Agroforest Syst (2021) 95:641–657
https://doi.org/10.1007/s10457-021-00614-w

# Hydraulic lift: processes, methods, and practical implications for society

**Salah M. Alagele · Shibu Jose · Stephen H. Anderson · Ranjith P. Udawatta**

Received: 16 May 2020 / Accepted: 12 March 2021 / Published online: 20 March 2021

**Abstract** Soil water is an essential factor in soil–water–plant studies and larger-scale hydrological investigations. It is considered more critical than other factors that limit plant growth and also affects many fundamental biophysical processes. New strategies are needed to overcome drought and to maintain environmental sustainability. Hydraulic lift (HL) or hydraulic redistribution (HR) processes are one of these strategies found in soil–plant systems, but their effects on crop production and the environment have not been well documented. This article reviews (1) the process of HL, (2) methods showing evidence of HL using soil water potential (Ψs) and sap flow techniques, (3) hydraulically-lifting plants, and (4) practical implications for society. The HL is whereby soil water may be transported upward by deep roots of trees and grasses from the moist region (subsurface) to dry region (surface) at night. Thus, HL provides water to areas planted to shallow rooted plants at the upper soil layers. The HL of water by roots from wet to dry soil layers is a potential approach for better use of water resources for crop/grass growth. Also, increases in soil water by HL improve root growth and function which include soil carbon decomposition or nutrient mineralization rates, and this can probably be associated in nutrient cycling. Another benefit is that mycorrhizal fungi play a relevant role in HL and in the redistribution of this water among plants. Thus, HL provides many soil, agricultural, and environmental benefits.

**Keywords** Agroforestry · Climate change · Crop production · Hydraulic distribution · Sap flow · Soil water content · Soil water potential

## Abbreviations

| | |
|---|---|
| HL | Hydraulic lift |
| HR | Hydraulic redistribution |
| SWC | Soil water content |
| Ψs | Soil water potential |

## Introduction

Soil water has a predominant influence in prescribing engineering, agronomic, ecological, biological, and hydrological properties of the soil, and it is an

S. M. Alagele (✉)
Department of Desertification Combat, College of Agricultural Engineering Sciences, University of Baghdad, Baghdad, Iraq
e-mail: salah.alagele@coagri.uobaghdad.edu.iq

S. Jose · S. H. Anderson · R. P. Udawatta
School of Natural Resources, University of Missouri, 302 Anheuser-Busch Natural Resources Building, Columbia, MO 65211, USA

R. P. Udawatta
The Center for Agroforestry, University of Missouri, 203 Anheuser-Busch Natural Resources Building, Columbia, MO 65211, USA

environmental, hydrological, and climatic variable that has an impact on many fundamental biophysical processes (Susha Lekshmi et al. 2014). Soil water is a critical component in agricultural production for optimal plant yields (Ofori et al. 2014). The availability of sufficient amounts of soil water throughout the growing season, particularly during dry climatic regions is essential for plant growth which is influenced by water stored in the soil (Al-Kaisi et al. 2012). Soil water content (SWC) is an essential factor for determining the water and energy balances in the soil, transporting chemicals (e.g., fertilizers or pesticides) and managing irrigation (Seyfried and Murdock 2001). Thus, soil water becomes quite important in the field of agricultural, hydrological, and environmental aspects (Robinson et al. 2008).

When the SWC is lower than optimal, plants will not be capable of withdrawing water from the soil fast enough in response to potential evapotranspiration. Soil water extracted by plant roots, is transformed into transpiration (Novák and Hlaváčiková 2019). In general, transpiration is the transport of water from the roots to the substomatal cells of leaves. Then, the liquid phase changes to the gaseous phase (water vapor) and is transported from substomatal cells to the atmosphere following a decreasing water potential gradient (creating a lower osmotic potential in the leaf) (Hopkins and Hiiner 2009). Before the transpiration process can proceed, plant roots absorb soil water and potentially store water in the living plants or flow through the plant xylem. This stored water will be lost from the plant leaves and back to the atmosphere through the stomata (Liste and White 2008). Some of the water stored in the living plants is released from the root system into the soil at night by a phenomenon known as "hydraulic lift (HL) or hydraulic redistribution (HR)" (Burgess et al. 1998). The HL usually occurs at night when transpiration has diminished sufficiently to allow the water potential in the roots to exceed the Ψs in the drier portions of the soil. This process describes the water movement from plant roots into the soil where Ψs is lower (Caldwell et al. 1998; Neumann and Cardon 2012).

The transfer of water via roots from the moist and deeper soil layers to relatively drier upper soil layers is termed as "Hydraulic lift" (Richards and Caldwell 1987; Hirota et al. 2004). This phenomenon may be useful for improvement in crop production, the environment, and restoration of degraded land (Liste and White 2008). However, HL may occur when plants (trees or grasses) have access to sufficient amounts of water in deeper layers; therefore, they can transfer the water from the moist layers to dry soil layers through their roots. Emerman and Dawson (1996) defined HL and reported that the water is absorbed at night by deep tree roots, or possibly grasses, and delivered to the dry and upper soil layers. This can provide the opportunity for parasitism of the released water to roots of neighboring plants (Caldwell 1990).

Strategic planning of agricultural management systems is required to improve water productivity as well as a good understanding of crop water use. For instance, in dry seasons during the growing period, plant water demand exceeds water supply, and hence plants may suffer from severe water stress. Finding alternative water sources is important (1) to reduce plant water stress, (2) to meet the metabolic requirements and transpiration demand, and to overcome other environmental challenges (Horton and Hart 1998; Gerjets et al. 2017). The process of HL can play a vital role in water movement from the deep tree roots to the drier upper soil; this process may provide additional water for shallow-rooted and neighboring crops (Gerjets et al. 2017). Additionally, the integration of trees with crops could improve and maintain soil water resources available for plants during drought periods due to the reduction of potential evapotranspiration from plants and soil (shading) as well as wind speed (Lin 2010).

Richards and Caldwell (1987) reported that plant roots commonly pass through dry soil layers to layers that contain more moisture. In general, Ψs is often more negative in the drier soil layers than the root water potential. If water is lost from plant roots to drier soil, the root systems can form a bridge for water transport between soil layers. Therefore, this phenomenon can be defined as a process of water movement from wet to dry soil layers using the plant system as a conduit. In this process, the water movement direction is upward towards the drier and shallower soil layers (Caldwell et al. 1998).

The HL has been observed in many natural tree-grass mixtures and ecosystems (Burgess et al. 1998; Ludwig et al. 2003). The HL has been documented for various plant species with different climates. Several researchers have conducted many studies to examine the impacts of various plant species on the HL

(Richards and Caldwell 1987; Dawson 1993; 1996). Richards and Caldwell (1987) found in the field plots of interspersed sagebrush (*Artemisia tridentata* ssp. *vaseyana* (*Rydb.*) Beetle) and tussock grasses (*Agropyron desertorum* and *Agropyron spicatum*) that the water was absorbed and transported at night from moist to drier upper soil layers by deeper roots of these plant species. Using a sugar maple (*Acer Saccharum*), Dawson (1993, 1996) found that greater aboveground growth occurred under plants that utilized a high amount of hydraulic-lifted water with significantly higher leaf water potentials as compared with another neighboring plant that used little or no hydraulically-lifted water. Also, a study implemented by Kurz-Besson et al. (2006) indicated that there were apparent relationships which were found between leaf water potential and xylem sap isotopic composition, and these relationships confirmed the critical effect of the redistribution of groundwater in the Cork-oak tree (*Quercus suber* L.).

A better understanding of the HL process and its use in various vegetative management systems (trees/-grass) can improve agricultural sustainability. The HL may have positive environmental benefits such as climate change mitigation, production improvement, and sustainable use of soil and water resources (Burgess 2011). Also, this phenomenon can contribute to providing a water source to irrigate neighboring plants and conserving soil with implications to potentially improving crop production. The approach used for this review consisted of collecting several published papers on the process of HL to illustrate evidence for supporting this process. Also, this review (1) provides details on field and laboratory methods and different techniques (measurement of soil water potential (Ψs) and sap flow) for evaluating hydraulically-lift by plants and (2) shares the practical implications of the HL for society.

