Estimation of *Populus euphratica* Forest Leaf Litterfall and Time Variation of Nutrient in Leaf Litter during Decomposition along the Main Channel of the Tarim River, China

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Abstract: Accurate determination of annual leaf litter amount constitutes the basis of scientific leaf litter nutrient release assessment. In this study, we tried to establish an equation between leaf litter amount and relevant tree characteristics of *Populus euphratica* (*P. euphratica*) tree on an individual scale, and to find the leaf litter nutrient content variation within 760 d incubation experiment in the main channel of the Tarim River, China. Results showed that there was no proper equation between leaf litter amount and tree height or diameter at breast height. There was great difference in leaf litter amount on an individual scale. The mean annual leaf litter amount per tree was 10.2, 14.83 kg/y obtained by field survey and the equation between annual leaf litter amount and canopy area on an individual scale, respectively. Leaf litter mass changed over incubation time and exhibited three main phases: an initial slow decomposition phase (0–173 d) with mass loss; a rapid mass loss phase (173–290 d); and a second rapid mass loss phase (470–560 d). Overall, carbon (C) and potassium (K) content decreased, and nitrogen (N) and phosphorus (P) content increased in a fluctuating manner over time in the *P. euphratica* leaf litter.

Keywords: arid; litter; decomposition; nutrient; Tarim River

1. Introduction

Desert riparian forest, an important vegetation type and forest resources for the inland river valley in arid zones, is also a natural protection shield for the ecological system in the arid regions of Northwest China. The natural riparian vegetation consisting of trees, shrubs, and herbage was prone to grow with flooding, or disappeared with the variation of the river course. *Populus euphratica* Oliv., one of the first confirmed 388 rare and endangered plants in China, is the oldest and most primitive deciduous tree of desert riparian forests. It widely distributed in the semi-arid and hyper-arid regions of midwestern Asia, southern Europe, and north Africa (30–50° N) [1,2]. China has the largest *P. euphratica* forest in the world, mainly distributed in the Tarim River basin [3,4]. In the Tarim River basin, the river stream and groundwater sustain the desert riparian forests which form a landscape corridor of natural vegetation zone to protect the oasis. However, due to the large-scale utilization of water and soil resources, and the influence of global climate changes, the mainstream of the Tarim River has been discontinuous. Since 1970, the lower reaches (321 km from Qiala station to TaitemaLake) of the Tarim River have been completely cut off, and the terminal lake—TaitemaLake—subsequently dried up in 1972 [3]. Therefore, since the 1950s, more than half of the natural *P. euphratica* forest in China has disappeared, especially in the lower reaches. In order to protect the endangered desert riparian forest and restore the damaged ecological system, the Ecological Water Diversion Project, recharging water into the lower reaches of the Tarim River by water transfers from Bosten Lake to the Daxihaizi Reservoir by Kongque River, was initiated in 2000 (Figure 1). From 2000 to
the end of 2020, water has been transferred to the lower reaches of the Tarim River for 20 times, with a total of \(84.45 \times 10^8\) m\(^3\), which has raised groundwater significantly during the past 20 years, and the desert riparian forest with *P. euphratica* as the constructive species has been restored in the lower reaches [5]. Many studies have focused on *P. euphratica's* physiological and ecological characteristics, population dynamics, above-ground biomass, etc. [6–8] since 2000, but study of estimation of leaf litter amount and impact of *P. euphratica* forest change on leaf litter amount are scarce.

![Figure 1. Sketch of the study area.](image)

Plant litter, a major bridge between vegetation and mineral soil, plays a key role in nutrient cycling in forest ecosystems [9]. Leaf litter, a part of plant litter, can account for 22–81% of a plant annual litter production, and it has received considerable focus on its decay in tropical and subtropical forests [10,11], but less attention in temperate forests in arid area. Litter amount is a key parameter in measuring, modelling, and predicting terrestrial ecosystem dynamics [12]. Forest biomass is an important parameter to estimate regional forest carbon reserves and a key symbol of forest carbon sequestration ability. In order to obtain biomass of a forest or individual tree, it is essential to establish an equation between the biomass and the relevant tree characteristics, such as tree height, diameter at breast height and so on, without cutting down or destroying the trees. Most of the equations of tree biomass take diameter at breast height, tree height or combination of both as the independent variables [13–15]. Most of the biomass equations of whole tree, root, trunk and bark, respectively, take combination of tree height and diameter at breast height as the independent variables, and the biomass equations of branches and leaves take diameter at breast height as the independent variables [16,17]. The tree biomass which determine the forest biomass varies with tree species. In order to obtain precise predictions of tree’s biomass and C stock, a site-specific or regionally-developed model which should ideally represent the trees growth in the area often is required. However, different biomass equations were reported in the literature for the same tree species, and most of these biomass equations mainly derived from trees in forests in the northeast and southwest regions, few studies focused on tree biomass, especially on leaf litter amount, in northwest, China.

