Water sources of riparian plants during a rainy season in Taihu Lake Basin, China: a stable isotope study

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1. Introduction

Riparian zone is the interface between aquatic and terrestrial ecosystems \cite{1,2}. Riparian plants are one of the most important components in riparian zones with a variety of vital ecological functions \cite{3}, for example, the roots of some plants can help remove nutrient \cite{4}. Water is the medium for chemical transport and exchange \cite{5}. Therefore, understanding the water sources for riparian plants can help understand the nutrient transportation in riparian zones and further provides a theoretical basis for ecological restoration and water quality control in riparian areas.

River water, groundwater, precipitation and soil water are usually the potential water sources of riparian plants \cite{6}, but the main water sources depend on the climate, hydrology, and plant species. Lots of studies showed that riparian plants used mostly groundwater regardless of the depth of the ground water and the distance to a stream or river \cite{7–9}. For example, Salix Gooddingii did not absorb water from upper soil layers during the summer rainy period, but only absorbed groundwater, even at an ephemeral stream site where the groundwater depth exceeded 4 m \cite{8}. Exceptions did exist \cite{10}, for example, Eucalyptus largiflorens F. Muell at flooded sites extracted shallow flood-derived soil water following the end of flooding on a semi-arid floodplain of the lower Murray River, southern Australia \cite{11}. Therefore, it is difficult to identify plant water sources and water utilization strategies in one region via the findings of previous studies conducted in other regions due to the differences in climatic conditions, plant species, geological conditions and/or soil hydrological processes.

In general, different water sources have different isotope compositions (\delta^{18}O and \delta^{2}H) due to unique isotope fractionation processes. There is no isotope fractionation during water uptake from the root systems or during water transportation in stems \cite{12,13}. Therefore, it is possible to identify plant water sources by comparing the isotope compositions of plant xylem water with those of potential water sources \cite{14–17}. To quantitatively assess the water use of plants, different mass balance models were developed, such as two- to three- components mixing model and multi-source mass balance model which can include more than three components \cite{18}.

In the Taihu Lake Catchment, East China, the water levels of river and groundwater vary significantly with seasons due to the flat topography and monsoon climate. The recharge-discharge relationship among river water, groundwater and soil water in the riparian zones is complex \cite{19–21}. Non-point pollution in the Taihu Lake Catchment is very severe \cite{22–24}, with 172 small rivers or channels discharging pollutants into the...
lake [25]. As one solution to these problems, a large number of ecological restoration projects have been conducted in riparian zones [26,27]. Therefore, it is important to identify the water sources for different riparian plants in order to help reduce the water pollution. In this study, dual isotopes of $\delta^{18}O$ and $\delta^2H$ were used to identify the water sources and estimate the contribution of each water source to the water uptake for three dominant plant species in a riparian zone of Taihu region.

2. Materials and methods

2.1. Study area

This study was conducted in the riparian zone of Yincungang river, an inflowing river of Taihu Lake, which is located in Yixing City, Jiangsu Province, China (31°27’22”N, 120°00’18”E, Figure 1). In the study area, there is a subtropical humid monsoon climate. The annual mean temperature is 16.1 °C, with the lowest in January (~9.0 °C) and the highest in August (36.7 °C). In 2014, there were 131 rainy days with a total precipitation of 1457.6 mm, mainly between April and September. Throughout the year, the river water table depth remains shallow ranging from 1 to 2.5 m below the soil surface.

Riparian zone trees are predominated by Ginkgo biloba (Ginkgo biloba L.) and Green soybean (Glycine max (L) Merr.), with some Mulberry trees (Morus L.). Ginkgo biloba is the only living species in the division Ginkgophyta, and has various uses in traditional medicine and as a source of food. In this area, Ginkgo biloba is mainly served as an ornamental plant. The average diameter of the Ginkgo biloba trunk is ~20 cm and the depths of vertical roots are up to 160 cm, in addition to the large lateral fibrous roots (mainly at 20–70 cm depth). Mulberry is common plant species in this region because of the silk industry. The average diameter of the Mulberry trunk is ~50 cm with the vertical root depth of 250 cm. The Green soybean is a plant species in the legume family, and a very popular bean for food in China. The root of the Green soybean can reach 50 cm deep below the soil surface. The soil at the study area is mainly clay soil, with a soil bulk density of 1.0–1.5 g cm$^{-3}$ and a porosity of 50–60%.

