterns of trees in the forest and is given with visualization purpose. Each regression coefficient has a biological explanation: c_1 is a maximal possible value of growth function, i.e., it represents the level of used growth capability in respective forest conditions; c_2 scales up temporal axis and characterizes stand growth velocity, simultaneously being proportional to the age of the highest increment. Hence, value $c_2(1 - 1/c_3) \exp(c_3 - 1)$ represents the maximal value of the current increment, while $[\ln(c_3)/c_2]$ is an intercept of growth function [20].

Based on stand growth models for each site index, there has been an approximation of coefficients for soft-leaved tree species with the use of quadratic polynomial equations (3–5):

$$c_1 = c_{13}B^2 + c_{12}B + c_{11} \tag{3}$$

$$c_2 = c_{23}B^2 + c_{22}B + c_{21} \tag{4}$$

$$c_3 = c_{33}B^2 + c_{32}B + c_{31} \tag{5}$$

where B is a site index encoded, $c_1 \dots c_3$ and $c_{11} \dots c_{33}$ are the regression coefficients.

Since growth and yield modelling implied use of site indexes, here we utilized a digital encoding system (where initial letters (a–f) in site index titles indicate the growing trend in forest productivity) for adequate visualization of their influence (Table 2).

Table 2. Encoding system for site indexes.

Parameter	Appropriateness										
	Site Index	I ^f	I ^e	I ^d	I ^c	I ^b	I ^a	I	II	III	IV
Respective code		−5	−4	−3	−2	−1	0	1	2	3	4
Mean tree height (m) at 50 years old (seed origin)		35.9	33.1	30.3	27.5	25.1	21.8	18.9	16.1	13.2	10.4
Mean tree height (m) at 50 years old (vegetative origin)		40.4	37.4	34.4	31.3	28.3	25.3	22.3	19.3	16.3	13.2

Distribution of Ukrainian Polissya forests’ area by site indexes is given in Table 3. Typically, stands of Common aspen are high-productive (site index I takes 43.1% of area) there, while the most common forests of Silver birch and Black alder belong to site index II (41.7% and 54%, respectively). The proportion of low-productive stands of studied tree species is rather insufficient.

Table 3. Distribution of area of studied tree species by site indexes.

Tree Species	Site Index							
	I ^c	I ^b	I ^a	I	II	III	IV	Other
Silver birch	0.7	3.0	9.2	28.0	41.7	12.3	3.4	1.7
Black alder	0.4	1.2	5.0	20.1	54.0	16.8	1.9	0.6
Common aspen	1.0	2.7	15.5	43.1	30.2	5.1	0.7	1.6

To assess accuracy, we used an experimental dataset of 382 temporary sample plots (TSP) established for studying growth and yield of stands of soft-wood deciduous species and live biomass dynamics of Ukrainian Polissya’s forests. The plots are almost equally arranged among studied tree species (119 of Silver birch, 139 of Black alder and 124 of Common aspen). We utilized three different metrics (6–8) to validate models’ performance on this dataset: root mean square error (RMSE), residual sum of squares (RSS) and model efficiency (ME).

$$RMSE = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n} \quad (6)$$

$$RSS = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (7)$$

$$ME = 1 - \left| \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \right| \quad (8)$$

where y_i is observed value, \hat{y}_i is mean observed value, \bar{y}_i is respective predicted value, and n is sample size. Additionally, we used the Shapiro–Wilk test to examine whether residuals of predicted GSV follow normal distribution.

2.2. Sampling and Measuring ^{90}Sr Activity

Aiming to estimate parameters of radioactive contamination of wood stem, here we used standard sampling methods that allow us to examine unbiased means of ^{90}Sr density of soil contamination and biomass. Composite soil samples were collected using the envelope method ([21] as an industry standard implemented in Ukraine). After full accounting of all trees and measurement of their diameters at breast height (DBH) at forest sites, we selected three model trees near the AM of stand DBH, and two model trees around values AM – SD and AM + SD. Wood samples of these 5 model trees were collected using an increment borer (5.5 mm) at a tree height of 1.3 m for radiological investigation. Soil samplings were gathered with use of special cylindrical sampler ($d = 37$ mm) digging to the 30-cm layer depth in five points per plot with 5–10 m distance between those: four in the corners and one in the center of a plot. The samples were subsequently combined to form a composite. The soil composites were dried (at 105 °C), sifted through sieve (cells $d = 1$ mm), carefully homogenized and 100 cm³ volume was taken for ^{90}Sr activity measurements. ^{90}Sr activity in samplings was estimated based on radiochemical method described by Pavlotskaya [22] with the next use of β -spectrometer SEB-01-70 (Research and Production Enterprise AKP—Atom Komplex Prylad, Ukraine). All measured ^{90}Sr activity values for the samples were recalculated as of 1 January 2018.

Experimental dataset of collected stem wood samplings includes 44 samplings: Silver birch – 32 pcs, Black alder – 6 pcs and Common aspen – 6 pcs, which were used for estimation of ^{90}Sr content within. Experimental dataset of collected stemwood samplings includes 1122 samplings: Silver birch—504 pcs, Black alder—336 pcs and Common aspen—282 pcs, which were used for estimation of basic wood density. Basic wood density was 512 ± 18 kg·m⁻³ for Common aspen, 444 ± 21 kg·m⁻³ for Black alder, and 415 ± 12 kg·m⁻³ for Silver birch.

3. Results

3.1. Forest Growth Modelling

Performance of developed models in terms of abovementioned metrics is given in the Table 4. The best predictive ability was achieved by the mean height (H) models, while models of growing stock volume (GSV) and diameter (D) were performed moderately.

Table 4. Accuracy of developed growth models.

Metrics of Model Performance	Biophysical Parameters of the Stands								
	Silver Birch			Black Alder			Common Aspen		
	D, cm	H, m	GSV, m ³	D, cm	H, m	GSV, m ³	D, cm	H, m	GSV, m ³
RMSE	4.3	2.1	58.4	4.2	2.0	82.3	4.1	2.3	65.3
RSS	2154	504	40,5228	1795	403	88,2523	2136	629	52,8953
ME	0.73	0.88	0.58	0.79	0.87	0.43	0.72	0.90	0.78

RMSE (Table 4) of growing stock volume in validation Silver birch stands equals 33.4% of mean value of observed GSVs, regarding Black alder stands, 33.7% and Common aspen stands, 24.4% of respective values. Residuals of predicted GSV for Black alder follows normal distribution (p -value = 0.07), while this is not a case for other two species (p -value < 0.05 for both).