## Process of hydraulic lift

Water is a vital component of every living organism (Novák and Hlaváčiková 2019). Although it is one of nature's simplest chemicals, water has unique properties that contribute to a wide variety of physical, chemical, and biological processes (Susha Lekshmi et al. 2014). These processes significantly affect almost every portion of soil development and behavior, as well as the growth of plants (Weil and Brady 2016). Fifty percent of the world's population could be subjected to water stress if present trends of global climate change, as well as local/global climate warming and rising human consumption of water resources, continue (Zhang et al. 2018). Water deficit can adversely influence plant growth and sustainable agricultural production (Dawson 1993). Finding other water sources and developing more efficient water utilization methods are significantly needed. The HL is one of these solutions, but its potential for agronomic and agricultural applications has received little consideration.

The HL is the movement of water from moist to dry soil layers by plant root systems (Caldwell et al. 1998). Many researchers have studied the process of HL (Caldwell et al. 1998; Emerman and Dawson 1996; Burgess et al. 1998; Jackson et al. 2000; Liste and White 2008; Armas et al. 2010; O'Keefe and Nippert 2017). These researchers reported that water is absorbed by plants from all depths (soil layers) in which soil moisture is available, and this water passes into the transpiration stream through living plants during the day. At night when whole-plant transpiration is reduced (due to stomata being closed), and plant water potential rises; water moves from moist soil through the root system to drier soil layers. Movement of water during nighttime depends on a passive mechanism driven by a water potential gradient that transports water through the root system, from the deep moist to the upper drier soil layers (Richards and Caldwell 1987). If the soil in deeper layers is wetter, water moves from deeper to more shallow, drier soil layers (Fig. 1). Patterns of water flow from plants to soil can occur as described by Prieto et al. (2012). They indicated plant transpiration draws water inflow from the soil through stems and to the atmosphere through stomata during the daytime. However, when stomata are closed during periods of reduced plant transpiration which occurs during the night, plant water potential equilibrates with the soil water potential. This effect can cause water transport due to the water potential gradient between active plant roots and the drier soil resulting in water flow to drier soil (Prieto et al. 2012).

The HL may have important consequences for ecosystem water balance where plant roots create large gradients in Ψs (Hultine et al. 2004). Also, HL is affected mainly by the physical properties of root and

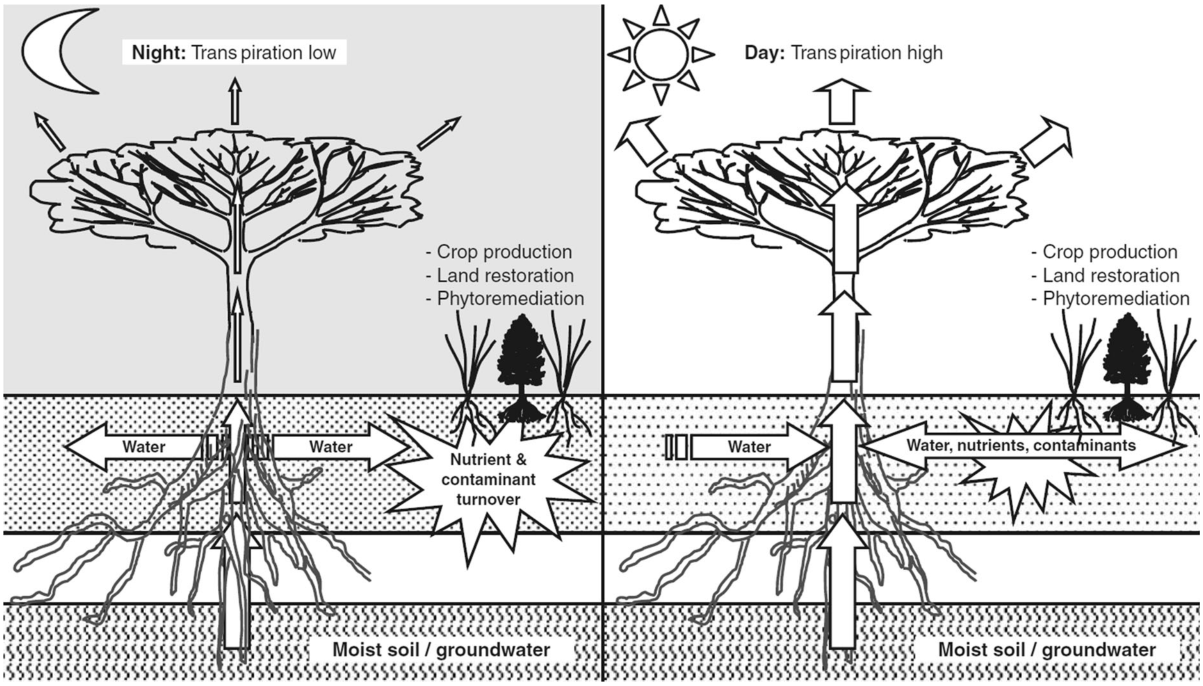

**Fig. 1** Schematic showing the hydraulic lift (HL) process and some possible benefits for the water-lifting plant and neighboring plant (from Liste and White 2008)

soil, and it may occur whenever root systems penetrate soil layers at different Ψs (Leffler et al. 2005). Liste and White (2008) stated that water moves from all regions of soil from regions of higher Ψs toward regions of lower water potential into the transpiration stream during the day when leaf stomata are open. At night when stomata are closed, transpiration decreases or ceases through the taproot of trees or grasses to plant leaves (Fig. 1). Water moves from roots into the upper soil layers, and this amount of water may irrigate neighboring plants. The transport of water is available not only for the plant itself but also for its neighbors (Sekiya et al. 2011).

Although the water release mechanism is not entirely understood, the amount of hydraulically-lifted water can be substantial each night. Therefore, HL is useful for plants, and transporting the water may be considered a significant water source with water uptake by neighboring plants (Horton and Hart 1998). This system enables deeper-rooted trees or grasses to obtain water, which is out of reach of shallow rooted crops, and may be of significant benefit to these crops in water-scarce environments (Burgess 2011). Thus, HL places soil water resources where they would otherwise not occur and assists a range of ecological and hydrological consequences (Neumann and Cardon 2012). The HL deserves more attention from landowners, farmers, economists, soil/crop scientists and policymakers due to this process having important environmental consequences for (1) soil water recharge and (2) survival of plants through drought periods (Leffler et al. 2005).

## Methods showing evidence of hydraulic lift

The HL can provide many positive environmental benefits such as crop production and sustainable use of soil and water resources. Hydraulically-lifted water can be detected through different measurement techniques, which include assessment of daily oscillations in bulk soil around root systems, evaluation of sap flow, and other techniques (Prieto et al. 2012). Table 1 shows the main methods that have been employed for supporting and showing evidence of HL for both field and laboratory conditions. The HL can be recognized through different methods (Table 1), but these often depend on detecting daily changes in bulk soil moisture around root systems. Several researchers studied the process of HL and employed various

**Table 1** The main techniques used to show evidence of HL for field and laboratory conditions ( modified from Prieto et al. 2012)

| Evidence method | Technique | Variable measured | Soil Status | References |
|---|---|---|---|---|
| Soil moisture and Soil water potential | Soil psychrometers | Water potential (Ψs) | Nondestructive | Richards and Caldwell (1987), Dawson (1993), Prieto et al. (2010a) |
| | Time-domain reflectometry | Water content (θ) | Nondestructive | Topp et al. (1996), Wan et al. (2000) |
| | Frequency domain capacitance | Water content (θ) | Nondestructive | Paltineanu and Starr (1997), Brooks et al. (2002) |
| Sap flow | Heat ratio method | Sap velocity/ direction | Semidestructive | Burgess et al. (1998, 2000) |
| | Stem heat balance | Sap velocity/ direction | Nondestructive | Wan et al. (2000) |
| | Thermal Dissipation | Sap velocity/ direction | Nondestructive | Brooks et al. (2002) |

techniques to support evidence of the occurrence of this phenomenon (Richards and Caldwell 1987; Dawson 1993; Burgess et al. 1998; Wan et al. 2000; Prieto et al. 2010a).

## Measurement of diel fluctuations using soil water potential (Ψs)

The soil water potential (Ψs) is sometimes more negative in the drier soil than the root water potential (Ψr) for roots in moist soil. Most evidence for the process of HL has come from the studies of measurement of Ψs. Water movement in unsaturated soil zones is based on both Ψs and gravity, but when gravity is less significant, differences in soil water potential (matric and/or osmotic) are the main force for water movement and act as drivers for the HL. However, recent experimental evidence shows that HL is much more complex than previously thought and a complex source-sink system in the plant-soil interface (Scholz et al. 2002). Many researchers believe that a gradient in Ψs between the upper and lower soil layers can be established, which is the driving force for the HL. The mechanism employed to demonstrate this process is based on the passive movement of water down a water potential gradient. Thus, several researchers have studied and measured Ψs to illustrate evidence of the HL (Richards and Caldwell 1987; Caldwell 1990; Dawson 1993, 1996; Emerman and Dawson 1996; Yoder and Nowak 1999; Kurz-Besson et al. 2006; Prieto et al. 2010a, b).