Figure 1. Sampling locations of the riparian zone of the Yin Cungang River in Wuxi City, Jiang Su province, China.
We selected three sampling sites perpendicular to the riverbank at distances of 5 m (Site 1), 10 m (Site 2), and 30 m (Site 3). At each site, we constructed a groundwater monitoring well with a 4 cm diameter PVC pipe by a standard bucket auger. The depth of the monitoring well extended to 2.5 m below the soil surface to ensure that groundwater can permeate into the PVC pipe during the driest season.

2.2. Sampling

Rainwater was collected from a standard rainwater container on August 16th, 18th, 19th, 24th, 26th, 28th, and 29th, 2014 when there was a rainfall event. The plant water, soil, groundwater, and river water samples were collected on August 30th, 2014. Three river water samples were collected across the water body at a water depth of 0.5 m, and then mixed together as a composite river water sample. Groundwater samples were collected from the monitoring wells. All water samples were stored in 100 ml glass bottles with polyseal caps sealed with parafilm, and kept at a temperature of <4 °C for the determination of $\delta^{18}$O and $\delta^2$H.

Three tresses of Green soybean and Ginkgo biloba were selected and shoots ranging from 1.0 to 2.0 cm in diameter and 4 to 5 cm in length were collected from each of the three sites. Mulberry shoot samples were only collected at Site 3 because we only observed Mulberry at site 3. The outer bark and phloem of all the shoots were removed to avoid any bias for isotopic analysis, as evaporative gas exchange in the bark tissue can result in isotopically enriched water [13].

Within a 2 m radius around the selected plants at each site, soil profile samples were taken at a 30 cm interval (0–30, 30–60, 60–90, 90–120, 120–150 cm). One fraction of the soil samples were for isotope determination and the other for the analysis of soil properties. All plant and soil samples were placed in glass bottles with polyseal caps, sealed with parafilms and kept at <4 °C during transportation to laboratory. In the laboratory, plant and soil samples were stored at <-80 °C and water extraction was conducted within 24 h.

2.3. Water extraction and isotope analyses

The extraction methods for plant and soil water include cryogenic vacuum distillation [28], physical squeezing [29], and accelerated solvent extraction [30]. In this study, we used cryogenic vacuum distillation to extract plant and soil water [28], with plant water taking 60 min and soil water taking 40 min. Stable isotope composition were measured for all water samples using a Finnigan DELTA plus XP isotope ratio mass spectrometer in the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. The measurement precision was 0.05‰ for $\delta^{18}$O and 0.15‰ for $\delta^2$H, respectively.

The ratio of stable isotopes can be expressed as:

$$\delta [%] = \left( \frac{R_{\text{sam}}}{R_{\text{std}}} - 1 \right) \times 1000 \quad (1)$$

where $\delta [%]$ refers to the isotopic difference of the sample relative to the Vienna Standard Mean Ocean Water (V-SMOW), $R_{sam}$ is the ratio of heavy and light isotope abundances in the sample ($^{18}$O$_{sam}$/^{16}$O$_{sam}$/$^2$H$_{sam}$/$^1$H$_{sam}$), and $R_{std}$ is the ratio of heavy and light element concentrations of the national universal reference material ($^{18}$O$_{std}$/^{16}$O$_{std}$/$^2$H$_{std}$/$^1$H$_{std}$).

2.4. Soil property measurement

The soil pH was measured by a pHs-3E pH Meter (Yoke instrument Co., LTD) in a 1:5 (volume basis) suspension of soil in a solution of 1 M KCl after shaking on a side-to-side shaker (300 rpm) for 60 min [31]. Soil water contents were measured at 105 °C for 24 h. Soil oxidation-reduction potential (ORP) was measured using a soil FJA-5 ORP Depolarization Automatic Analyzer (Xi’an Yima opto-electrical technology CO., LTD). Soil porosity was calculated from bulk density measured by the volumetric ring method [32].