Visualization of 1:1 agreement between observed and predicted values illustrates overall sufficient adequacy of developed models (Figure 1):

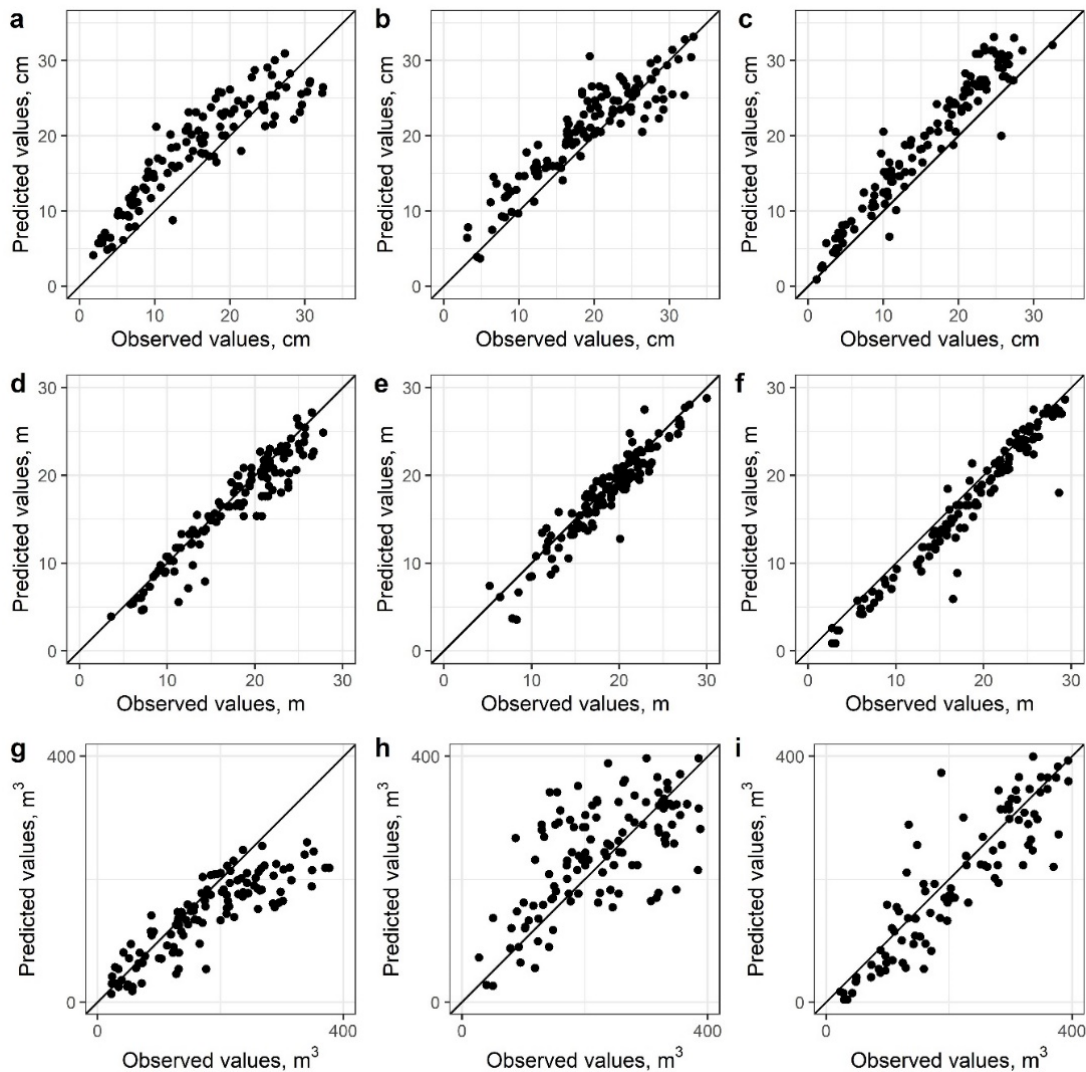


Figure 1. Observed versus predicted values: top row indicates D, middle - H and bottom - GSV. Plots are arranged according tree species: (a,d,g—Silver birch; b,e,h—Black alder; c,f,i—Common aspen). Red line illustrates 1:1 agreement between values.

Polynomial coefficients for calculating values c_1 – c_3 (3–5) given in each model (2) are presented in Appendix A.

3.2. Transfer Factors Estimation

Experimental data of wood samplings was used for estimation of current TFs from soil to the wood without bark for all tree above mentioned species: Silver birch, Black alder and Common aspen, although the number of samplings for the last two species was small. However, results obtained agreed quite well with data provided by Perevolotskiy [11] and Davydov et al. [12], but substantially exceed

data provided by the IAEA [23]. Data on main descriptive statistics of our estimated experimental TFs (with standard deviations (SD) and geometrical standard deviations, GSD) is presented in Table 5.

Table 5. Experimental data on estimated transfer factors (TFs) for ^{90}Sr (as of January 2018).

Tree Species	No. of Samplings	TF from Soil to Stemwood, $n \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$			
		Arithmetic Mean	SD	Geometrical Mean	GSD
Silver birch	32	27.5	26.6	18.0	2.1
Black alder	6	12.8	10.1	8.7	2.8
Common aspen	6	12.6	7.3	10.4	6.0

3.3. Content of ^{90}Sr in the Stemwood of Studied Tree Species

Based on developed GSV models, data on wood density for studied tree species, common levels of soil contamination and estimated TFs, capability potential of forest stands to deposit ^{90}Sr was assessed. An example of produced data at equal ^{90}Sr contamination density of soil for estimated geometric mean values of studied wood species TF is given in Figure 2.

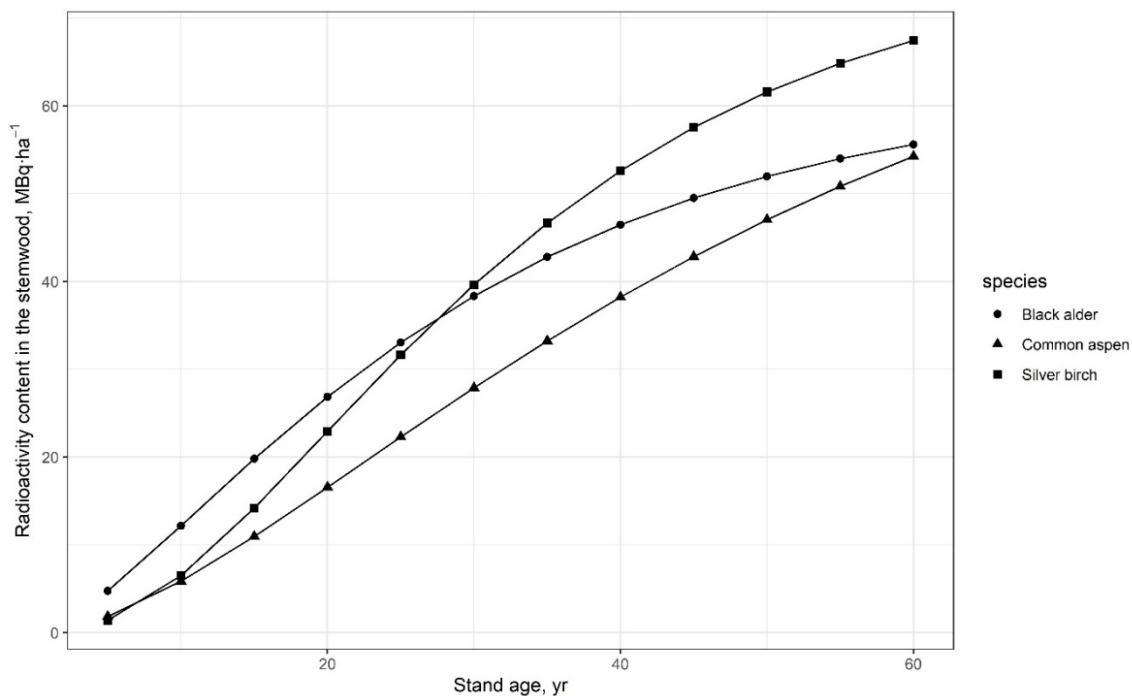


Figure 2. Dependence of the ^{90}Sr activity stock in stemwood (at $40 \text{ kBq} \cdot \text{m}^{-2}$ in soil and site index I) on various age of forest stands.