Desert riparian forest dominated by *P. euphratica* has always been an important vegetation type and forest resources in the Tarim River basin (Figure 1). It is very important to establish an appropriate biomass equation to determine the biomass of individual trees for evaluating natural *P. euphratica* forest productivity and forest carbon storage in arid area. For the *P. euphratica* tree, annual leaf litter amount is almost equivalent to annual leaf
biomass. Therefore, two pertinent questions are: (1) what tree characteristics should be used to construct the annual leaf litter amount equation of *P. euphratica* tree along the main channel of the Tarim River; and (2) how does *P. euphratica* leaf litter decompose over time? The objectives of this research were to find a biomass equation between *P. euphratica* leaf litter amount and the tree characteristics, quantitatively estimate *P. euphratica* forest annual leaf litter amount, leaf litter nutrient release with incubation time and to discuss possible ecological effects induced by changes in leaf litter amount. Accurate determination of *P. euphratica* leaf litter amount and a better understanding of nutrient decomposition behavior of the leaf litter could guide management practices to make optimal use of decomposing litter in desert riparian forest in arid region.

2. Materials and Methods

2.1. Study Area

The Tarim River basin in Northwestern China, mainly located between 34°–45° N and 73°–97° E, is the largest inland river basin in China. The main channel of the Tarim River, defined as the river course below the confluence of the Hetian, Yarkan, and Akesu Rivers, is 1320 km in length [18]. From Aral to Taitema Lake, the length of the main channel of the Tarim River is divided into an upper, middle, and lower channel from Xiaojiake to Yingbaza, Yingbaza to Qiala, and Qiala to Taitema lake, respectively (Figure 1). The region has a typical continental climate, arid, with precipitation usually <50 mm and evaporation as high as 2300–3000 mm; mean annual temperature of 10–11 °C. The landscape comprises a desert riparian forest on a flat floodplain with slopes ≤3%. The major plant species include *P. euphratica*, *Tamarix* spp., *Lycium ruthenicum*, and so on. The zonal soil is a brown desert soil, and the area of solonchak soil is large [18].

2.2. Annual Leaf Litter Amount and Tree Characteristics of Individual *P. euphratica* Trees

In 19 September 2015, *P. euphratica* trees with different diameters (ranging from 25 cm to 47 cm) were randomly selected along the middle and lower reaches of the main channel of the Tarim River. With the trunk as the center, five litter traps (1 m × 1 m × 0.2 m) were randomly set under the canopy to collect individual *P. euphratica* leaf litter, and canopy width and diameter at breast height (1.2–1.5 m above ground) for individual *P. euphratica* were measured in order to calculate canopy area. After abscission of all leaves, the collected leaves in the traps were taken to laboratory, brushed to remove dust and debris, dried at 65 °C until reaching a stable weight, and weighed. After calculating for five traps per tree, an average value per trap was used to extrapolate annual leaf litter amount per tree based on canopy area. The canopy area of *P. euphratica* tree was calculated according to the canopy width.

Tree characteristics such as canopy width, diameter at breast height and tree height were measured by a steel tape. Canopy width (in the east-west and north-south directions), or average diameter of the projection area of the canopy on the ground was measured by a steel tape when the litter collectors were arranged.