A study was conducted by Richards and Caldwell (1987) to monitor the process of HL using soil moisture techniques for two consecutive years (1985 and 1986). The (Ψs) was measured by screen-cage thermocouple psychrometers during drying cycles in the midsummer of 1985 and 1986 with field plots of two plant species, which included sagebrush (*Artemisia tridentata* ssp. *vaseyana* (Rydb.)) and tussock grasses (*Agropyron desertorum* and *Agropyron spicatum*). Figure 2 shows that water is rapidly lost from the plant during the day (stomates open in the daytime), with results illustrating that a high decrease in Ψs during the day. At night, increasing Ψs was observed with time due to stomatal closure of the shrubs, and the uptake of root water from the 35 to 80 cm soil depths quickly slowed when plants were no longer transpiring. The daytime decreases of Ψs exceeded the nocturnal increases. As evidence that these differences in Ψs at day and night come from the HL process, the researchers noticed during transpiration-suppression experiments using plastic bags over the plant shoots that there was an increase in Ψs during both day and night.

Prieto et al. (2010a) assessed the HL patterns under different arid land shrubs. They also performed transpiration suppression experiments in the two locations: during spring 2005 in Chile and during spring 2008 in Spain on five different shrub species.

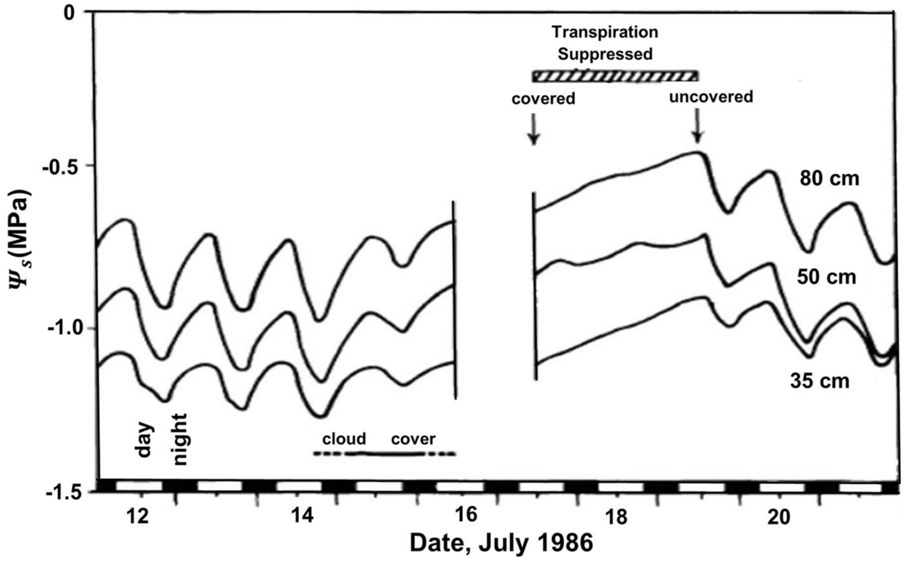

**Fig. 2** Graph showing measurement of soil water potential (Ψs) (megapascal, MPa) at three soil depths (35, 50, and 80 cm) during the daily cycle with a transpiration-suppression in July 1986 ( modified from Richards and Caldwell 1987)

Transpiration suppression experiments were conducted with covered shrubs by black, opaque plastic fabric for a period of 48–72 h, and measurements of Ψs were recorded at different depths under these shrubs. Determinations of Ψs were implemented using soil psychrometers, which were installed at 40-, 60-, and 80-cm depths in Quebrada El Romeral in Chile and at 30-, 50-, and 80-cm depths in Rambla del Saltador in Spain. They found that Ψs decreased during the day as plants were actively losing water, whereas Ψs increased in the upper soil layers at night when transpiration was lower. The significance of the cycle was the greatest at a depth of 30 cm in Spain or 40 cm in Chile (Fig. 3). A continuous increase in Ψs was recorded with suppressed transpiration. They concluded that the increases in Ψs during prolonged periods of low transpiration could be significant with plants performing the HL.

A study conducted by Dawson (1993) reported that at 20 and 35 cm soil depths demonstrated distinct diel oscillations. A fragipan layer (hardpan) was observed at a depth of approximately 50 cm. From their observations of root distributions, some larger diameter (1.9–3.7 cm) roots penetrated the fragipan layer, and they established new roots in the deeper soil layers near the groundwater table. These results illustrated that the moisture found in the upper soil layer was not come from capillary rise, from the shallow water table, during the night due to the presence of the hydraulically restrictive fragipan at 50 cm depth. The fragipan layer prevents movement of water from deeper layers to upper soil layers due to this layer having very low permeability for water movement. They concluded that the tree roots absorbed water at night from the deeper layer and released it into the upper 35-cm soil layer, above the fragipan (Fig. 4).

These observations from different studies explain that an increase in Ψs (less negative) and SWC within the upper soil layer is much higher than can be supplied by the upward movement of water in the soil alone. At night or under cloudy days, transpiration and evaporation processes will be lower; these could help to transfer water from plant roots to soil and also allow recharging water into upper soil layers from deeper layers, which may irrigate neighboring shallow-rooted plants (Bayala et al. 2008; Bayala and Prieto 2020). Also, these studies stated that the water employed by some of the neighboring plants may have a positive impact on their water use patterns and plant growth.

## Measurement of sap flow

It is essential to know how much water is used by plants to determine better soil–plant conditions. This information could be useful to identify plant water use under different conditions which include well-watered

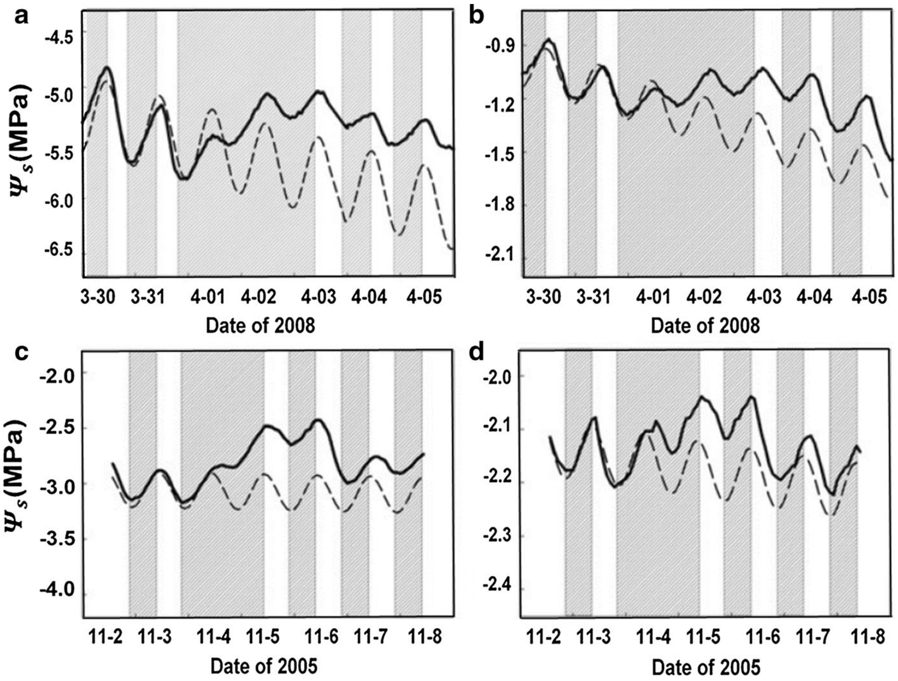

**Fig. 3** Graphs showing soil water potential (Ψs) (megapascal, MPa) measured at 30 cm depth under representative individuals of *Retama sphaerocarpa* (**a**) and *Artemisia barriers* (**b**) in Spain and at 40 cm depth under representative individuals of Flourensia thurifera (**c**) and Senna cumingii (**d**) in Chile. Solid lines are the measured water potential. Dashed lines are modeled HL patterns in the absence of transpiration suppression. Grey bars are nighttime periods. Thick grey bars are the period when the plants were covered ( modified from Prieto et al. 2010a)