2.5. Water source modelling

The direct inference approach was generally used to qualitatively identify water sources by comparing $\delta^{18}$O and $\delta^2$H of various water sources (e.g. river water, precipitation, groundwater, soil water from different depths) with those of plant water. The multi-source mass balance, on the other hand, is used to quantify the proportion of each water source. According to the mass balance, the proportion of each water source ($f_i$) can be determined by their isotopic signature ($\delta X_i$) and the mixture ($\delta X$), where $\delta X_i$ is the isotopic values of plant water:

$$\delta X = f_1 \delta X_1 + f_2 \delta X_2 + f_3 \delta X_3 + \cdots + f_n \delta X_n \quad (2)$$

$$f_1 + f_2 + f_3 + \cdots + f_n = 1 \quad (3)$$

In this study, the IsoSource algorithm [33] was used to estimate the relative contribution of each water source to plant water uptake. The fractional increment was set to 1%, and the uncertainty level was set to 0.2.

3. Results and discussion

3.1. Soil properties

At the three sites, soil water contents ranged from 18% to 23% and increased with depth, soil pH were all below 7 and increased with depth. There were no significant differences in the soil properties and oxidation-reduction potential between the three sites (Table 1). However, site
The amount effect of the rainfall that higher amount of rainfall tends to have more depleted $^2$H and $^{18}$O [34]. We used the weighted isotope composition of rainfall to estimate its contribution to the water uptake of plants.

As shown in Figure 2, the local meteoric water line (LMWL) in the study area is $\delta^2$H = 8.47 $\delta^{18}$O + 17.52 [35] and its slope and intercept are both larger than those of the global meteoric water line (GMWL, $\delta^2$H = 8 $\delta^{18}$O + 10). The isotopic compositions of soil water, river water, and groundwater fell along the LMWL (Table 3, Figure 2), reflecting a dominance of precipitation input. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36]. The isotopic compositions of most precipitation samples were more depleted than those of river water and groundwater. It could be due to the isotope fractionation during precipitation infiltration or during the redistribution and evaporation of soil water [36].

3 which was the farthest to the river bank showed the lowest soil water contents and highest pH in each soil profile.

### 3.2. Isotopic compositions of various water sources

The isotopic composition of precipitation varied significantly in August with $\delta^{18}$O values ranging from −11.57 to −8.00 ‰ and $\delta^2$H values ranging from −84.99 to −48.55 ‰ (Table 2). It could be due to the negative

### Table 1. Physical and chemical properties of soil profiles at the three sites.

| Depth/cm | Porosity | SWC/% | pH     | ORP/mv |
|----------|----------|-------|--------|--------|
| Site 1   |          |       |        |        |
| 0–30     | 0.561 ± 0.07 | 20.62 ± 1.02 | 5.61 ± 0.33 | 1441.3 ± 8.59 |
| 30–60    | 0.593 ± 0.04  | 21.21 ± 1.04  | 5.79 ± 0.22  | 1561.3 ± 8.12 |
| 60–90    | 0.585 ± 0.03  | 21.14 ± 1.31  | 5.73 ± 0.11  | 1622.4 ± 11.23 |
| 90–120   | 0.611 ± 0.06  | 21.32 ± 1.16  | 5.98 ± 0.15  | 1767.0 ± 8.45 |
| 120–150  | 0.545 ± 0.02  | 22.13 ± 1.01  | 5.95 ± 0.13  | 1721.7 ± 8.98 |
| Site 2   |          |       |        |        |
| 0–30     | 0.593 ± 0.03  | 20.53 ± 1.13  | 5.53 ± 0.18  | 1842.5 ± 9.83 |
| 30–60    | 0.576 ± 0.05  | 21.16 ± 2.05  | 5.49 ± 0.29  | 1632.5 ± 8.12 |
| 60–90    | 0.538 ± 0.02  | 21.39 ± 1.24  | 5.73 ± 0.10  | 1606.5 ± 10.11 |
| 90–120   | 0.618 ± 0.08  | 21.41 ± 1.35  | 5.73 ± 0.21  | 1868.0 ± 7.43 |
| 120–150  | 0.530 ± 0.01  | 22.72 ± 1.76  | 5.84 ± 0.15  | 1715.5 ± 8.51 |
| Site 3   |          |       |        |        |
| 0–30     | 0.577 ± 0.10  | 18.62 ± 1.12  | 5.93 ± 0.18  | 1692.6 ± 7.08 |
| 30–60    | 0.557 ± 0.06  | 19.21 ± 1.64  | 5.98 ± 0.21  | 1590.0 ± 15.19 |
| 60–90    | 0.541 ± 0.09  | 19.14 ± 1.52  | 6.15 ± 0.14  | 1583.6 ± 9.67 |
| 90–120   | 0.552 ± 0.01  | 20.32 ± 1.76  | 6.25 ± 0.39  | 1809.3 ± 9.44 |
| 120–150  | 0.602 ± 0.02  | 21.13 ± 2.01  | 6.27 ± 0.42  | 1573.8 ± 8.98 |