Typically, considering higher TF and growth rate, Silver birch stands accumulate the largest stocks across their life (Figure 2). Black alder stands can reach higher stocks up to a 25-year-old threshold. Differences between ^{90}Sr stock related to various site indexes at the same (60 yr) age and soil ($40 \text{ kBq} \cdot \text{m}^{-2}$) contamination level are visualized in Figure 3.

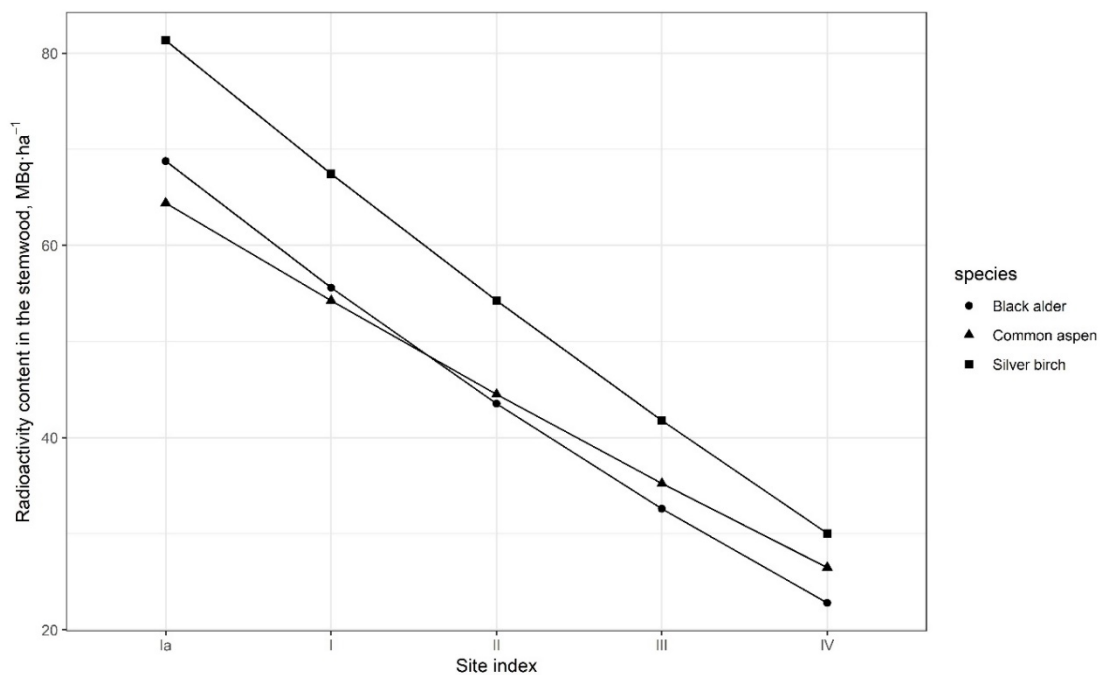


Figure 3. Dependence of the ^{90}Sr activity stock in stemwood (at $40 \text{ kBq}\cdot\text{m}^{-2}$ in soil and stands age 60 years) on various site index of forest stands.

Since nowadays restrictions for use of stemwood regarding ^{90}Sr contamination in Ukraine are determined only for fuelwood, respective probabilities of excess related to implemented activity levels ($60 \text{ Bq}\cdot\text{kg}^{-1}$) were estimated (Table 6).

Table 6. Probability of excess for ^{90}Sr activity concentration in fuel wood ($>60 \text{ Bq}\cdot\text{kg}^{-1}$).

Tree Species	$\text{TF} \times 10^3, \text{m}^2\cdot\text{kg}^{-1}$			At a Density Contamination Larger, $\text{kBq}\cdot\text{m}^{-2}$		
	$p = 50\%$	$p = 95\%$	$p = 99\%$	$p = 50\%$	$p = 95\%$	$p = 99\%$
Silver birch	18.0	77	97	3.33	0.78	0.62
Black alder	8.7	48	68	6.90	1.25	0.88
Common aspen	10.4	38	53	5.77	1.56	1.14

4. Discussion

Based on (i) growth patterns of deciduous forests, (ii) dynamics of stemwood as well as on (iii) features of radionuclides transition from soil to the wood of tree, we developed empirical models of ^{90}Sr content depending on different age of forest stands for respective tree species widely presented in forests of Ukrainian Polissya. Such data are crucial for understanding and modelling of radionuclide biogeochemical fluxes and depots within forest ecosystems and for prediction of changes in environmental contamination.

To date, information about updated TFs for different species typical for Ukrainian Polissya is limited. Davydov et al. [12] developed transfer factors (TF) for Silver birch, while respective values for Black alder and Common aspen were studied by Perevolotskiy [11]. Data provided by the IAEA [23] which are obtained based on studying the Kyshtym accident, and early studies by Scheglov [13], are different from the aforementioned studies by a large margin. If the first case (Kyshtym accident), the regional soil conditions cause this difference, while the contrast of our data to the results by Scheglov [13] is a consequence of the lack of ^{90}Sr ‘saturation’ in depot biomass compartments of the woody plants. Additionally, the content of ^{90}Sr is given in a biologically inaccessible form in the matrix

of fuel particles during the first period after Chernobyl accident [24,25]. The comparison of various TFs is presented in Figure 4.