2.3. The Population Density of *P. euphratica* and Area of *P. euphratica* Forest

Fourteen study sections, 1050–1500 m long and 50 m wide, were constructed along one side of the river way for investigating population density of *P. euphratica* tree. Five sections were situated in the middle reaches of the river at approximately 50 km intervals from the Yinbazar to the Qiala station, and nine sections were located in the lower reaches (from Qiala station to Taitema Lake) [3]. All sections were perpendicular to the main channel. At each section, based on plant community and species type, two to six plots were set up at 150 m or 200 m intervals along a transect. A total of 74 plots were chosen (30 and 44 plots were in the middle and the lower reaches, respectively, Figure 1). Each 50 m × 50 m plot was further split into four 25 m × 25 m tree and shrub sampling plots. The number of *P. euphratica* tree was recorded. The population density of *P. euphratica* was 594.2 trees/ha [19], 65.3 trees/ha, and 36.1 trees/ha in the upper, middle and lower reaches.
of the main channel of the Tarim River, respectively. The area of *P. euphratica* forest in the Tarim River basin and global was obtained from Wang et al. [1] and Bai [19].

2.4. Litterbag Experiment

We studied leaf litter decomposition and nutrient change using litterbags. Intact whole fresh yellow leaves that had fallen to the ground in the *P. euphratica* forest were picked up on 15 October 2015, and then dried at 50 °C for 24 h in laboratory, and subsequently stored at room temperature. 10.0 g dried leaves was filled in each 25 cm × 15 cm litterbag made of polyethylene nets with dimensions of 1 mm mesh size. The litterbags prepared in the laboratory were transported to study site in individual plastic bags. On 11 November 2015, 40 bags were settled on a clearing, without weeds and leaf litter ground in the *P. euphratica* forest, and they were arranged in one block to avoid large variations in soil properties in the lower reaches of the main channel of the Tarim River. Within the block, the litterbags were at least 20 cm apart from each other. Litterbags were placed on the soil surface and held in place by nails. Three intact litterbags were retrieved randomly at 173, 290, 380, 470, 560, 640, and 760 d after installation. The litterbags were taken to laboratory after cleaning overlain debris. After all exogenous material, such as soil particles was carefully cleaned by hand from each intact litterbag, the residual leaf litter oven-dried at 65 °C until the mass stabilized and weighed to determine dry mass [20].

2.5. Nutrient Chemical Analysis

For the retrieved leaf litter, the oven-dried leaf litter samples were ground and sieved through a 0.5 mm mesh and analyzed for total C, N, phosphorus (P), and potassium (K) contents. Total C content was determined by total organic carbon analyzer (Aurora 1030, College Station, TX, USA). The ground samples were digested with a triacid mixture (concentrated sulphuric acid, hydrofluoric acid, and perchloric; 5:1:1). The extract was subjected to chemical analysis to determine the leaf contents of N, P, and K [21]. Prior to installation, leaf litter from three litterbags was used to analyze initial nutrient content.

2.6. Data Analysis

In general, canopy width (CW, m) per tree was calculated by:

\[ CW = \frac{(Ad + Bd)}{2} \]  

where *Ad* is the maximum diameter of the canopy (m); and *Bd* is the minimum diameter of the canopy (m). The canopy area (m²) is the area of a circle calculated with the canopy of individual *P. euphratica*.

Annual leaf litter amount of *P. euphratica* forest (M, kg) was calculated by:

\[ M = A \times D \times L \]  

where *A* is the area of *P. euphratica* forest (ha); *D* is the *P. euphratica* population density (individual number in unit area, trees/ha); and *L* is the annual leaf litter amount of individual *P. euphratica* (kg/tree), which was calculated by:

\[ L = M_t \times S_c \]  

where *M_t* is the mean weight of dry leaf litter collected from five litter traps (kg/m²); and *S_c* is the canopy area of a circle calculated with the canopy width of an individual *P. euphratica* (m²).

Rate of leaf litter mass loss (R, %) was determined as:

\[ R = \left(\frac{(X_0 - X)}{X_0}\right) \times 100 \]  

where *X* is the dry mass of the leaf at a given time of decomposition; and *X_0* is the initial dry mass of the leaf litter.
The remaining nutrient (F, %) was determined as:

\[
F = \left[ \frac{(E \times X)}{E_0 \times X_0} \right] \times 100
\]

where \(E\) is the nutrient content of the leaf litter after a given time of decomposition; \(X\) is the leaf litter dry mass at a given time of decay; \(E_0\) is the initial content in the leaf litter; and \(X_0\) is the initial dry mass of the leaf litter.