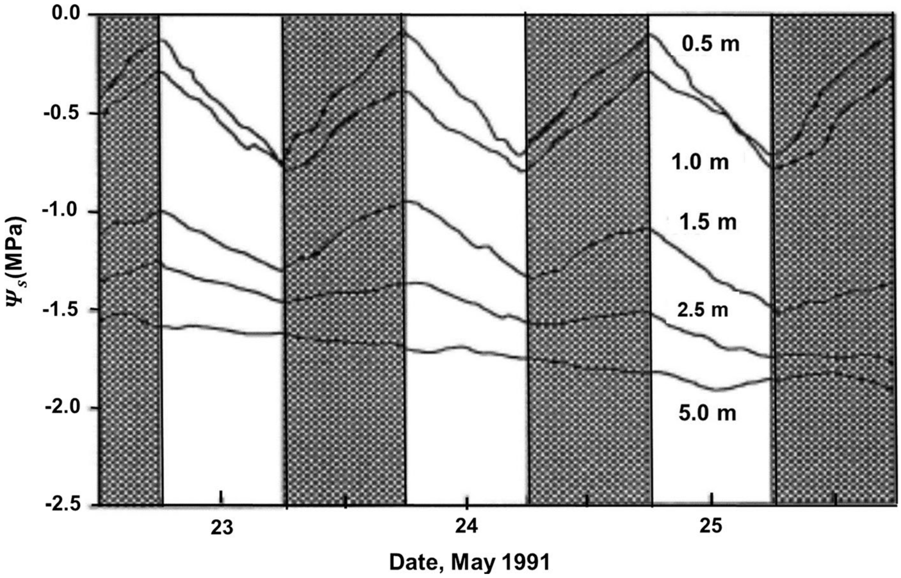

**Fig. 4** Graph showing diel fluctuations in soil water potential (Ψs) (megapascal, MPa) measurements at selected distances away from each tree at five positions (0.5, 1.0, 1.5, 2.5, and 5.0 m. Lines represent an average of 20 and 35 cm soil depths ( modified from Dawson 1993)

versus water-stressed conditions and sunny versus cloudy conditions. Further evidence of the HL process using the sap flux technique is among the most useful methods to detect water stress and to assess plant water consumption (Fu et al. 2016). The measurement of the whole plant transpiration has many applications. A constant power heat balance gauge method has been shown to provide accurate stem flow measurements, where the xylem mass flow rate is calculated from a balance of heat into and out of a stem (Dugas 1990). The constant heat balance technique measures the mass flow of sap depending on heat dissipation by convection (Lott et al. 1996). This method can be used to estimate crop water use (Nicolas et al. 2005) since transpiration is closely related to xylem sap flow (Fernández and Moreno 1999; Bethenod et al. 2000). Therefore, sap flow measurement within root systems is one of the methods to study the HL phenomenon more closely. Some researchers have proven hydraulically-lifted water using a sap flow technique to show evidence for HL (Dawson 1996; Burgess et al. 1998, 2000; Kurz-Besson et al. 2006; Wan et al. 2000; Prieto et al. 2010b).

A study conducted by Burgess et al. (1998) used a modification of the heat pulse method to measure sap flow in plant roots of *Grevillea robusta* and *Eucalyptus camaldulensis* as well as demonstrated a redistribution of soil water from the deeper soil profile to the dry upper soil layers by the root systems. They found that there were two different water movement patterns which include: (i) movement of water from deeper to upper soil layers (they reported this as the HL process), and (ii) flow of water from upper to deeper layers in the soil profile (they stated that this is the reverse of the HL process). Figure 5 shows that there were two periods: (1) before rain (days 1–6) and (2) after rain (days 7–12). Before the rain, flow rates in lateral roots of G. *robusta* were negative, moving away from the stem base towards the root tips, during the night and at lower rates of transpiration, and flow rates were only favorable during periods of high transpiration demand. This pattern of sap flow strongly supports the process of HL. After the rain, sap flow was positive in the lateral roots as the water was quickly absorbed from the surface layers, and water transported to roots in deeper and drier soil layers (this is reverse of HL).

Baker and Van Bavel (1987) and Wan et al. (2000) evaluated the impacts of the HL process on plant transpiration. They employed the technique of sap flow using a stem heat balance from 9 to 11 April involving two drought-tolerant maize (*Zea mays* L.) hybrids (TAES176 and P3223) during the flowering stage (Fig. 6). Two drought-tolerant maize (TAES176 and P3223) were selected because these plant species represent high and low capacities of HL, respectively. The peak transpiration of TAES176 was 42 and 27% higher than that of P3225 on 9 and 10 April, respectively. These results imply that higher transpiration in drought-tolerant maize (*Zea mays* L.) hybrid (TAES176) may have probably resulted from water exudation into the upper soil, which triggered a higher stomatal conductance. On the other hand, drought-tolerant maize (*Zea mays* L.) hybrid (P3225) seems unable to meet the higher transpiration demand due to root hydraulic conductance being insufficient and hence lower for hydraulically-lifted water. Thus, the sap flow technique using the stem heat balance and heat ratio method detects the process of HL, and this method can measure changes in direction and quantity of sap flow (Burgess et al. 2000).

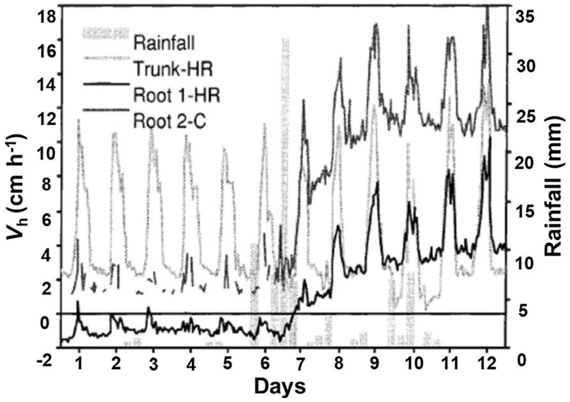

**Fig. 5** Graph showing hourly averages of heat pulse velocity ($V_h$) (6–17 November 1996) measured by the heat ratio in the Trunk (Trunk-HR) as well as the heat ratio (Root 1-h) and compensation (Root 2-C) method in two lateral roots of G. *robusta* at Machakos Field Station, Kenya. Negative flow in Root 1-h indicates the flow away from the trunk, towards the root tips (from Burgess et al. 1998)

Two processes which include HL and reversal of the process of HL have been noted during their observations when they used these techniques (Burgess et al. 2000). The researchers suggested that the term HL is inappropriate, and hence they used the term HR, which is more appropriate and more comprehensive for a description of these observations. Also, they concluded that more water may be transported into the

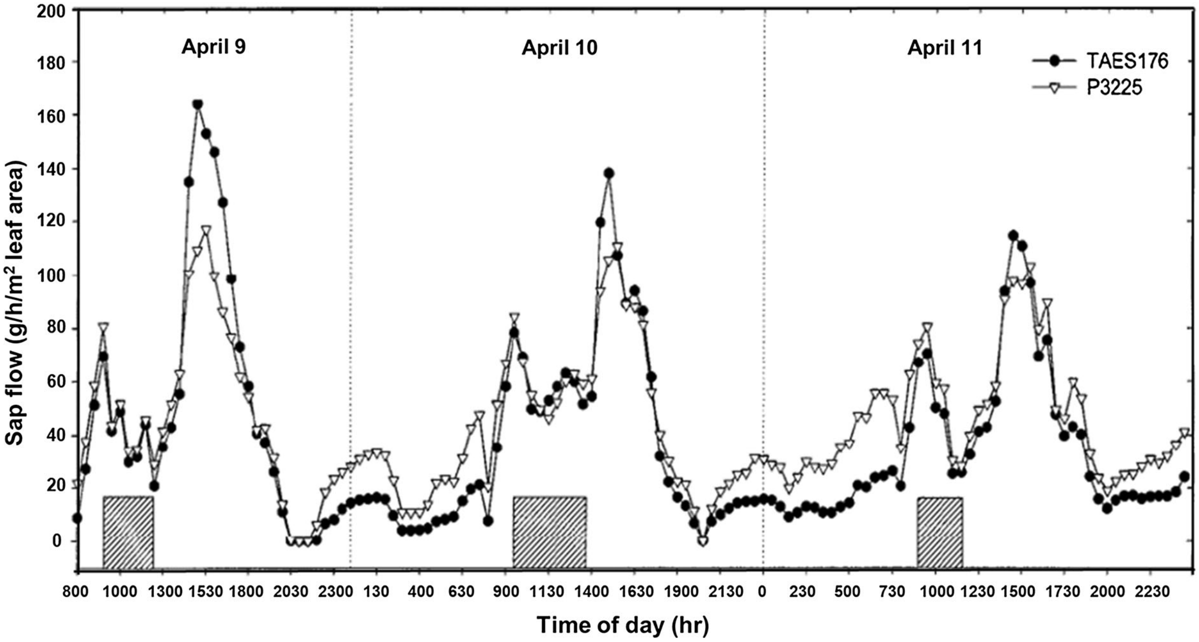

**Fig. 6** Graph showing sap flow average of the hybrids TAES176 and P3225 on 9–11 April. The plants were shaded in mid-morning (the hatched bars), and the shade was removed in the early afternoon ( modified from Wan et al. 2000)

upper drier soil layers when transpiration is suppressed by shading and during nighttime (Warren et al. 2008). Investigations during many studies have been conducted to detect the HL process. They have employed measurements of diurnal SWC and Ψs patterns and sap flow techniques that have focused on the magnitude of HL and its contribution to ecosystem water flux. Although these techniques are time-consuming, often are difficult to perform for certain conditions, and often are expensive, these methods also provide a better understanding and extent to which HL occurs in soil–plant systems. Thus, using these techniques has shown that there was obvious evidence of the occurrence of the HL, and both of these two types of approaches should be extensively used for investigating the HL.