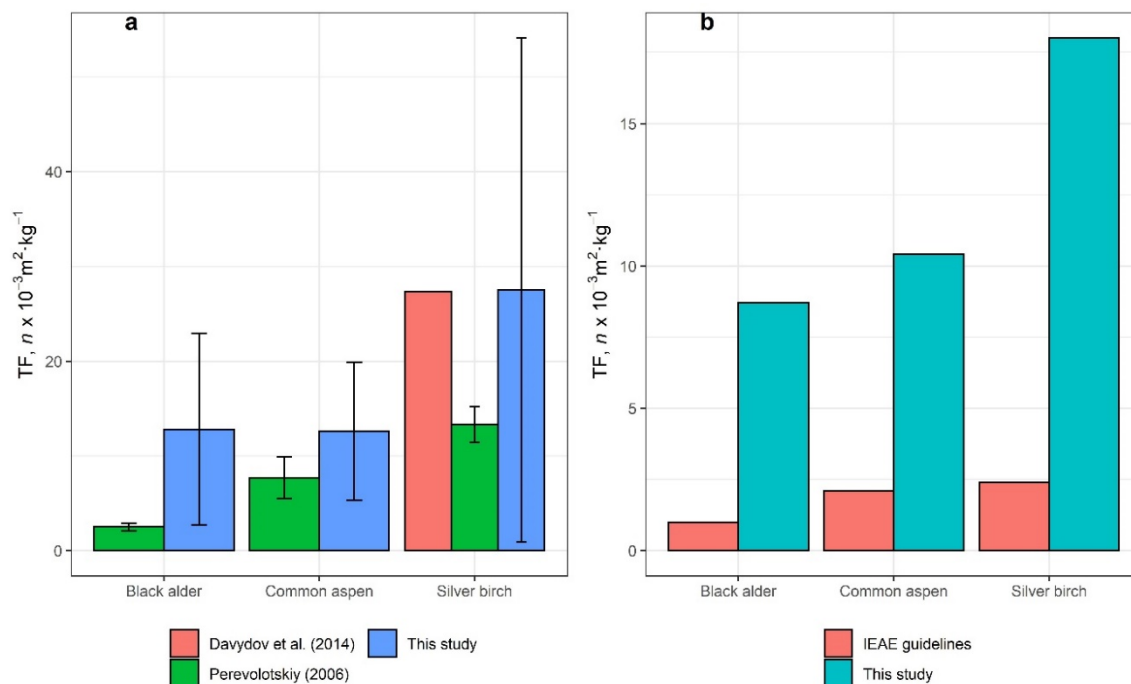


Figure 4. Comparison of transfer factors (TF) of ^{90}Sr from soil to the stemwood of studied tree species (a—arithmetical means, b—geometrical means). Error bars show arithmetical standard deviations (SD) of TFs.

Geometrical means of developed TFs do not agree with data provided by the IAEA (Figure 4b, [23]), while arithmetical means are almost the same relating to [12] data on Silver birch (Figure 4a). Herewith, SD of TF arithmetical means range tremendously, when respective values for geometrical means do not exceed critical thresholds.

To date, while the ratio of bioenergy in global energy markets is likely to be increased, efforts to use forest live biomass for energy purposes in Ukraine are facing great challenges due to a high (exceeding restrictions) level of radioactive contamination that impacts environment and human well-being.

The stock of ^{90}Sr is dependent on the growth potential, basic wood density, TF and level of the soil contamination (Figure 2). The last two factors mentioned, typically being changed over time [11], are the main features that determine whether stemwood from a given ecosystem can be used for utilization in various spheres.

To date, there are no legal restrictions for woody product use according to the level of ^{90}Sr contamination in Ukraine. Using respective standards implemented in the Russian Federation (Table 1, [8]) and estimated TFs (Table 4) for the stemwood, we can create a heatmap for all studied tree species (Figure 5), different soil contamination levels (2–100 $\text{KBq} \cdot \text{m}^{-2}$) and target commodities (use as a firewood, wood chips, sawn wood either for furniture or construction).

Only relatively high ($>100 \text{ kBq} \cdot \text{m}^{-2}$) soil ^{90}Sr contamination levels thus can entail prohibition to use local timber for the lumber materials, while the highest restrictions are met only for Silver birch at $300 \text{ kBq} \cdot \text{m}^{-2}$ soil contamination density (Figure 5). On the other hand, such large levels of soil contamination are presented only in a few areas within the Chernobyl Exclusion Zone [2], while forests of Ukrainian Polissya are mainly characterized by much lower ^{90}Sr soil contamination level (IAEA, [26]). However, aiming to avoid credible biases and thus provide sufficient level of safety for people, there is an explicit necessity to develop and implement national regulations for wood use from the contaminated areas.

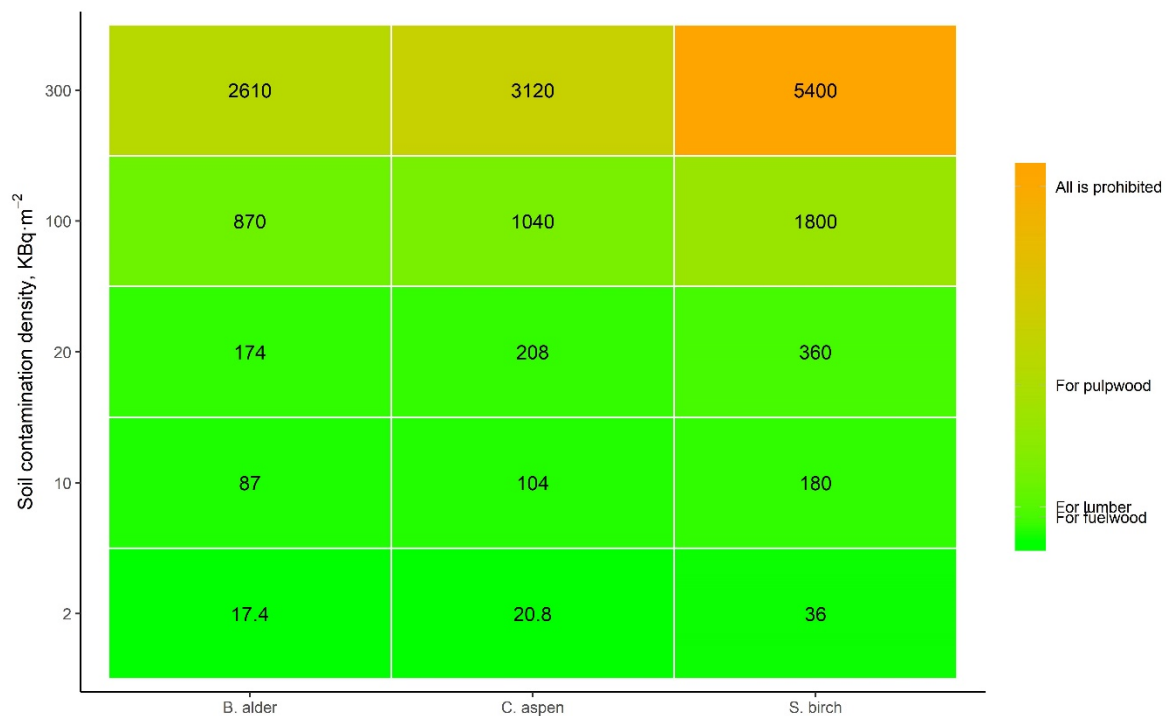


Figure 5. Heatmap of ^{90}Sr transition to the stemwood at different soil contamination (kBq m^{-2}) levels according to restrictions implemented in Russia. Only specific discrete values of the soil contamination density are given.

Exceeding the permissible level of ^{90}Sr activity concentration in fuelwood ($>60 \text{ Bq}\cdot\text{kg}^{-1}$) in Ukraine (Table 6) can be observed practically throughout the entire territory of the Chernobyl exclusion zone [10], as well as in the adjacent Ivankiv district of Kiev region and also Narodichy district of Zhytomyr region where ^{90}Sr contamination density of soil is higher than $5.5 \text{ kBq}\cdot\text{m}^{-2}$ [2].