2.7. Statistical Analysis

The relationship between the tree characteristics, such as canopy width, diameter at breast height and tree height (independent variable \(x\)) and the annual leaf litter amount of a tree (dependent variable \(y\)) was fitted by curve estimation (SPSS 11.0) (SPSS Inc., Chicago, IL, USA). Using the curve estimation method, the equations between the canopy area and the leaf litter amount per tree was fitted too. The annual leaf litter amount of *P. euphratica* forest was estimated by using the fitted equations. The leaf litter nutrient content variations among different incubation times were further analyzed using one-way ANOVA with a least-significant difference (LSD) test (SPSS 11.0). Significant results were assumed for \(p < 0.05\).

3. Results

3.1. Equation between Leaf Litter Amount and Relevant Tree Characteristics on an Individual Scale

There was no proper equation between leaf litter amount and tree height, nor between leaf litter amount and diameter at breast height. An equation was identified between leaf litter amount (\(y\), g) and canopy width (\(x\), m) for a tree. Compound model \((y = b_0 \times b_1 x)\) and growth \((y = e^{(b_0 + b_1 x)})\) model existed between leaf litter amount and canopy width for a tree (Table 1), both of which have statistical significance \((p < 0.05)\) (Table 1). Canopy width exhibited a line, while the tree canopy was nearly round. Furthermore, canopy area \((m^2)\) per tree was taken as independent variable \(x\), and the annual leaf litter amount per tree as dependent variable \(y\) (kg). The equation between them was \(y = 3570.93e^{0.034x}\) \((R^2 = 0.21, p < 0.05)\), \(y = e^{(8.18+0.034x)}\) \((R^2 = 0.21, p < 0.05)\), and \(y = e^{(11.12−10.97/x)}\) \((R^2 = 0.39, p < 0.05)\).

| Equation  | \(R^2\) | \(F\)  | df | Sig.  | \(b0\)  | \(b1\)  |
|-----------|---------|-------|----|-------|---------|---------|
| Compound  | 0.271   | 6.327 | 18 | 0.022 | 1192.1  | 1.422   |
| Growth    | 0.271   | 6.327 | 18 | 0.022 | 7.083   | 0.352   |

The independent variable is canopy width (m). The dependent variable is leaf litter amount (kg).

3.2. Leaf Litter Amount per Tree

A great difference was found in leaf litter amount per tree. Indeed, almost a 15-times difference existed between the maximum and the minimum leaf litter amount for a tree, according to the field survey (Table 2). Based on the minimum population density (36.1 plants/ha), maximum population density (594.2 plants/ha), and average population density (231.9 plants/ha) of the *P. euphratica* forest in the main channel of the Tarim River, the minimum, maximum, and mean canopy area per tree were calculated, and then the minimum, maximum, and average annual leaf litter amount per tree were estimated by two fitted equations (Table 2), respectively. The average leaf litter amount per tree estimated by \(y = e^{(11.12−10.97/x)}\) \((R^2 = 0.39, p < 0.05)\) was closer to the mean field surveyed value.
Table 2. Annual leaf litter amount per tree obtained by different methods.

| Methods           | Minimum (Kg/Year) | Maximum (Kg/Year) | Mean (Kg/Year) |
|-------------------|-------------------|-------------------|----------------|
| Field survey      | 2.05              | 30.70             | 10.20          |
| $y = e^{(11.121 - 10.97/x)}$ | 3.63              | 22.53             | 14.83          |
| $y = 3570.9e^{0.034x}$  | 0.65              | 4.62              | 2.62           |

Note. Canopy area (m$^2$) per tree was taken as independent variable $x$, the annual leaf litter amount per tree as dependent variable $y$ (kg).

3.3. Change in Leaf Litter Mass and Nutrients over Time during Decay

Leaf litter mass changed over time and exhibited three phases: (1) an initial slow decomposition phase (0–173 d) with mass loss; (2) a rapid mass loss phase (173–290 d); and (3) a second rapid mass loss phase (470–560 d) (Figure 2). The rate of leaf mass loss was approximately 30% and 42% after 380 d and 760 d incubation, respectively. Moreover, the average remaining mass of leaf litter was obviously different among the three phases. The change of remaining nutrients can indicate whether the nutrient elements were enriched or released during the decomposition of litter. Patterns of nutrient release differed among elements in the leaf litter (Figure 3). Overall, C and K content were decreased during decomposition. K was rapidly decreased in 173–290 d, and then remained constant. N and P content increased in a fluctuating manner, and reached their maximum at 470 d.