## Hydraulically lifting plants

Throughout the world, the process HL has been reported in over 60 plant species in many biomes, from tropical and temperate forests to arid and semi-arid ecosystems (Prieto et al. 2012). The HL has clearly been detected for a few species of herbs, grasses, shrubs, and trees, but it is believed to be a more general phenomenon (Caldwell and Richards, 1989). The diversity of plant species in different studies and experiments, including field and laboratory, doesn't indicate that the process of HL is necessarily limited to particular plant species. Tables 2 and 3 show different experiments in the laboratory and field, respectively, with diverse species of plants. Researchers have utilized different plant species such as woody taxa (trees and shrubs) and various species of herbs and grasses in selected experiments in order to prove that the phenomena of HL can occur. Most of these studies have reported that HL occurs because they found variations in Ψs in an individual species.

Studies were conducted by Richards and Caldwell (1987) and Caldwell and Richards (1989) using sagebrush (*Artemisia Tridentata*), which is an aromatic shrub from the family Asteraceae and grows in arid and semi-arid conditions. They found that the deep roots of the shrub were significantly enhanced with HL, as indicated by reductions of 25–50% in transpiration. They reported that HL has important implications for plant water relations, mineral nutrient uptake, competitive interactions among neighboring plants, and arid land hydrology. Results also demonstrated that deeper roots seem to absorb and transport water during both day and night.

**Table 2** A list of selected plant species used in laboratory hydraulic lift (HL) experiments and the nature of evidence

| Plant species | Reference | Nature of evidence |
|---|---|---|
| *Phaseolus vulgaris* (bean) | Schippers et al. (1967) | Water efflux from hypocotyl |
| Populous species (poplar) | Hansen and Dickson (1979) | Water transfer between roots of neighboring seedlings |
| *Cynodon dactylon* * C. *transvaalensis* (bermudagrass) | Baker and van Bavel (1986) | Water transfer between soil compartments |
| *Medicago sativa* (alfalfa) | Corak et al. (1987) | Water transfer to maize plants in the same pot |
| *Gossypium hirsutum* (cotton) | Baker and van Bavel (1988) | Water transfer between soil compartments |
| *Prunus persica* (peach) | Glenn and Welker (1993) | Water transfer between soil compartments |
| *Eucalyptus viminalis* | Phillips and Riha (1994) | Water transfer between soil compartments |
| *Zea mays* (maize) | Topp et al. (1996) | Water efflux from individual roots |
| A markhamia tree (*Markhamia lutea* (Benth.) Schumann) and upland rice (*Oryza sativa* (L.)) | Hirota et al. (2004) | Sap flow measurement and soil volumetric water content |

Different studies were performed by Dawson (1993, 1996) and Emerman and Dawson (1996) using sugar maple (*Acer saccharum*). These experiments found that neighboring trees, which conduct HL, can utilize a significant proportion of this water source, which comes by absorbing water from deep roots of trees, and this water passes from the deeper roots into the upper soil layer at night, for irrigating neighboring plants. The process of HL could also lessen the impact of drought on the performance and growth of neighboring plants. A study conducted by Jackson et al. (2000) demonstrated that large trees (e.g., sugar maple) may lose around 350–600 L day$^{-1}$ and can transfer 100 L of water into the rhizosphere each night throughout much of the growing season at the soil surface. On the other hand, small trees require access to deeper groundwater and do not redistribute much water. Jackson et al. (2000) concluded from field measurements that soil and root water potential, soil properties, and the size distribution of trees were the most important parameters that are needed for assessing the HL phenomenon.

The HL was investigated by Wan et al. (2000) in greenhouse research including two drought-tolerant maize (Zea mays L.) hybrids throughout the flowering stage. They stated, as mentioned before in the upper soil under TAES176 and P3223 hybrids, that higher root volume and larger primary roots (20–28% larger diameter) for TAES176 may contribute to higher root hydraulic conductance and more significant water efflux from the roots than a drought-susceptible hybrid (P3225). Using blue oak (*Quercus douglasii*) woodland as indictor, Ishikawa and Bledsoe (2000) found that there were diurnal Ψs fluctuations (gradual increase at night and rapid decrease during daytime). This observation has provided significant evidence for continued blue oak root activity throughout the summer.

A study carried out at the Texas Agricultural Experiment Station using savanna tree-shrub clusters as evidence, Zou et al. (2005) indicated that the process of HL is common but temporally dynamic in these Savanna (tree-shrub groups), as well as HL is considered an important process for some of these communities (tree-shrub), but not all understory shrubs. Kurz-Besson et al. (2006) found at the peak of the drought season that hydraulically-lifted water in the cork oak (*Quercus suber*) trees were estimated to account for 17–81% of the water used during the following day by tree transpiration. Also, a positive influence was noted with xylem sap isotopic composition and leaf water potential in early September; this observation confirmed the redistribution of groundwater in the rhizosphere on tree water status.

**Table 3** A list of selected plant species illustrating HL in the field from different studies and the nature of evidence

| Plant species | Reference | Nature of evidence |
|---|---|---|
| *Artemisia tridentate* (sagebrush) | Richards and Caldwell (1987)<br>Caldwell and Richards (1989) | Ψs fluctuations, daytime bagging experiment, deuterium labeling, nighttime lighting experiments |
| *Agropyron desertorum* (crested wheatgrass) | Caldwell (1990) | Ψs fluctuations, nighttime lighting experiments |
| Gutierrezia sarothrae (broom snakeweed) | Wan et al. (1993) | Water accumulation in the upper root zone, soil water content fluctuations |
| *Acer saccharum* (sugar maple) | Dawson (1993, 1996) | Ψs fluctuations, natural abundance of deuterium |
| *Acer saccharum* (sugar maple) | Emerman and Dawson (1996) | Ψs fluctuations, nighttime—lighting |
| *Grevillea robusta and Eucalyptus camaldulensis* | Burgess et al. (1998) | Sap flow measurement |
| *Larrea tridentata* (deep-rooted species)<br>*Ephedra nevadensis* (shallow-rooted species)<br>*Ambrosia dumosa* (shallow-rooted species)<br>*Lycium pallidum* (drought-deciduous species)<br>*Yucca schidigera*<br>*Achnatherum hymenoides* | Yoder and Nowak (1999) | Ψs fluctuations, nighttime lighting/shading experiments |
| *drought-tolerant maize* (*Zea mays L.*) *hybrids* | Wan et al. (2000) | Sap flow measurement and soil volumetric water content |
| blue oak woodland | Ishikawa and Bledsoe (2000) | Ψs fluctuations, day-night cycles |
| *P. palustris, Q. laevis, Q. incana, Q. margaretta, A. stricta and S. scoparium* | Espeleta et al. (2004) | Ψs fluctuations and soil temperature, nighttime and lighting experiments |
| *savanna tree–shrub clusters* | Zou et al. (2005) | Diel cycling and nocturnal increases in soil water potential (Ψs) |
| Cork-oak (*Quercus suber L*) | Kurz-Besson et al. (2006) | Ψs daily fluctuations, day-night cycles as well as soil water isotopic composition |
| karite´ (*Vitellaria paradoxa*) and ne´re´ (*Parkia biglobosa*) tree species | Bayala et al. (2008) | Ψs fluctuations, day-night cycles |
| *Juniperus phoenicea subsp. Turbinate* (*Cupressaceae*) | Armas et al. (2010) | physiology measurements, including water relations, CO2 exchange, photochemical efficiency, sap osmolality, and water and C isotopes |
| *Flourensia thurifera, Senna cumingii and Pleocarphus revolutus* (*Chile*)*, Retama sphaerocarpa and Artemisia barrelieri* (*Spain*) | Prieto et al. (2010a) | Ψs fluctuations, day-night cycles |
| *Retama sphaerocarpa* (*L.*) *Boiss,* a tree-like shrub | Prieto et al. (2010b) | Ψs fluctuations, day-night cycles, and sap flow measurement |
| woody and herbaceous tallgrass prairie species (*Rhus glabra, Amorpha canescens, Vernonia baldwinii, and Andropogon gerardii*) | O'Keefe and Nippert (2017) | Diurnal changes in the isotopic signature of soil and plant xylem water |