The data of dosimetry certification of the affected settlements as a result of radioactive contamination after the Chernobyl accident (Dosimetry certification, 1991) and field surveys [2] made it possible to allocate territories with ^{90}Sr content more than $60 \text{ Bq}\cdot\text{kg}^{-1}$ in the stemwood for the studied species at a probability of 50% (Figure 6). The map (Figure 6) also shows sampling points of this research indicating the ^{90}Sr activity concentration in wood and the density of soil contamination by radionuclide which was obtained as a result of laboratory measurements.

A deeper analysis of the geographical interpretation of the output data (Figure 6) indicates a significant likelihood of exceeding hygiene standards for ^{90}Sr content of fuelwood from tree stems beyond the conditional line on the map. This is caused by the variability of the spatial contamination of radionuclides (point spots), even at considerable distances from the Chernobyl nuclear power plant (NPP), as well as by the growth of these species on the typical mineral poor soils of the region, where high ^{90}Sr TF are usually observed. Such a situation is especially true for Silver birch, which is simultaneously deemed by calciphyte, and at a low content of exchange calcium in the soil, in tree organs happens to replace calcium on chemically similar strontium, including radioactive strontium [11,13]. We have several sampling points with values of ^{90}Sr activity concentration for Silver birch stemwood more than $60 \text{ Bq}\cdot\text{kg}^{-1}$ at a considerable distance from the Chernobyl exclusion zone. The real area with stem wood contaminated over the permitted level can be even larger, taking into account uneven distribution within the stem and higher level of ^{90}Sr concentration in the bark [15].

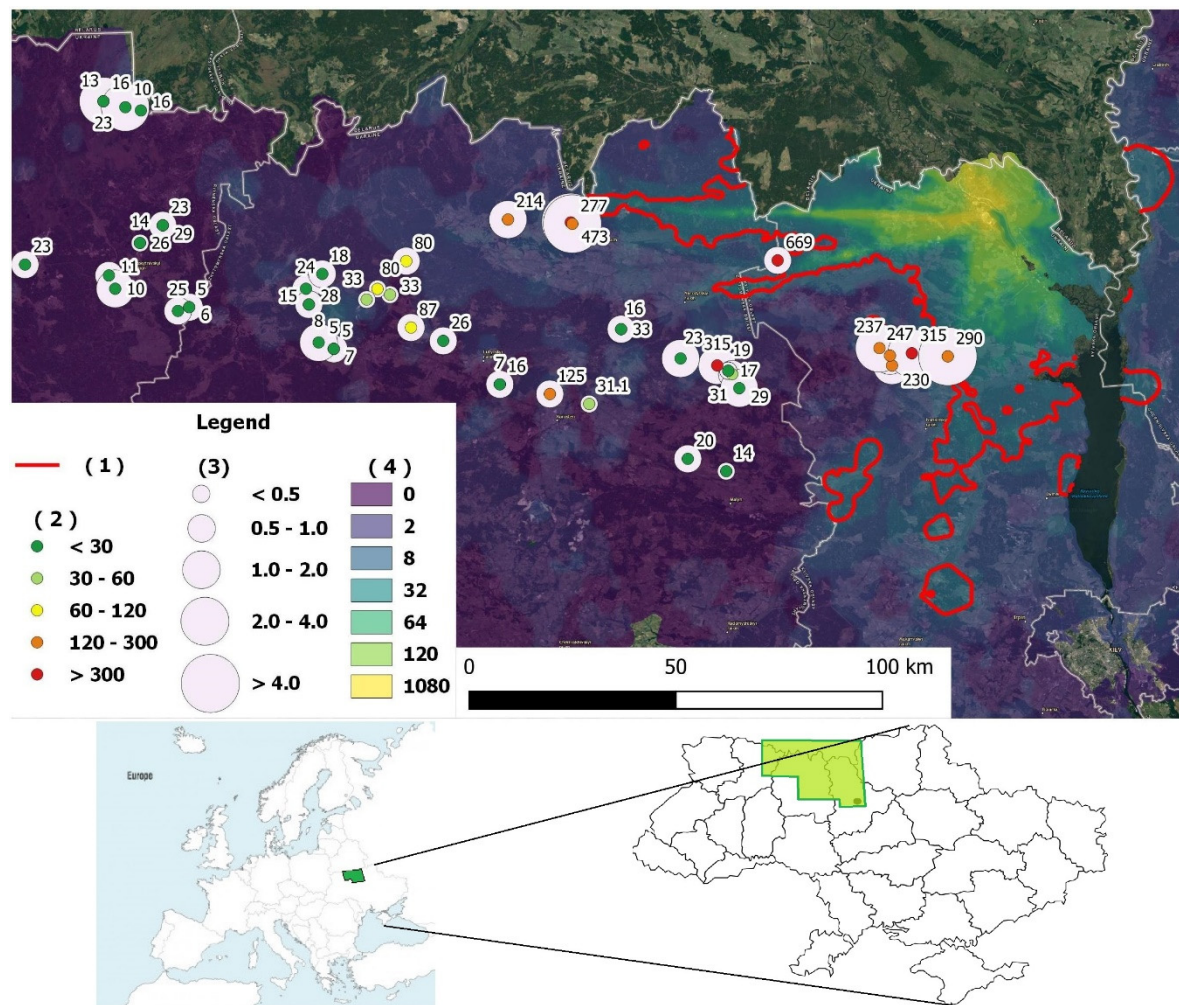


Figure 6. ^{90}Sr contamination density of soil and sampling points for stem wood and soil within forest stands: 1—border of territories with contamination of stem wood $>60 \text{ Bq}\cdot\text{kg}^{-1}$ at $P = 50\%$; 2— ^{90}Sr activity concentration of stem wood from sampling point (with ^{90}Sr activity concentration values on the map), $\text{Bq}\cdot\text{kg}^{-1}$; 3— ^{90}Sr contamination density of soil from sampling point, $\text{kBq}\cdot\text{m}^{-2}$; 4— ^{90}Sr contamination density of soil, $\text{kBq}\cdot\text{m}^{-2}$. **Note:** Google Maps and Environmental Systems Research Institute (ESRI) Boundaries and Place are a background of the map.

Nowadays there is an issue related to forest management on contaminated areas. Importantly, there are three groups of stands according to land management features that require certain decision making. The first group is represented by state forests protected and managed by the Ukrainian forest service. Those stands are likely to be harvested after reaching the age of maturity. Logging will lead to spatial spreading of ^{90}Sr accumulated in the tree stems with wood products during their entire life cycle. Second group includes forests within the Chernobyl Exclusion Zone, both existed before the disaster in 1986 and appeared after due to recovering of abandoned agricultural lands [17]. They accumulate ^{90}Sr and its redistribution will be dependent on the fate of abovementioned stands.

The third group is presented by young forests that arose in Ukrainian Polissya after 1991 on abandoned arable land. Typically, these stands are owned by local settlers and do not have the official status of forest, and thus they do not have legal restrictions in their management and use. These occasionally can either reach maturity age or be cut with the aim to produce firewood or charcoal. The future of these three groups is likely to be different, and all of them will cause an impact on strontium redistribution in the environment. Thus, the study results confirm the hypothesis that by combining data of stand growth prediction and estimation of potential ^{90}Sr content in the

stemwood we can provide an informational basis for decision-making regarding radionuclide fluxes, and forest management and planning as well. Consequently, such an assessment opens the perspectives for further investigations of the secondary ^{90}Sr environmental contamination emerged because of harvesting and other kinds of loggings.