Notes: Data values are mean values ± standard deviation (n = 3). SWC = soil water content; ORP = Oxidation-Reduction Potential.

### Table 2. The amount of precipitation and its isotope compositions of each rainfall.

| Sampling date | Rainfall amount (cm) | $\delta^{18}$O | $\delta^2$H |
|---------------|----------------------|----------------|-------------|
| Aug. 16th     | 15.0                 | −8.33          | −55.58      |
| Aug. 18th     | 24.7                 | −11.57         | −84.37      |
| Aug. 19th     | 12.6                 | −11.45         | −84.99      |
| Aug. 24th     | 3.2                  | −8.82          | −56.57      |
| Aug. 26th     | 6.9                  | −8.00          | −48.55      |
| Aug. 28th     | 22.5                 | −11.20         | −82.02      |
| Aug. 29th     | 27.9                 | −11.36         | −80.69      |
| Weighted isotope composition | −10.79 | −76.25 |

### Figure 2. Dual-isotope plot ($\delta^{18}$O vs. $\delta^2$H) for water samples of rainfall, soil water at different depths, river water, xylem water, and groundwater in the study area.

Notes: GMWL (solid line) and LMWL (dash line), stand for global and local meteoric water line, respectively.
Generally, most isotopic fractionation occurred during evaporation near the soil surface, and the isotopic compositions of antecedent rainwater, groundwater, and river water recharging soil profiles [37–40]. When there is no recharge from other water sources, the isotopic composition of soil water shows a regular variation gradient with depth, with enrichment near the surface and an exponential decline with increasing depth due to soil capillary processes and soil water evaporation [41–43]. In this study, the variation of isotopic compositions across the soil profile was similar at all the three sites with enriched \( ^{18}O \) and \( ^{2}H \) in the shallow soil layers, but did not show continuing decreases with depth (Figure 3). The enrichment within the shallow soil layers was likely due to soil water evaporation, while the fluctuations with depth may reflect recharge from different precipitation events with different isotopic compositions. Furthermore, recharge from precipitation diminished the soil evaporative enrichment process to some extent [44].

| Table 3. Stable isotope composition (\( \delta^{18}O \) and \( \delta^{2}H \)) of xylem water for three riparian species and potential water sources at three sites (mean ± standard deviation, \( n = 3 \)). |
| Xylem water | Site 1 | Site 2 | Site 3 |
| Ginkgo biloba | −8.57 ± 0.09 | −8.64 ± 0.06 | −8.85 ± 0.14 |
| Green soybean | −8.37 ± 0.12 | −8.74 ± 0.04 | −8.69 ± 0.11 |
| Mulberry* | −8.21 ± 0.14 | −8.21 ± 0.14 | −8.21 ± 0.14 |
| Soil water | | | |
| 0–30 | −8.26 ± 0.18 | −8.49 ± 0.20 | −8.81 ± 0.32 |
| 30–60 | −9.19 ± 0.19 | −9.24 ± 0.20 | −9.39 ± 0.40 |
| 60–90 | −8.11 ± 0.22 | −8.21 ± 0.24 | −8.25 ± 0.38 |
| 90–120 | −8.55 ± 0.34 | −8.83 ± 0.29 | −8.72 ± 0.30 |
| 120–150 | −8.21 ± 0.29 | −8.16 ± 0.28 | −8.12 ± 0.43 |
| Ground water | | | |
| River water | −8.24 ± 0.15 | −8.15 ± 0.21 | −8.10 ± 0.09 |

| Site 1 | Site 2 | Site 3 |
| Site 1 | | | |
| Soil depth (cm) | | | |
| Sol depth (cm) | | | |
| Site 2 | | | |
| Site 3 | | | |

*Mulberry was only observed at the site 3.