Newly reported examples of hydraulically-lifted water in the field come from different studies in Mediterranean climates, arid ecosystems, and mesic prairie. Prieto et al. (2010a, b) conducted field studies using different plant species which included two drought-deciduous shrubs, *Flourensia thurifera* (Molina) D.C. and *Senna cumingii* (Hook. and Arn.) H.S. Irwin et Barneby, as well as an evergreen shrub, *Pleocarphus revolutus* D. Don. All of these species are endemic to Chile. Also, the species selected for study in Spain included *Retama sphaerocarpa* (L.) Boiss., which is an evergreen species with a dimorphic root system that can reach 30 m deep, and *Artemisia barrelieri* Besser, which is a small evergreen shrub that also has a dimorphic root system, which reaches > 1 m deep. They developed a model that was used to simulate the temporal evolution and magnitude of the HL during a soil drying cycle under relatively stable climatic conditions. They reported that these plant species have carried out the HL process.

The study conducted by Sekiya et al. (2011) used deep-rooting systems of different perennial forage plants of guinea grass (*Panicum maximum*), tall fescue (*Festuca arundinacea*), white clover (*Trifolium repens*), smooth bromegrass (*Bromus inermis*) and sun hemp (*Crotalaria juncea*) with their shoots removed to minimize the effect of light interception. They confirmed that the approach of deep-rooting associated plants with their shoots removed is a vital method for HL study, and it may consider an important irrigation tool and improvement of crop production in water-scarce environments. A study conducted by O'Keefe and Nippert (2017) observed diurnal changes in the isotopic signature of soil and plant xylem water to evaluate if the process of HL occurs in woody and herbaceous tallgrass prairie species. They used different species in their study which included one clonal C3 shrub (*Rhus glabra* L., smooth sumac), one leguminous C3 subshrub (*Amorpha canescens Pursh*., leadplant), one C3 forb (*Vernonia baldwinii Torr*., Baldwin's ironweed), and one C4 grass (*Andropogon gerardii*, big bluestem). They stated that the HL could be a patchy process, particularly in heterogeneous soils. However, further investigations may be needed to detect other plant species that show this process, particularly under arid conditions. Although the consequences of the HL for neighboring species are many, various studies and evidence explain that the provision of water through the HL can be a facilitative mechanism in many plant communities (Prieto et al. 2012).

## Practical implications for society

The recent food crisis has highlighted challenges with producing sufficient crops for increased food, fiber, and fuel demands (Mittal 2009). In addition, challenges exist in using water resources efficiently for production needs (Godfray et al. 2010; McLaughlin and Kinzelbach 2015). These challenges have increased over time. Desa (2009) stated that the world population would increase from 6.9 billion people in 2010 to 9.1 billion by 2050. Therefore, world food demand will significantly increase, and the competition for land and water resources will also increase. Certain areas are vulnerable to food insecurity particularly the Middle East and Africa. Water shortages, particularly freshwater shortages and desertification in many parts of the world, worsen, and costs for farmers are a challenge in several countries. These challenges can have severe environmental and economic effects within these regions (Shetty 2006).

To overcome some of these challenges, a better understanding of the expected climate change effects, such as increases in temperature and evapotranspiration as well as changes in rainfall distribution and growing season length, are essential for adapting management systems. Extensive lands in the world, particularly in the Middle East and Africa, also need to implement irrigation systems to meet water demand for crops, and these irrigation systems are expensive due to design, equipment and water application costs (Laraus 2004). The process of HL is potentially one of the solutions which may provide water to some of the neighboring plants grown in combination with HL plants which can subsequently have a positive influence on water use patterns and crop growth (Dawson 1993). The HL can provide a natural alternative to mitigate the effects of current high water consumptive engineered irrigation approaches.

The HL process may become a critical component of innovative, sustainable, and low-cost irrigation solutions around the world. For regions in the Middle East and Africa, this natural process may be an applicable solution for increasing crop production since HL may work as an irrigation system and supply water from deeper soil layers to upper soil layers (shallower plant roots). This increase in soil water at the soil surface may irrigate adjacent crops and may enhance the productivity and reduce the challenges for the food security (Liste and White 2008). This biological phenomenon can be used to design water-efficient crop-tree integrated systems that utilize deep water below the crop root zones while reducing the evaporation losses from the near-surface due to reduced temperature and wind velocity conditions with the integrated trees. For example, perennial forage plants, particularly P. *maximum* and F. *arundinaceae*, have proven to function as efficient biological irrigation systems (Sekiya et al. 2011). Many studies propose that the process of HL may be manipulated to create "self-irrigating" agroecosystems in which rows of deep-rooted "water donor" plants alternate with water-receiving areas planted to shallow-rooted neighboring plants in upper soil layers in water-scarce environments which can possibly increase crop production (Weil and Brady 2016).

The process of HL has been shown to enhance the performance and water status of neighboring species, particularly under dry conditions (Filella and Penuelas 2003). Necessarily, access to groundwater or other sufficient deep-water sources in the soil is considered a key to any bioirrigation impact in intercropping systems, including the agroforestry management system (Liste and White 2008). The use of selected agroforestry management and sustainable vegetation practices has been recommended to improve environmental and ecological challenges (Udawatta et al. 2002; Kumar et al. 2012). Deep-rooted tree species, such as casuarina (*Casuarina equisetifolia* L.), which is also a drought-tolerant species, can be used in alley-cropping practices to reduce soil surface evaporation and to supplement irrigation by HL while improving soil and environmental quality.

Agroforestry is a land management system that utilizes trees in the landscape as well as traditional plants simultaneously in the same area for environmental and economic benefits (Nair 1993). Therefore, fast-growing and deep rooting crops that are capable of HL could improve the survival rates of young trees with shallow root systems in arid regions or during periods of drought (Armas et al. 2010). Also, hydraulically-lifted water by trees may wet upper soil layers sufficiently to allow roots to take up nutrients that might otherwise be unavailable and hence increase crop production (McCulley et al. 2004).

If the HL is a widespread phenomenon, it can have an important impact on ecosystem nutrient cycling (Horton and Hart 1998). For example, HL might delay soil dry-down, and this may allow mycorrhizae and other soil microorganisms to remain active for a longer period (Dawson 1993). This may enhance nutrient mineralization and may lead to higher nutrient availability and uptake by plants (Liste and White 2008). Thus, the role of deep roots of trees with nutrient uptake with HL can move nutrients directly around roots where nutrient uptake occurs (Hultine et al. 2004). For example, sagebrush, a deep-rooted woody plant found in the deserts of North America, conducts enough HL to enhance the microbial mineralization of nitrogen from organic matter in surface soil (Weil and Brady 2016). Nutrients are usually stored in shallow soil layers, but a pool of nitrate ($NO_3$) is stored deeper in the soil in some arid and semi-arid ecosystems (Walvoord et al. 2003). Although the presence of $NO_3$ and other chemicals in the root zones of plants may cause contamination of underground water if leached, the water movement from deep soil layers through HL may increase nutrient uptake by deep roots and incorporate deep-stored nutrients into plant tissues (e.g., leaves) (Prieto et al. 2012).

The HR affects nutrient uptake by plants, and this hence contributes to increasing soil water availability that enhances soil microbial and enzymatic activity (Prieto et al. 2012). Several researchers have indicated that neighboring plants that are grown by the process of HL can improve soil macrofauna (earthworm) activity and subsequent nutrient availability under hedgerow species (Richards and Caldwell 1987; Dawson 1993; Rao et al. 1998; Scholz et al. 2002). These researchers reported that increasing soil microbial biomass (e.g., bacteria and fungi) may have the potential to enhance soil biodiversity. Also, they stated that neighboring crops could environmentally improve the soil surface and increase soil microbial activity, such as mycorrhizal fungi. This can enhance nutrient and water uptake by plants and organic matter accumulation; thereby these plants are of significant agricultural and ecological importance.