Figure 2. Leaf mass change during decomposition. Within graph, histograms with the same letter indicate that the value was not significantly different ($p < 0.05$). Values are means ±SE.

Figure 3. Leaf litter nutrient change during decomposition. Values are means ±SE ($n = 3$).

4. Discussion

4.1. Leaf Litter Amount Estimation

Litterfall and leaf decomposition represent the main pathway for nutrient cycling in forest ecosystems. Studies on *P. euphratica* biomass have mainly focused on the biomass change rules, biomass prediction methods, models and the relationship between the
biomass and other related environmental factors [22,23]. Within 300 m distance to the river, the best equation model, using canopy area to estimate canopy biomass, was \( S = 0.016 A^2 + 2.291 A + 11.084 \), where \( A \) and \( S \) refer to area and biomass of canopy, respectively [22]. However, the canopy biomass equation cannot estimate leaf biomass because the canopy biomass includes the biomass of stems, branches and leaves. Furthermore, the leaves of \( P. euphratica \) will fall and some of them will decompose every autumn. Therefore, the biomass of \( P. euphratica \) estimated by using the equation [22] would be slightly higher than the actual biomass. Moreover, a leaf biomass equation of \( P. euphratica \), \( W = 0.0482 \times (D^2H)^{b} \), was obtained, where \( W \) is the leaf biomass, \( D \) is the diameter at breast height, \( H \) is the height of the tree [24]. In this study, there was no proper equation between the leaf litter amount and diameter at breast height or height of tree. We tried to find a mathematical model for the relationship between leaf litter amount and canopy width or canopy area. However, the equations between the leaf litter amount and canopy width or canopy area at individual scale, respectively, had a low R-squared value, which indicated that the equations had limited predictive power, but the average leaf litter amount per tree estimated by \( y = e^{(11.12−10.97/x)} \) \( (R^2 = 0.39, p < 0.05) \) was closer to the mean field surveyed value, which indicates that this equation can be used to estimate the annual amount of forest leaves. Therefore, the relationship between leaf litter amount and tree characteristics deserves further study.

Leaf litter amount are intensely affected by forest type, plant composition, population density, biological characteristics and age of tree, anthropogenic activities, environmental conditions, diversity, successional stage, canopy cover, and nutrient availability [25,26]. The total annual litterfall was more in primary forests than in secondary forests, less in tree plantations [27,28], and more in mixed stands than in monocultures [29]. Annual litter for global forests, temperate broadleaved evergreen forest and temperate needle-leaved forest [12] and natural secondary forests was 1600–9200 kg/ha, 4700–6000 kg/ha and 3040 kg/ha [30,31], respectively, and annual dry leaf litter was 1400–5800 kg/ha [12]. In this study, based on the average annual leaf litter amount per tree (10.2–14.83 kg/year) and average population density (231.9 plants/ha), the average annual leaf litter amount of \( P. euphratica \) forest in the main channel of the Tarim River basin was within the range of 2365.38–3439.08 kg/ha which was similar to that of temperate broadleaved evergreen forest and temperate needle-leaved forest. Furthermore, the minimum, maximum, and average annual leaf litter amount of \( P. euphratica \) forest were estimated based on the average population density (231.9 plants/ha) and the data of leaf litter amount per tree from field survey in different countries and regions, respectively (Table 3). These leaf litter amount decreased when they decomposed, and forest productivity depends on rapid turnover of litter nutrients.