Considering growth patterns of forest stands and transfer of ^{90}Sr from the soil to wood biomass, we have predicted values of ^{90}Sr content in the stemwood of studied tree species relating to soil contamination level, various site indexes and stand age (Appendix B). Use of such tables can foster previous analysis of the total ^{90}Sr amount stored in the stemwood of forest ecosystems or that may be removed to the environment during logging.

5. Conclusions

Silver birch, Black alder, and Common aspen are fast growing and storing GSV species of Ukrainian Polissya. The largest growth velocity of S. birch and B. alder trees matches 10–40 years of stand age, while after 50 years this process tends to slow down, reaching the natural maturity age. Trees of Common aspen perform similarly, having the highest growth rate in age of 10–30 years and reaching the maturity age at above 50 years old.

Transfer factors of ^{90}Sr to wood obtained in this study are dampening following the tree species order: Silver birch → Common aspen → Black alder. According to potential site productivity and soil contamination level, Silver birch forests can deposit in stemwood live biomass up to $300 \text{ MBq}\cdot\text{ha}^{-1}$, while for other species this value will be lower due to more limited growth capacity.

IAEA guidelines regarding ^{90}Sr transfer factors from different soil to the stemwood are should be reviewed, since this study overall agrees with previous papers of other authors, which demonstrate the relatively high values of the developed TFs.

The paper demonstrates that ^{90}Sr activity concentration of fuelwood of deciduous species can exceed critical level (according to the Ukrainian legislation) even at considerable distances (more than 50 km) from the Chernobyl Exclusion Zone.

Author Contributions: Conceptualization, A.B., V.K.; Methodology, A.S., D.S., A.B., D.H., and V.K.; Software, D.H.; Validation, M.M., D.H.; Formal analysis, M.M., D.S., V.M. and V.K.; Investigation, A.B., D.H. and M.M.; Resources, A.B. and D.S.; Data curation, A.B., D.H., M.M., L.O. and D.S.; Writing—original draft preparation, M.M., D.H. and A.B.; Writing—review and editing, A.S., V.K., D.S., V.M. and P.L.; Visualization, M.M. and D.H.; Supervision, A.B., D.S. and V.K.; Project administration, A.B., D.S.; Funding acquisition, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Education and Science of Ukraine (Grant No. M/39-2019) and OeAD-GmbH (Grant No. UA 08/2018) within the joint scientific project "Disturbances impact on forest ecosystem services of Chernobyl Exclusion Zone".

Acknowledgments: The authors thank Liudmyla Yoschenko for technical support.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Polynomial coefficients (3–5) of developed models of dynamics of major indicators of growth (Equation 2) for studied tree species.

Para-Meters	Model Coefficients								
	c ₁₁	c ₁₂	c ₁₃	c ₂₁	c ₂₂	c ₂₃	c ₃₁	c ₃₂	c ₃₃
	Silver birch (seed origin)								
<i>H</i>	3.1013E+01	−4.1085E+00	−1.1739E−03	2.9481E−02	−1.5460E−05	3.4627E−05	1.3704E+00	−7.0528E−04	9.3915E−04
<i>D</i>	3.7892E+01	−4.7129E+00	−3.3323E−02	2.6053E−02	2.9035E−08	4.9777E−05	1.3579E+00	−4.3205E−04	1.5840E−03
<i>GSV</i>	2.5236E+02	−4.4178E+01	1.1201E+00	5.0381E−02	4.5905E−05	−2.6364E−05	2.6670E+00	1.7175E−03	−1.0777E−03
	Black alder (vegetative origin)								
<i>H</i>	3.3876E+01	−4.1798E+00	4.3079E−03	2.4364E−02	1.0670E−04	−2.4075E−05	8.2401E−01	1.4254E−03	−4.8521E−04
<i>D</i>	4.4881E+01	−4.4452E+00	−8.1368E−02	1.6278E−02	6.5589E−06	1.7410E−05	8.5576E−01	3.2882E−04	1.6957E−04
<i>GSV</i>	4.1694E+02	−8.3191E+01	3.4416E+00	4.4714E−02	6.5404E−05	−1.0022E−04	1.5995E+00	1.8133E−03	−2.8117E−03
	Common aspen (vegetative origin)								
<i>H</i>	3.4820E+01	−4.2585E+00	1.1593E−03	3.0171E−02	−1.4408E−05	−1.7904E−05	1.3725E+00	−1.0778E−03	−3.7602E−04
<i>D</i>	4.7245E+01	−5.1804E+00	−4.4162E−02	2.3480E−02	−3.6746E−05	−7.3929E−06	1.3471E+00	−3.1509E−03	−4.4189E−04
<i>GSV</i>	6.5557E+02	−1.0606E+02	2.6089E+00	2.7809E−02	8.0186E−05	−7.0258E−05	1.8449E+00	3.9320E−03	−3.4469E−03

Appendix B

Table A2. Support tables of ⁹⁰Sr content in stemwood live biomass of various stand age, tree species, and site indexes.