Although the role of mycorrhizal fungi in the HL process still remains unknown, Mycorrhizal fungi correlated with plant roots often enhance plant water relations through the increased extension of root growth and improved surface absorption (Allen 2007; Lehto and Zwiazek 2011). Thus, mycorrhiza can play a major role in the process of HL. Under dry soil conditions, water can flow from roots to soils through mycorrhizal fungi bristles through higher water absorption (Querejeta et al. 2003), and this may increase the quantity of HL. Since the diffusion of nutrients becomes insufficient in dry soil, water efflux through mycorrhizal fungi may also increase diffusion rates and thus nutrient uptake by plant roots correlated with mycorrhiza (Egerton-Warburton et al. 2007). Therefore, many studies illustrated that the process of HL can provide water supplied from the tap-root of trees to fine roots by mycorrhizal fungi and thereby promote nutrient ion mobility and uptake during the dry periods of the growing season (Brooks et al. 2002; McCulley et al. 2004).

When the process of HL occurs, the potential production of biomass crops and sustainable use of soil and water resources could provide more perennial roots, which have created a marked abundance of biopores and added organic matter in the soil profile and may improve soil hydraulic properties, particularly in the soil surface (Jackson et al. 2000). Growing these vegetative covers utilizing HL can also potentially protect the ground with living vegetation and living roots to prevent/reduce soil erosion/soil degradation as well as add significant quantities of organic matter and higher amounts of residues that are readily used by soil organisms (Weil and Brady 2016; Han et al. 2018). Also, when soils are covered with living vegetation for a longer period, there tends to be reduced loss of nitrate ($NO_3$) and less groundwater contamination (Magdoff and Van Es 2009) as well as reduce wind exposure and potential evapotranspiration of soils and crops (Gerjets et al. 2017). Thus, the process of HL may play a major role in ensuring soil, water, and environmental quality.

## Conclusions

This paper reviews the process, evidence, diverse plant species, and practical implications for the society of HL. This review showed that the HL may significantly contribute to improving crop production. This phenomenon describes water movement from plant roots into the soil with lower Ψs. Plants absorb water during the daytime to meet the transpiration demand. When the transpiration process is very low or suppressed at nighttime due to stomata being closed, plant water potential is equilibrated with the soil where most active roots are found. Therefore, gradients in Ψs can be created between the drier soil and plants; subsequently, water may flow from plant roots to these dry soil layers in the upper layers and may irrigate neighboring plants. This review gives further support of the occurrence of HL measured using two techniques which include SWC and Ψs studies and sap flow evaluations. The two techniques have provided a better understanding of the occurrence of HL under different plant species and climate conditions. Some practical implications for the society of HL have been presented, and these implications may affect hydrological and biogeochemical cycles. Thus, the establishment of trees (e.g., agroforestry) on strategic locations (e.g., degraded or agricultural lands) is useful for improving soil and environment quality. Additionally, planting neighboring crops may enhance soil quality by increasing soil carbon sequestration and water storage, particularly in damaged landscapes. The benefits of the HL process are greater when vegetative management practices are grown on degraded or marginal lands than when these practices are used in agriculture or forest lands. Although this review provides information, evidence, and applicable studies for the occurrence of HL, many questions are still unanswered. These questions include: (1) which plant species implement HL most effectively under particular conditions and grow rapidly and robustly, (2) how much water is lifted overnight, (3) is the process of HL widespread, (4) is it appropriate or best to use in different cropping management systems, and (5) or may HL meet regional economic and social requirements. Therefore, more studies and investigations may be needed to elucidate the process and answer these questions. Overall, the successful establishment of trees and grasses for implementing HL can be one of the viable management options to accomplish essential improvement in soil and environmental quality as well as crop production.

### Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Al-Kaisi M, Taylor SE, Elmore RW (2012) Soil moisture conditions and crop water use. Integrated Crop Management News 218. Iowa State University, Ames. http://lib.dr.iastate.edu/cropnews/218

Allen MF (2007) Mycorrhizal fungi: highways for water and nutrients in arid soils. Vadose Zone J 6:291–297

Armas C, Padilla FM, Pugnaire FI, Jackson RB (2010) Hydraulic lift and tolerance to salinity of semiarid species: consequences for species interactions. Oecologia 162:11–21

Baker JM, Van Bavel CHM (1986) Resistance of plant roots to water loss. Agron J 78:641–644

Baker JM, Van Bavel CHM (1987) Measurement of mass flow of water in the stems of herbaceous plants. Plant Cell Environ 10:777–782

Baker JM, Van Bavel CHM (1988) Water transfer through cotton plants connecting soil regions of differing water potential. Agron J 80:993–997

Bethenod O, Katerji N, Goujet R, Bertolini JM, Rana G (2000) Determination and validation of corn crop transpiration by sap flow measurement under field conditions. Theor Appl Climatol 67:153–160

Bayala J, Heng LK, Van Noordwijk M, Ouedraogo SJ (2008) Hydraulic redistribution study in two native tree species of agroforestry parklands of West African dry savanna. Acta Oecol 34:370–378

Bayala J, Prieto I (2020) Water acquisition, sharing and redistribution by roots: applications to agroforestry systems. Plant Soil 453:17–28

Brooks JR, Meinzer FC, Coulombe R (2002) Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. Tree Physiol 22:1107–1117

Burgess SS, Adams MA, Turner NC, Ong CK (1998) The redistribution of soil water by tree root systems. Oecologia 115:306–311

Burgess SS, Adams MA, Bleby TM (2000) Measurement of sap flow in roots of woody plants: a commentary. Tree Physiol 20:909–913

Burgess SS (2011) Can hydraulic redistribution put bread on our table? Plant Soil 341:25–29

Caldwell MM, Richards JH (1989) Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79:1–5

Caldwell MM (1990) Water parasitism stemming from hydraulic lift: a quantitative test in the field. Isr J Plant Sci 39:395–402

Caldwell MM, Dawson TE, Richards JH (1998) Hydraulic lift: consequences of water efflux from the roots of plants. Oecologia 113:151–161

Corak SJ, Blevins DG, Pallardy SG (1987) Water transfer in an alfalfa/maize association: survival of maize during drought. Plant Physiol 84:582–586

Dawson TE (1993) Hydraulic lift and water use by plants: implications for water balance, performance, and plant-plant interactions. Oecologia 95:565–574

Dawson TE (1996) Determining water use by trees and forests from isotopic, energy balance, and transpiration analyses: the roles of tree size and hydraulic lift. Tree Physiol 16:263–272

Desa U (2009) World population prospects: the 2008 revision. Department for Economic and Social Affairs, New York

Dugas WA (1990) Comparative measurement of stem flow and transpiration in cotton. Theor Appl Climatol 42:215–221

Egerton-Warburton LM, Querejeta JI, Allen MF (2007) Common mycorrhizal networks provide a potential pathway for the transfer of hydraulically lifted water between plants. J Exp Bot 58:1473–1483

Emerman SH, Dawson TE (1996) Hydraulic lift and its influence on the water content of the rhizosphere: an example from sugar maple, *Acer saccharum*. Oecologia 108:273–278

Espeleta JF, West JB, Donovan LA (2004) Species-specific patterns of hydraulic lift in co-occurring adult trees and grasses in a sandhill community. Oecologia 138:341–349

Fernández JE, Moreno F (1999) Water use by the olive tree. J Crop Prod 2:101–162

Filella I, Penuelas J (2003) Indications of hydraulic lift by *Pinus halepensis* and its effects on the water relations of neighbor shrubs. Biol Plant 47:209–214

Fu S, Sun L, Luo Y (2016) Combining sap flow measurements and modeling to assess water needs in an oasis farmland shelterbelt of Populus simonii Carr in Northwest China. Agric Water Manag 177:172–180

Gerjets R, Richter F, Jansen M, Carminati A (2017) Soil hydrology of agroforestry systems: Competition for water or positive tree-crops interactions? In: EGU general assembly conference abstracts, vol 19, p 6683

Glenn DM, Welker WV (1993) Water transfer diminishes root competition between peach and tall fescue. J Am Soc Hort Sci 118:570–574

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Han Y, Feng G, Ouyang Y (2018) Effects of soil and water conservation practices on runoff, sediment and nutrient losses. Water 10:1333

Hansen EA, Dickson RE (1979) Water and mineral nutrient transfer between root systems of juvenile Populus. For Sci 25:247–252