**Table 3.** Annual leaf litter amount of \( P. euphratica \) forest globally.

| Country/Region | Area (Ha) | Annual Leaf Litter Amount (Kg/Year) |
|----------------|-----------|-------------------------------------|
|                |           | Minimum | Maximum | Average |
| China          | 395.200   | 13.15 \( \times 10^7 \) | 26.11 \( \times 10^8 \) | 8.59 \( \times 10^8 \) |
| Central Asia   | 200.000   | 6.65 \( \times 10^7 \)  | 13.21 \( \times 10^8 \) | 4.35 \( \times 10^8 \) |
| Iraq           | 20.000    | 0.66 \( \times 10^7 \)  | 1.32 \( \times 10^8 \)  | 0.43 \( \times 10^8 \)  |
| Iran           | 20.000    | 0.66 \( \times 10^7 \)  | 1.32 \( \times 10^8 \)  | 0.43 \( \times 10^8 \)  |
| Syria          | 5818      | 0.19 \( \times 10^7 \)  | 0.38 \( \times 10^8 \)  | 0.13 \( \times 10^8 \)  |
| Turkey         | 4900      | 0.16 \( \times 10^7 \)  | 0.33 \( \times 10^8 \)  | 0.10 \( \times 10^8 \)  |
| Total          | 648.719   | 21.47 \( \times 10^7 \) | 42.67 \( \times 10^8 \) | 14.01 \( \times 10^8 \) |

Source: Area data of \( P. euphratica \) forest adapted from Bai, 2010 [19].

4.2. Leaf Litter Decomposition

The proper litter management could help to match nutrient release rates to plants’ needs. Improving C sequestration by converting non-forested sites to forest plantations has been recognized as an efficient method to mitigate elevated atmospheric CO\(_2\) concentra-
tions and global warming [32]. In this study, less leaf litter mass changed within 0–173 d, indicating that less leaf mass was mineralized to CO$_2$ by microorganisms and released back to the atmosphere, converted to biomass by plant or microorganisms in soil, leached to the soil, groundwater or runoff within 0–173 d. Moreover, the in situ leaf litter decay experiment was conducted in this study, then the time variation characteristics of leaf litter mass constituted an accurate reflection of natural decomposition of litter of _P. euphratica_ in this area. This study provided some basic data on the leaf litter decomposition rates and nutrients change, which will be benefit further research in future.

4.3. Ecological Effects of Leaf Litter Amount Change

The magnitude of litterfall indirectly regulates soil respiration rate and soil organic C content, and leaf litter is not only the main source of soil C returning in forest ecosystems, but also an important route of C release in forest ecosystems [33–36]. Human interference and environmental variation may intensively affect forest productivity and consequently change above-ground litter inputs to soils [37]. On the ground, litter accumulation can influence soil condition, plant community structure, and ecosystem processes by controlling the nutrient cycling and organic matter formation [36,38]. In the process of C transfer from forest above-ground biological bank to underground soil bank, leaf litter is the main source of soil C returning in forest ecosystems and an important route of C release in forest ecosystems [34]. Litter cover can also indirectly or directly influence soil CO$_2$ flux by influencing soil hydrothermal factors, soil microenvironment, and microbial species and quality [35]. Harvest disturbance stimulated net C losses of 400–700 g C/m$^2$ y$^{-1}$ for 6–17 y after harvesting in northern temperate forests. In this study, _P. euphratica_ forest can produce approximately 14.01 × 10$^8$ kg leaf litter annually average, it is equivalent of 6.29 × 10$^8$ kg C estimated by the content of carbon of leaf, 44.9% [24] in the world (Table 3). The leaf litter layer offers refuge for everything from microorganism to small mammals. Therefore, the leaf litter production decreased with the loss of _P. euphratica_ forest may affect the forest nutrient status, soil respiration, soil microenvironment, microbial species and so on.

Litter turnover is a major carbon flux in terrestrial ecosystems. Litterfall inputs and their decay could contribute effectively to the long-term forest nutrient status [39,40]. Seasonal change in litterfall and decomposition leads to seasonal differences in the carbon cycle [39]. The annual amount of total N, P, and K that returned to the soil by the forest through litter decomposition accounts for 70–80%, 65–80%, and 30–40% of the total N required for plant growth, respectively [40]. In the present study, the C and K content of leaf litter declined over time, and the N and P content also increased in a fluctuating manner over time, which indicates that N and P were enriched over time instead of C and K in the leaf litter.