Figure 3. \( \delta^{18}O \) and \( \delta^{2}H \) values (mean ± standard error) of soil water at different soil depths, plant xylem water, ground water and river water, for the three sites.
the three sites (Figure 4), whereas the primary water source for the Mulberry at Site 3 was the soil water at 120–150 cm depth.

3.4. IsoSource modelling: quantitative analysis of water sources

Selecting potential water sources for plants is dependent on the specific environmental conditions of a study area. For example, because of the infrequent precipitation, only groundwater and soil water are usually considered as potential water sources in arid areas [48]. For example, in Homestead National Monument, Nebraska, United States, the water used by Bur Oak was 70–88% groundwater, 10–12% deep soil water, and only up to 8% shallow soil water [49]. However, in the cold semi-arid ecosystem of the upper Kherlen River catchment of Mongolia, [50] reported that Poplar (Populus spp.) and willow (Salix spp.) near the riverbank used water from the river during August. That the river or stream water could be a potential water sources, usually occurred when the study area is close to a river or stream [6,13]. In wet areas or during the rainy season, precipitation is generally considered to be the most important water source [50,51]. Beech trees in small pre-alpine catchments, for instance, preferentially absorbed rainwater.
and soil water (instead of streamflow or groundwater) during the wet season [52]. Additionally, different water sources interacted with each other [53]. Here, we divided the plant water sources into direct and indirect inputs. The direct or internal water sources included soil water from different depths, while the indirect or external water sources included precipitation, river water, and groundwater.

Generally, the shallow soil water (0–60 cm) was the primary water source for Ginkgo biloba and Green soybean at all the three sites. For example, Ginkgo biloba obtained approximately 55–74% of its water from the 0–30 cm soil layer, 10–30% from the 30–60 cm soil layer, <10% from the 60–90 cm soil layer, and at most 28% from the >90 cm soil layers (Figure 4). For the Green soybean, soil water at 0–30 cm depth contributed more than 65% of the water. However, the Mulberry tree at Site 3 mainly used deep soil water at 120–150 cm depth, accounting for 82.3% of the total water. These results agreed with the result of the qualitative direct inference approach that during the rainy season, Ginkgo biloba and Green soybean in this region mainly use shallow soil water, while Mulberry prefers deep soil water.

Considering precipitation, river water, and groundwater as potential external water sources, for Ginkgo biloba and Green soybean, precipitation was the primary water source, accounting for as much as 70–90% of the water used by the plants (Figure 4). However, Mulberry at Site 3 mainly used ground water, which contributed 88.9% of water. The differences in water sources between Ginkgo biloba, Green soybean and Mulberry in the rainy season could attribute to their different root distribution. The Green soybean has a shallow root system, and Ginkgo biloba has lateral fibrous roots, which favor the uptake of shallow soil water. On the contrary, with the deep root system, Mulberry prefers to use ground water-derived deep soil water.

4. Conclusions

In this study, we qualitatively and quantitatively investigated the water sources for three dominated plants in a riparian zone of Taihu area in the rainy season. It was showed that precipitation and top 0–60 cm soil water were the major water sources for Ginkgo biloba and Green soybean, while ground water and deep soil water (>90 cm depth) contributed the most to Mulberry’s water uptake. Different root distribution of the three different plants could lead to the different water use strategy. The distance to the river bank did not show any significant difference in the water sources estimation. It will be interesting to explore the seasonal pattern of water use in this riparian area. Additionally, due to the economic significance of Green soybean and Mulberry to the farmers, more attention needs to be paid for the water management during wetland restoration in this area.

Disclosure statement

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