Hirota I, Sakuratani T, Sato T, Higuchi H, Nawata E (2004) A split-root apparatus for examining the effects of hydraulic lift by trees on the water status of neighboring crops. Agrofor Sys 60:181–187

Hopkins WG, Hiiner NPA (2009) Introduction to plant physiology. Library of Congress Cataloging, Washington

Horton JL, Hart SC (1998) Hydraulic lift: a potentially important ecosystem process. Trends Ecol Evol 13:232–235

Hultine KR, Scott RL, Cable WL, Goodrich DC, Williams DG (2004) Hydraulic redistribution by a dominant, warm-desert phreatophyte: seasonal patterns and response to precipitation pulses. Funct Ecol 18:530–538

Ishikawa CM, Bledsoe CS (2000) Seasonal and diurnal patterns of soil water potential in the rhizosphere of blue oaks: evidence for hydraulic lift. Oecologia 125:459–465

Jackson RB, Sperry JS, Dawson TE (2000) Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci 5:482–488

Kumar S, Anderson SH, Udawatta RP, Kallenbach RL (2012) Water infiltration influenced by agroforestry and grass buffers for a grazed pasture system. Agrofor Sys 84:325–335

Kurz-Besson C, Otieno D, Do Vale RL, Siegwolf R, Schmidt M, Herd A, Nogueira C, David TS, David JS, Tenhunen J, Pereira JS (2006) Hydraulic lift in cork oak trees in a savannah-type Mediterranean ecosystem and its contribution to the local water balance. Plant Soil 282:361–378

Laraus J (2004) The problems of sustainable water use in the Mediterranean and research requirements for agriculture. Ann Appl Biol 144:259–272

Leffler AJ, Peek MS, Ryel RJ, Ivans CY, Caldwell MM (2005) Hydraulic redistribution through the root systems of senesced plants. J Ecol 86:633–642

Lehto T, Zwiazek J (2011) Ectomycorrhizas and water relations of trees: a review. Mycorrhiza 21:71–90

Lin BB (2010) The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric For Meteorol 150:510–518

Liste HH, White JC (2008) Plant hydraulic lift of soil water-implications for crop production and land restoration. Plant Soil 313:1–17

Lott JE, Khan AAH, Ong CK, Black CR (1996) Sap flow measurements of lateral tree roots in agroforestry systems. Tree Physiol 16:995–1001

Ludwig F, Dawson TE, Kroon H, Brendse F, Prins HHT (2003) Hydraulic lift in Acacia tortilis trees on an East African savanna. Oecologia 134:293–300

Magdoff FR, Van Es HM (2009) Building soils for better crops: sustainable soil management. Waldorf, Maryland

McCulley RL, Jobbágy EG, Pockman WT, Jackson RB (2004) Nutrient uptake as a contributing explanation for deep rooting in arid and semi-arid ecosystems. Oecologia 141:620–628

McLaughlin D, Kinzelbach W (2015) Food security and sustainable resource management. Water Resour Res 51:4966–4985

Mittal A (2009) The 2008 food price crisis: rethinking food security policies. UN

Nair PR (1993) An introduction to agroforestry. Springer, Berlin

Neumann RB, Cardon ZG (2012) The magnitude of hydraulic redistribution by plant roots: a review and synthesis of empirical and modeling studies. New Phytol 194:337–352

Nicolas E, Torrecillas A, Ortuño MF, Domingo R, Alarcón JJ (2005) Evaluation of transpiration in adult apricot trees from sap flow measurements. Agric Water Manag 72:131–145

Novák V, Hlaváčiková H (2019) Applied soil hydrology: theory and applications of transport in porous media. Springer Nature Switzerland AG, New York City

Ofori E, Oteng-Darko P, Berchie JN, Nimako FO, Yeboah S, Danquah EO (2014) Monitoring of soil moisture regime and water use efficiency under maize cowpea cropping system. Int J Curr Microbiol App Sci 3:837–848

O'Keefe K, Nippert JB (2017) An assessment of diurnal water uptake in a mesic prairie: evidence for hydraulic lift? Oecologia 183:963–975

Paltineanu IC, Starr JL (1997) Real-time soil water dynamics using multisensory capacitance probes: laboratory calibration. Soil Sci Soc Am J 61:1576–1585

Phillips JG, Riha SJ (1994) Root growth, water uptake, and canopy development in Eucalyptus viminalis seedlings. Aust J Plant Physiol 21:69–78

Prieto I, Martínez-Tillería K, Martínez-Manchego L, Montecinos S, Pugnaire FI, Squeo FA (2010a) Hydraulic lift through transpiration suppression in shrubs from two arid ecosystems: patterns and control mechanisms. Oecologia 163:855–865

Prieto I, Kikvidze Z, Pugnaire FI (2010b) Hydraulic lift: soil processes and transpiration in the Mediterranean leguminous shrub *Retama sphaerocarpa* (L.) Boiss. Plant Soil 329:447–456

Prieto I, Armas C, Pugnaire FI (2012) Water release through plant roots: new insights into its consequences at the plant and ecosystem level. New Phytol 193:830–841

Querejeta JI, Egerton-Warburton LM, Allen MF (2003) Direct nocturnal water transfer from oaks to their mycorrhizal symbionts during severe soil drying. Oecologia 134:55–64

Rao MR, Nair PKR, Ong CK (1998) Biophysical interactions in tropical agroforestry systems. Agrofor Syst 38:3–50

Richards JH, Caldwell MM (1987) Hydraulic lift: substantial nocturnal water transport between soil layers by Artemisia tridentata roots. Oecologia 73:486–489

Robinson DA, Campbell CS, Hopmans JW, Hornbuckle BK, Jones SB, Knight R, Ogden F, Selker J, Wendroth O (2008) Soil moisture measurement for ecological and hydrological watershed-scale observatories: a review. Vadose Zone J 7:358–389

Schippers B, Schroth MN, Hildebrand DC (1967) Emanation of water from underground plant parts. Plant Soil 27:81–91

Scholz FG, Bucci SJ, Goldstein G, Meinzer FC, Franco AC (2002) Hydraulic redistribution of soil water by neotropical savanna trees. Tree Physiol 22:603–612

Sekiya N, Araki H, Yano K (2011) Applying hydraulic lift in an agroecosystem: forage plants with shoots removed supply water to neighboring vegetable crops. Plant Soil 341:39–50

Seyfried MS, Murdock MD (2001) Response of a new soil water sensor to variable soil, water content, and temperature. Soil Sci Soc Am J 65:28–34

Shetty S (2006) Water, food security, and agricultural policy in the Middle East and North Africa region. World Bank, Washington

Susha Lekshmi SU, Singh DN, Baghini MS (2014) A critical review of soil moisture measurement. Measurement 54:92–105

Topp GC, Watt M, Hayhoe HN (1996) Point specific measurement and monitoring of soil water content with an emphasis on TDR. Can J Soil Sci 76:307–316

Udawatta RP, Krstansky JJ, Henderson GS, Garrett HE (2002) Agroforestry practices, runoff, and nutrient loss. J Environ Qual 31:1214–1225

Wan CG, Sosebee RE, McMichael BL (1993) Does Hydraulic lift exist in shallow-rooted species? a quantitative examination with a half-shrub Gutierrezia sarothrae. Plant Soil 153:11–17

Wan CG, Xu W, Sosebee RE, Machado S, Archer T (2000) Hydraulic lift in drought-tolerant and-susceptible maize hybrids. Plant Soil 219:117–126

Walvoord MA, Phillips FM, Stonestrom DA, Evans RD, Hartsough PC, Newman BD, Striegl RG (2003) A reservoir of nitrate beneath desert soils. Science 302:1021–1024

Warren JM, Brooks JR, Meinzer FC, Eberhart JL (2008) Hydraulic redistribution of water from Pinus ponderosa trees to seedlings: evidence for an ectomycorrhizal pathway. New Phytol 178:382–394

Weil RR, Brady NC (2016) The nature and properties of soils. Prentice-Hall Inc, Upper Saddle River

Yoder CK, Nowak RS (1999) Hydraulic lift among native plant species in the Mojave Desert. Plant Soil 215:93–102

Zou CB, Barnes PW, Archer S, McMurtry CR (2005) Soil moisture redistribution as a mechanism of facilitation in savanna tree–shrub clusters. Oecologia 145:32–40

Zhang X, Zhao W, Wang L, Liu Y, Liu Y, Feng Q (2018) Relationship between soil water content and soil particle size on typical slopes of the Loess Plateau during a drought year. Sci Total Environ 648:943–954