Stand Age	⁹⁰ Sr Content in Stemwood Live Biomass, MBq·ha ⁻¹																													
	Soil Contamination Level 2 kBq·m ⁻²					Soil Contamination Level 4 kBq·m ⁻²					Soil Contamination Level 10 kBq·m ⁻²					Soil Contamination Level 20 kBq·m ⁻²					Soil Contamination Level 40 kBq·m ⁻²					Soil Contamination Level 100 kBq·m ⁻²				
	I ^a	I	II	III	IV	I ^a	I	II	III	IV	I ^a	I	II	III	IV	I ^a	I	II	III	IV	I ^a	I	II	III	IV	I ^a	I	II	III	IV
Silver birch (seed origin)																														
10	0.4	0.3	0.3	0.2	0.1	0.8	0.6	0.6	0.4	0.2	2	1.5	1.5	1	0.5	4	3	3	2	1	8	6	6	4	2	20	15	15	10	5
15	0.9	0.7	0.6	0.4	0.3	1.8	1.4	1.2	0.8	0.6	4.5	3.5	3	2	1.5	9	7	6	4	3	18	14	12	8	6	45	35	30	20	15
20	1.4	1.1	0.9	0.7	0.5	2.8	2.2	1.8	1.4	1	7	5.5	4.5	3.5	2.5	14	11	9	7	5	28	22	18	14	10	70	55	45	35	25
25	1.9	1.6	1.3	1	0.7	3.8	3.2	2.6	2	1.4	9.5	8	6.5	5	3.5	19	16	13	10	7	38	32	26	20	14	95	80	65	50	35
30	2.4	2	1.6	1.2	0.9	4.8	4	3.2	2.4	1.8	12	10	8	6	4.5	24	20	16	12	9	48	40	32	24	18	120	100	80	60	45
35	2.8	2.3	1.9	1.4	1	5.6	4.6	3.8	2.8	2	14	11.5	9.5	7	5	28	23	19	14	10	56	46	38	28	20	140	115	95	70	50
40	3.2	2.6	2.1	1.6	1.2	6.4	5.2	4.2	3.2	2.4	16	13	10.5	8	6	32	26	21	16	12	64	52	42	32	24	160	130	105	80	60
45	3.5	2.9	2.3	1.8	1.3	7	5.8	4.6	3.6	2.6	17.5	14.5	11.5	9	6.5	35	29	23	18	13	70	58	46	36	26	175	145	115	90	65
50	3.7	3.1	2.5	1.9	1.4	7.4	6.2	5	3.8	2.8	18.5	15.5	12.5	9.5	7	37	31	25	19	14	74	62	50	38	28	185	155	125	95	70
55	3.9	3.2	2.6	2	1.4	7.8	6.4	5.2	4	2.8	19.5	16	13	10	7	39	32	26	20	14	78	64	52	40	28	195	160	130	100	70
60	4.1	3.4	2.7	2.1	1.5	8.2	6.8	5.4	4.2	3	20.5	17	13.5	10.5	7.5	41	34	27	21	15	82	68	54	42	30	205	170	135	105	75
65	4.2	3.5	2.8	2.2	1.5	8.4	7	5.6	4.4	3	21	17.5	14	11	7.5	42	35	28	22	15	84	70	56	44	30	210	175	140	110	75
70	4.3	3.6	2.9	2.2	1.6	8.6	7.2	5.8	4.4	3.2	21.5	18	14.5	11	8	43	36	29	22	16	86	72	58	44	32	215	180	145	110	80
Black alder (vegetative origin)																														
10	0.9	0.8	0.5	0.4	0.3	1.8	1.6	1	0.8	0.6	4.5	4	2.5	2	1.5	9	8	5	4	3	18	16	10	8	6	45	40	25	20	15
15	1.5	1.2	0.8	0.6	0.4	3	2.4	1.6	1.2	0.8	7.5	6	4	3	2	15	12	8	6	4	30	24	16	12	8	75	60	40	30	20
20	2	1.7	1.1	0.8	0.5	4	3.4	2.2	1.6	1	10	8.5	5.5	4	2.5	20	17	11	8	5	40	34	22	16	10	100	85	55	40	25
25	2.5	2	1.3	1	0.7	5	4	2.6	2	1.4	12.5	10	6.5	5	3.5	25	20	13	10	7	50	40	26	20	14	125	100	65	50	35
30	2.9	2.4	1.5	1.1	0.8	5.8	4.8	3	2.2	1.6	14.5	12	7.5	5.5	4	29	24	15	11	8	58	48	30	22	16	145	120	75	55	40
35	3.2	2.6	1.7	1.3	0.9	6.4	5.2	3.4	2.6	1.8	16	13	8.5	6.5	4.5	32	26	17	13	9	64	52	34	26	18	160	130	85	65	45
40	3.5	2.9	1.8	1.4	0.9	7	5.8	3.6	2.8	1.8	17.5	14.5	9	7	4.5	35	29	18	14	9	70	58	36	28	18	175	145	90	70	45
45	3.7	3.1	1.9	1.4	1	7.4	6.2	3.8	2.8	2	18.5	15.5	9.5	7	5	37	31	19	14	10	74	62	38	28	20	185	155	95	70	50
50	3.9	3.2	2	1.5	1.1	7.8	6.4	4	3	2.2	19.5	16	10	7.5	5.5	39	32	20	15	11	78	64	40	30	22	195	160	100	75	55
55	4	3.3	2.1	1.6	1.1	8	6.6	4.2	3.2	2.2	20	16.5	10.5	8	5.5	40	33	21	16	11	80	66	42	32	22	200	165	105	80	55
60	4.1	3.4	2.2	1.6	1.1	8.2	6.8	4.4	3.2	2.2	20.5	17	11	8	5.5	41	34	22	16	11	82	68	44	32	22	205	170	110	80	55
65	4.2	3.5	2.2	1.7	1.2	8.4	7	4.4	3.4	2.4	21	17.5	11	8.5	6	42	35	22	17	12	84	70	44	34	24	210	175	110	85	60
70	4.3	3.6	2.3	1.7	1.2	8.6	7.2	4.6	3.4	2.4	21.5	18	11.5	8.5	6	43	36	23	17	12	86	72	46	34	24	215	180	115	85	60
Common aspen (vegetative origin)																														
10	0.3	0.3	0.2	0.2	0.1	0.6	0.6	0.4	0.4	0.2	1.5	1.5	1	1	0.5	3	3	2	2	1	6	6	4	4	2	15	15	10	10	5
15	0.7	0.5	0.5	0.4	0.3	1.4	1	1	0.8	0.6	3.5	2.5	2.5	2	1.5	7	5	5	4	3	14	10	10	8	6	35	25	25	20	15
20	1	0.8	0.7	0.5	0.4	2	1.6	1.4	1	0.8	5	4	3.5	2.5	2	10	8	7	5	4	20	16	14	10	8	50	40	35	25	20
25	1.3	1.1	0.9	0.7	0.5	2.6	2.2	1.8	1.4	1	6.5	5.5	4.5	3.5	2.5	13	11	9	7	5	26	22	18	14	10	65	55	45	35	25
30	1.7	1.4	1.1	0.9	0.7	3.4	2.8	2.2	1.8	1.4	8.5	7	5.5	4.5	3.5	17	14	11	9	7	34	28	22	18	14	85	70	55	45	35
35	2	1.7	1.4	1.1	0.8	4	3.4	2.8	2.2	1.6	10	8.5	7	5.5	4	20	17	14	11	8	40	34	28	22	16	100	85	70	55	40
40	2.3	1.9	1.6	1.2	0.9	4.6	3.8	3.2	2.4	1.8	11.5	9.5	8	6	4.5	23	19	16	12	9	46	38	32	24	18	115	95	80	60	45
45	2.5	2.1	1.8	1.4	1	5	4.2	3.6	2.8	2	12.5	10.5	9	7	5	25	21	18	14	10	50	42	36	28	20	125	105	90	70	50
50	2.8	2.4	1.9	1.5	1.1	5.6	4.8	3.8	3	2.2	14	12	9.5	7.5	5.5	28	24	19	15	11	56	48	38	30	22	140	120	95	75	55
55	3	2.5	2.1	1.7	1.2	6	5	4.2	3.4	2.4	15	12.5	10.5	8.5	6	30	25	21	17	12	60	50	42	34	24	150	125	105	85	60
60	3.2	2.7	2.2	1.8	1.3	6.4	5.4	4.4	3.6	2.6	16	13.5	11	9	6.5	32	27	22	18	13	64	54	44	36	26	160	135	110	90	65