Forest loss is a main driver of litter decomposition [41]. Although temperate forest has the smallest area (16%) among the world’s principal forest biomes, it is one of those most threatened by forest loss [42]. In the Tarim River basin, during the period from 1958 to 1983, the _P. euphratica_ forest area expanded in the upper reaches and decreased in the middle and lower reaches of the main channel of the Tarim River, especially in the lower reaches [1]. Taking the field-measured annual leaf litter amount per tree as a reference and using the area and population density of _P. euphratica_ forest, the forest leaf litter amount was estimated in the upper, middle and lower reaches by Equation (2), respectively (Table 4). During the period from 1958 to 1983, the annual leaf litter amount reduced in the middle and lower reaches. In general, the annual leaf litter amount was the greatest in 1958. The _P. euphratica_ forest can produce approximately 14.01 × 10$^8$ kg leaf litter annually (the equivalent of 5.75 × 10$^8$ kg C) in the world (Table 3).
Table 4. Annual leaf amount of *P. euphratica* forest in different reaches along the main channel of the Tarim River (kg/year).

| Location          | Year | Area (Ha) | Population Density (Plants/Ha) | Annual Leaf Litter Amount (Kg/Year) | Minimum          | Maximum          | Average          |
|-------------------|------|-----------|-------------------------------|-------------------------------------|------------------|------------------|------------------|
|                   |      |           |                               |                                     |                   |                   |                   |
| The upper reaches | 1958 | 23,000    | 594.2                         |                                     | 19.56 × 10^6      | 38.93 × 10^7     | 12.82 × 10^7     |
|                   | 1978 | 58,200    |                               |                                     | 49.50 × 10^6      | 98.53 × 10^7     | 32.44 × 10^7     |
|                   | 1983 | 112,400   |                               |                                     | 95.61 × 10^6      | 190.3 × 10^7     | 62.65 × 10^7     |
|                   | 1958 | 175,800   |                               |                                     | 1.64 × 10^7       | 3.27 × 10^8      | 1.08 × 10^8      |
| The middle reaches| 1978 | 100,200   | 65.3                          |                                     | 0.94 × 10^7       | 1.86 × 10^8      | 0.61 × 10^8      |
|                   | 1983 | 110,800   |                               |                                     | 1.04 × 10^7       | 2.06 × 10^8      | 0.68 × 10^8      |
|                   | 1958 | 54,000    |                               |                                     | 2.79 × 10^6       | 5.55 × 10^7      | 1.83 × 10^7      |
| The lower reaches | 1978 | 16,400    | 36.1                          |                                     | 0.85 × 10^6       | 1.69 × 10^7      | 0.56 × 10^7      |
|                   | 1983 | 7333      |                               |                                     | 0.38 × 10^6       | 0.75 × 10^7      | 0.25 × 10^7      |

Source: Area of *P. euphratica* adapted from Wang, 1996 [2].

The leaf litter amount decrease with the loss of *P. euphratica* trees would lead to reduction in nutrient sources for plant and microorganisms in the desert riparian forest. During the period from 1990 to 2016, forest area decreased dramatically in the main channel of the Tarim River basin [43], but the forest area increased 5.47 × 10^3 hm^2 during 2000 the period from 2000 to 2020 in the lower reaches of the Tarim River [44]. The area and growth of *P. euphratica* forest depend on flow from the Tarim River. Change of the flow in the Tarim River thus affected the leaf litter amount and nutrient cycle in the desert riparian forest ecosystem, which may have exerted an impact on the regional ecological environment and climate.

5. Conclusions

Plant litter plays a crucial role in nutrient cycling as a bridge that links vegetation to mineral soil. The objectives of this research were to find equations between leaf litter amount and tree characteristics to quantitatively estimate *P. euphratica* forest annual litter amount, and to analyze leaf litter nutrient change with incubation time in the main channel of the Tarim River. The following conclusions can be drawn:

1. The equation between canopy area (x) and annual leaf litter amount (y) for a *P. euphratica* tree was $y = e^{(11.12 - 10.97/x)}$ ($R^2 = 0.39, p < 0.05$), which may be appropriate to estimate the average annual leaf litter amount for a tree. The mean annual leaf litter amount per tree was 10.2–14.83 kg/y. Loss of *P. euphratica* forest decreased the annual leaf litter amount.

2. Leaf litter mass changed with incubation time and exhibited three phases: an initial slow decomposition phase (0–173 d) with mass loss; a rapid mass loss phase (173–470 d); and a second rapid mass loss phase (470–560 d). Overall, C and K content decreased, while N and P content increased in a fluctuating manner within 760 d. Loss of the leaf litter would lead to a decrease in nutrient sources for plant and microorganisms in desert riparian forest.

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