References

1. Yoschenko, V.; Ohkubo, T.; Kashparov, V. Radioactive contaminated forests in Fukushima and Chernobyl. *J. For. Res.* **2018**, *23*, 3–14. [[CrossRef](#)]
2. Kashparov, V.; Levchuk, S.; Zhurba, M.; Protsak, V.; Khomutinin, Y.; Beresford, N.A.; Chaplow, J.S. Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone. *Earth Syst. Sci. Data* **2018**, *10*, 339–353. [[CrossRef](#)]
3. Nadtochii, P.; Malynovskiy, A.; Mozhar, A. *Experience of Chernobyl Disaster Consequences Overcoming (Agriculture and Forestry Sectors)*; Svit: Kyiv, Ukraine, 2003; p. 371.
4. Jakob, P.; Fesenko, S.; Bogdevitch, I.; Kashparov, V.; Sanzharova, N.; Grebenshikova, N.; Isamov, N.; Lazarev, N.; Panov, A.; Ulanovsky, A.; et al. Rural lands affected by the Chernobyl accident: Radiation exposure and remediation strategies. *Sci. Total Environ.* **2009**, *408*, 14–25. [[CrossRef](#)] [[PubMed](#)]
5. Fesenko, S.; Jacob, P.; Ulanovsky, A.; Chupov, A.; Bogdevich, I.; Sanzharova, N.; Kashparov, V.; Panov, A.; Zhuchenka, Y. Justification of remediation strategies in the long term after the Chernobyl accident. *J. Environ. Radioact.* **2013**, *119*, 39–47. [[CrossRef](#)] [[PubMed](#)]
6. Gupta, D.K.; Walther, C. *Behaviour of Strontium in Plants and the Environment*; Springer International Publishing: Basel, Switzerland, 2017; pp. 1–145.
7. HNPAP. *Hygienic Standard of the Specific Activity of ^{137}Cs and ^{90}Sr Radionuclides in the Wood and Woody Products; Implemented by the Order of Ministry of Health of Ukraine*: Kyiv, Ukraine, 2005; No. 573; p. 3.
8. Russian Science Institute of Forestry Chemistry of Russian State Forestry. *Allowable Levels of ^{137}Cs and ^{90}Sr Content in the Forestry Products*; Russian Science Institute of Forestry Chemistry of Russian State Forestry: Moscow, Russia, 1999; p. 2.
9. Otreshko, L.; Zhurba, M.; Bilous, A.; Yoschenko, L. ^{90}Sr and ^{137}Cs content in wood along the southern fuel trace of Chernobyl radioactive fallout. *Nucl. Phys. Atomic Energy* **2015**, *16*, 183–192. [[CrossRef](#)]
10. Yoschenko, V.; Kashparov, V.; Ohkubo, T. Chapter 1. Radioactive Contamination in Forest by the Accident of Fukushima Daiichi Nuclear Power Plant: Comparison with Chernobyl. In *Radiocesium Dynamics in a Japanese Forest Ecosystem: Initial Stage of Contamination After the Incident at Fukushima Daiichi Nuclear Power Plant*; Takenaka, C., Hijii, N., Kaneko, N., Ohkubo, T., Eds.; Springer Singapore: Singapore, 2019; pp. 3–22. [[CrossRef](#)]
11. Perevolotskiy, A. *Redistribution of ^{137}Cs and ^{90}Sr in the Forest Biogeocoenoses*; RNIUM ‘Institute of Radiology’: Homel, Belarus, 2006; p. 255.
12. Davydov, M.; Protas, I.; Savuschyk, M. Accumulation of radionuclides in the main compartments of forest ecosystems of Kyiv Polissya and Forest-Steppe. *Nucl. Energy Environ.* **2014**, *2*, 25–31.
13. Scheglov, A. *Biogeochemistry of Technogenic Radionuclides in Forest Ecosystems: Based on Materials of 10-Year Research in the Area Contaminated after Chernobyl NPP Disaster*; Nauka: Moscow, Russia, 1999; p. 268.
14. Orlov, A.; Krasnov, V.; Pryscheпа, A. Radioactively contaminated forests as the critical landscapes: Radioactivity of the food stuff and impact on the dose formation of the internal humans’ exposure (analytical review). *Zhytomyr ZITI* **2002**.
15. Holiaka, D.; Levchuk, S.; Protsak, V.; Kashparov, V. Distribution of ^{137}Cs activity concentration in wood Scots pine (*Pinus sylvestris* L.) of Zhytomyr Polissya after the Chernobyl accident. *Nucl. Phys. Atomic Energy* **2017**, *18*, 63–71. [[CrossRef](#)]
16. Mamikhin, S.; Manahov, D.; Scheglov, A. Comparative analysis of radionuclides distribution and their chemical analogues in the aboveground compartments of the tree plants in a quasi-equilibrium state. *Radiat. Biol. Radioecol.* **2008**, *48*, 654–659.
17. Bilous, A.; Myroniuk, V.; Holiaka, D.; Bilous, S.; See, L.; Schepaschenko, D. Mapping growing stock volume and forest live biomass: A case study of the Polissya region of Ukraine. *Environ. Res. Lett.* **2017**, *12*, 105001. [[CrossRef](#)]
18. Bilous, A.M.; Voloshchuk, N.M.; Kovbasa, I. Peculiarities of mortmass mycobiota formation in soft-deciduous young forests on old-tillage soils of the chernihiv polissya. *Mikrobiol. Zhurnal* **2013**, *75*, 59–65.
19. Lakyda, P.; Shvidenko, A.; Bilous, A.; Myroniuk, V.; Matsala, M.; Zibtsev, S.; Shepaschenko, D.; Holiaka, D.; Vasylyshyn, R.; Lakyda, I.; et al. Impact of disturbances on the carbon cycle of forest ecosystems in Ukrainian Polissya. *Forests* **2019**, *10*, 337. [[CrossRef](#)]
20. Richards, F. A flexible growth function for empirical use. *J. Exp. Bot.* **1959**, 290–300. [[CrossRef](#)]

21. Ministry of Agrarian Policy and Food of Ukraine. *The Quality of the Soil: Determining Density of the Contamination of Agricultural Land by Artificial Radionuclides*; Ministry of Agrarian Policy and Food of Ukraine: Kyiv, Ukraine, 2006.
22. Pavlitskaya, F. Main principles of radiochemical analysis of environment objects and methods of measurements of strontium and transuranium elements radionuclides. *J. Anal. Chem.* **1997**, *52*, 126–143.
23. International Atomic Energy Agency. *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Fresh-Water Environments*; IAEA-TRS-472; International Atomic Energy Agency: Vienna, Austria, 2010; p. 194.
24. Salbu, B.; Kashparov, V.; Lind, O.C.; Garcia-Tenorio, R.; Johansen, M.P.; Child, D.P.; Roos, P.; Sancho, C.M. Challenges associated with the behavior of radioactive particles in the environment. *J. Environ. Radioact.* **2018**, *186*, 101–115. [[CrossRef](#)] [[PubMed](#)]
25. Kashparov, V.; Salbu, B.; Levchuk, S.; Protsak, V.; Maloshtan, I.; Simonucci, C.; Courbet, C.; Nguyen, H.; Sanzharova, N.; Zabrotsky, V. Environmental behavior of radioactive particles from Chernobyl. *J. Environ. Radioact.* **2019**, *208–209*, 106025. [[CrossRef](#)] [[PubMed](#)]
26. International Atomic Energy Agency. Environmental consequences of the Chernobyl accident and their remediation: Twenty years of experience. In *Report of the Chernobyl Forum Expert Group 'Environment'*; IAEA: Vienna, Austria, 2006.



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